

The Use of Stereolithography and Related Technologies to Produce Short Run Tooling

D.S. van der Merwe

The Use of Stereolithography and Related Technologies to Produce Short Run Tooling

David Schalk van der Merwe

Dissertation submitted in fulfilment of the requirements of the

**Magister Technologiae
Engineering: Mechanical**

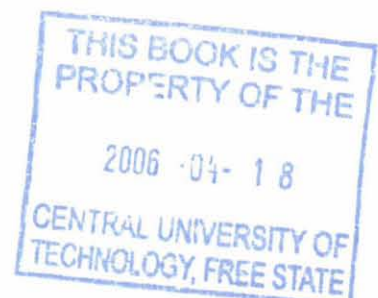
in the

**Faculty of Engineering
School of Mechanical Engineering**

at the

Central University of Technology Free State

**Supervisor : Prof. D. J. de Beer
Co- Supervisor : Dr. W. B. du Preez**



Bloemfontein
November 2005

Declaration of Independent Work

I David Schalk van der Merwe, hereby declare that the research project which has been submitted to CUT by me, for the attainment of the degree MAGISTER TECHNOLOGIAE ENGINEERING MECHANICAL, is my independent work and has not been previously submitted by me or anyone else in view of attaining any qualification.



Signature of Student

25 November 2005

Date

Acknowledgement

I would firstly like to thank CUT (Central University of Technology), in person Prof. Deon de Beer, for his continued support.

My deepest gratitude to the CSIR NPDC (National Product Development Centre), under the supervision of Dr. Willie du Preez, for the resources, keen interest and scientific leadership. To the numerous Employees of the CSIR that contributed to the practical research, thank you.

I would also like to express my appreciation to the commercial companies, which gave me the opportunity to apply rapid tooling methodologies as part of their development programs.

I am confident that the various studies conducted during the course of this project, will form the basis of a decision making process that will reduce risk to the client and the service provider in choosing a rapid tooling avenue.

I thank my wife and family, for their patience and tolerance throughout this birthing process.

Above all, I humbly thank GOD for his blessings and the gifts that I received from Him.

To all mentioned and those in the shadows, thank you once again.

David S. van der Merwe

Synopsis

Where material properties are critical to a polymer part, rapid prototype (RP) models are inappropriate for evaluation purposes and actual parts moulded in a range of materials are required for evaluation. Conventional tool making processes have extremely long lead times considering that numerous iterations may be required. The aim of this project was to generate polymer parts, utilising various approaches to Rapid Tooling (RT), including Stereolithography or related technologies, as part of the process. The objective was to establish decision-making criteria for deciding on the appropriateness of various processes and the risks involved to assist prospective users of these technologies.

The first phase of the project focused on the process validation of utilising Stereolithography as a direct means to generate injection mould tooling inserts, which were fitted into an injection mould designed for the trial purposes. The objective was to obtain process information with regard to insert generation for Stereolithography. A three dimensional model of the part was generated with CAD and the associated mould was generated around the part. The insert halves were processed and solid epoxy inserts were generated with the 3D Systems SLA500 Stereolithography machine. These inserts were post-finished and fitted to the injection mould. Additional features were added to the inserts to test cooling and gating and wear resistance of the cavity material.

The author attended the basic injection tool setting course of the Plastics Federation to enable him to contribute more directly to this process. This also highlighted some of the design issues to facilitate ease of production. Initial difficulties were experienced in finding optimal process parameters.

A total of 70 parts were produced, with measurable insert degradation. During the author's training at 3D Systems in the USA, he obtained additional insight in current methods of insert modelling and insert generation. If these process problems could be overcome, it would be possible to produce in excess of a 100 parts with one set of inserts, assuming a tolerance specification of 0.2mm. The cost of producing the inserts was approximately 50% that of conventional tooling fabrication. The time lapse between growing of the inserts and production of parts was one week compared to 6 to 8 weeks tool manufacture time with conventional methods.

The second phase of the project focused on methods to enhance the cavity surface. Electroplating of inserts and inserts generated from Aluminium filled epoxy were tested, to investigate the effects that plating has on tool life, dimensional accuracy, temperature distribution, and the cost implications for these subsequent process steps. Stereolithography inserts were generated, taking into account the design considerations. Aluminium filled epoxy inserts were subsequently cast from silicone moulds drawn off the Stereolithography master patterns. Two sets of Stereolithography inserts were plated with 20 μm of electrolytic nickel plating. One set of aluminium filled epoxy inserts were plated with electrolytic copper followed by electroless nickel. The mould sets were subjected to the same injection moulding trials using Polypropylene.

The third phase of the project evaluated the use of Stereolithography investment casting masters to produce tool steel inserts, through the QuickCast process. Porosity was evident, with substantial machining required to fit the inserts. Not all the detail was retained during the casting process. Thin rib features on the part were thus lost. Due to the porosity the cooling was changed to copper tubes fitted into the rear of the tool and back-filled with aluminium epoxy. As the Stereolithography patterns were not polished the metal inserts had to be hand finished. This was a time consuming process and skill is required to obtain a good finish. A cost comparison indicated that machining aluminium inserts would be more cost effective. The tool manufacture time and eventual cost is not significantly less than conventional machining. In fact, trials with aluminium High speed CNC machining proved to be more time, finish and cost effective. This is discussed as part of the trial examples.

Wax injection into AIM tooling was investigated on behalf of a client, with good results. As ceramic and polymer injection are very similar, apart from the ceramic being far more abrasive, it is the author's opinion that AIM tooling would be applicable, taking into account that fewer parts may be achieved.

The KelTool process was also investigated during the author's USA visit. The licensing fees and additional equipment are extremely costly due to the Rand /Dollar exchange rate. Issues related to this process are documented in this report.

Clearly the deciding factors remain the quantity of parts required and the complexity of form. Each manufacturing process has a certain level of risk involved. Accumulative risk not only sets manufactured parts at risk but could jeopardise project time scales and iterations of a process have significant impact on a project budget.

Oorsig

Waar materiaaleienskappe krities is in 'n polimeer komponent, is snel-prototipes nie toepaslik vir evaluasie doeleindes nie en is fisiese gegote komponente in 'n reeks plastiek-materiale vir evaluasie nodig. Konvensionele gereedskap vervaardigingsprosesse neem te lank - veral as in ag geneem word dat verskeie iterasies nodig mag wees. Die navorsingsprojek is gefokus om polimeer komponente te vervaardig deur verskeie "snel gereedskap" tegnieke te gebruik, veral Stereolitografie en verwante tegnologie as deel van die vervaardigingsproses. Die oogmerk was om besluitnemingskriteria vir voornemende gebruikers te ontwikkel, deur die toepaslikheid en risikos van die verskeie prosesse te bepaal.

Die eerste fase van die projek was gefokus op die bevestiging van die vervaardiging van gietvorms deur Stereolitografie as 'n direkte metode om inspuit gietvorm insetstukke te vervaardig. Die insetstukke is gepas in 'n inspuit gietvorm ontwerp vir die proses. Die doelwit was om proses informasie te verkry vir die generasie van insetstukke deur Stereolitografie. 'n Drie-dimensionele model is geskep met Rekenaar-Gesteunde Tekene (RGT) ontwerp, waarna die gereedskapstuk rondom die model/komponent ontwikkel is. Dit is van die gereedskap helftes afgetrek om so die komponent holte te skep. Die twee insetstukke is verwerk en die dele is as epoksie-insetstukke deur die 3D Systems SLA500 Stereolitografie stelsel geproduseer. Na afwerking is die dele in die gietvorm geïnstalleer. Om slytasieweerstand en verkoeling te toets, is addisionele detail aangebring.

Die outeur het die basiese opstellingskursus vir inspuit-gietvorming van die Plastiek Federasie bygewoon om meer direk tot die navorsingseksperimente by te dra. Hierdeur is verskeie ontwerp-kriteria uitgelig om produksie te vergemaklik. Aanvanklik is probleme ondervind om optimale vervaardigings-parameters te vind.

'n Totaal van 70 komponente is met aansienlike gepaardgaande slytasie van die insetstuk vervaardig. Tydens die outeur se opleiding by 3D Systems in die VSA, is addisionele insig in metodes vir inset-ontwerp en vervaardiging opgedoen. As bogenoemde probleme oorkom kon word, sou dit moontlik wees om meer as 100 komponente met een stel insetstukke te vervaardig, met die aanname dat 'n tolleransie van 0,2 mm aanvaarbaar is. Die vervaardigingskoste van die insetstukke was naastenby 50% van normale gereedskapvervaardiging. Die tydsverloop tussen insetstukgroei en produsering van komponente was een week vergeleke met 6 tot 8 weke gereedskapvervaardiging met normale metodes.

Die tweede fase van die projek was gefokus op metodes om verbrokkeling van die insetstukke te beperk. Platering van die insetstukke asook insetstukke van Aluminium-gevulde epoksie is getoets om die invloed van platering op gereedskapleef tyd, akuraatheid, hitteverspreiding, asook die koste van die verskeie prosesse te bepaal. Stereolitografie-insetstukke met inagneming van ontwerpvereistes is vervaardig. Aluminium-gevulde epoksie-insetstukke is verder gegiet deur van silikoonvorms, met Stereolitografie-onderdele as meestermodelle, gebruik te maak. Twee stelle Stereolitografie insetsukke is met 20 μm elektrolitiese koper, gevolg deur elektrolose nikkel geplateer. Die geplateerde en ongeplateerde stelle is aan gelyke plastiek-inspuit toetse onderwerp, deur van Polipropileen gebruik te maak.

Die derde fase van die projek is daarop toegespits om die toepaslikheid van Stereolitografie vervaardiging deur die "QuickCast" proses matryse vir die produksie van staal gereedskap insette te evalueer. Porositeit is opgemerk met aansienlike masjinerie nodig om die insette te pas. Nie al die detail is gedurende die gietproses behou nie. Dun web-detail op die komponent is nie gevorm nie. As gevolg van die porositeit is koperpype vir verkoeling vervolgens gebruik en is die holtes met aluminium epoksie gevul. Die Stereolitografie-matryse is nie gepoleer nie en dus moes die metaal insetstukke met die hand afgewerk word. Dit is 'n tydrowende proses en vakmanskap is nodig om 'n goeie afwerking te kry. 'n Kostevergelyking het uitgewys dat masjinerie van aluminium insette meer koste-effektief sou wees. Hoë-spoed CNC masjinerie van aluminium het bewys dat dit inderdaad minder tyd neem, minder kos en beter afwerking lewer. Die bevindings word bespreek as deel van die navorsingsresultate.

Goeie resultate is met was inspuiting in 'n "AIM" gietvorm behaal. Behalwe vir die feit dat keramiek meer afslytend is, is keramiek- en plastiek- inspuitgietvorms baie soortgelyk. Derhalwe is die outeur van opinie dat "AIM" gietvorms ook hiervoor gebruik kan word, met die aanname dat minder komponente gelewer sal word.

Die "KelTool"-proses is ook tydens die outeur se besoek aan die VSA ondersoek. Die lisensiefooi asook die adisionele toerusting wat benodig word om dié proses te bedryf, is geweldig duur, veral inaggenome die Rand/Dollar wisselkoers. Vraagstukke aangaande die proses, vorm deel van die verslag.

Dit is duidelik dat die beslissende faktore die hoeveelheid komponente en die kompleksiteit van die komponent is. Elke proses het 'n mate van risiko. Die kumulatiewe-risiko stel nie net vervaardigde komponente in gevaar nie, maar kan projek-tydskale in gevaar stel en veelvuldige herhalings van die proses kan 'n aansienlike impak hê op die projek begroting.

Contents

	Page
1. Introduction	1
1.1 Historical Background and Research Justification	1
1.2 Project Statement	5
1.3 Project Scope	6
1.4 Objectives	6
2. Literature Overview	8
2.1 Rapid Prototyping Systems Overview	8
2.2 Other Developments	19
3. Materials and Methods	22
3.1 Stereolithography	22
3.2 Calibration Parts and Procedures	45
3.3 The Process – Software	47
3.4 The Process – Built Parts	58
3.5 Injection Moulding	66
3.6 Mould Construction	81
3.7 Conventional Tool Manufacture	87
3.8 Tool Making Materials	92
3.9 Mould Installation	94
3.10 Running of an Injection Moulding Machine	97
3.11 Polymers Related to Trials	100
3.12 Fault Identification and Rectification	104
3.13 Coating Techniques	107
3.14 Temperature Distribution and Mould Cooling	114
4. Experimental Results	118
4.1 Study 1 – User Part	118
4.2 Study 2 – Bottle Opener	143
4.3 Study 3 – QuickCast Bottle Opener	173
4.4 Study 4 – QuickCast Blow Mould Bottle Tool	188
4.5 Study 5 – HSM Blow Mould Bottle Tool	190
4.6 Study 6 – Conventional Machining – Bottle Cap	191
4.7 Study 7 – Conventional Machining – Create Adapter	192
5. Discussion of Results	193
5.1 Observations	193
5.2 Comparison with other methods	196
6. Conclusion	198
6.1 Time, Cost, Quality and Risk Versus Quantity of Parts	198
7. References	201

List of Appendices

Appendix A – Injection Moulding Fault Finding Chart

202

Glossary

2D	Two Dimensional – Length (y), Width (x)
3D	Three Dimensional – Height (z), Width (x), Length (y)
ABS	Acrylonitrile Butadiene Styrene
ACES	Accurate Clear Epoxy Solid – Stereolithography Build Style
AEC	Atomic Energy Corporation
AIM	ACES Injection Moulding
AMP	Advanced Materials Program
AOM	Acoustic Optical Modulator
BUILD STATION	Rapid Prototyping System
CAD	Computer Aided Design
CNC	Computer Numeric Controlled
CSIR	Council for Scientific and Industrial Research
DTM	German manufacturer of Laser Sintering Systems
DXF	Data Exchange Format
EDM	Electro Discharge Machining “Spark Erosion”
FAD	Full Saturation Detector
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FTP	File Transfer Protocol
HATCH	Scan parameter for internal solid material of a layer – enclosed by a Boarder
HDPE	High Density Polyethylene
IGES	Initial Graphics Exchange Specification
KELTOOL	Proprietary Cast Tooling Method – 3D Systems

LOM	Laminated Object Manufacturing – Rapid Prototyping Technology
LWC	Line Width Compensation – Offset Calibration of Laser Beam
MATTEK	Materials Technology Division of the CSIR
PCA	Post Curing Apparatus – Used to Cure SLA Parts
PFSA	Plastic Federation of South Africa – Industry Training Body
PP	Polypropylene
PVC	Poly-Vinyl-Chloride – Thermoplastic Polymer
QUICKCAST	Quasi Hollow Stereolithography Part – Used for Investment Casting
QUICKCAST- CHIMNEY	Tubular device to connect air hose to hollow SLA part to check for leaks
RCD	Reliability Centred Design
RIM	Reaction Injection Moulding
RP	Rapid Prototyping
RP&M	Rapid Prototyping and Machining
RTV	Room Temperature Vulcanising – Silicone Rubber Compounds
SCF	Shrinkage Factor
SLA	Stereolithography Apparatus – A Rapid Prototyping Technology
SLA500	Model of 3D Systems Stereolithography Machine – (used for trials)
SLA5180	CIBA – Resin Formulated for the SLA500 Machine
SLA7000	Model of 3D Systems Stereolithography Machine – (0.01mm layers)
SLS	Selective Laser Sintering – A Rapid Prototyping Technology
STAIR STEPPING	Surface Effect of Layer Based Prototyping Systems
TCT	Time Compression Technology
TPM	Solvent used to wash Stereolithography parts while in green state
UV	Ultra Violet Light
VISTA	Support generating software for part preparation – 3D Systems
ZEPHYR BLADE	Vacuum re-coat arm fitted to 3D Systems Stereolithography Machines

List of Figures

Figure 1:	The Cost of Change	1
Figure 2:	Time the Competitive Weapon	2
Figure 3:	Schematic of Workflow – Project	7
Figure 4:	Schematic of FDM Operation	10
Figure 5:	Schematic of LOM Operation	11
Figure 6:	LOM Prototype Parts	14
Figure 7:	EOS – EOSINT M270 SLS System	15
Figure 8:	3D Systems – HIQ SLS System	16
Figure 9:	Schematic of SLS Operation	17
Figure 10:	SLA500 Machine	22
Figure 11:	SLA7000 Machine	23
Figure 12:	Cure Depth and Width by Laser Beam	30
Figure 13:	Curl Distortion	31
Figure 14:	Schematic of Resin Level Sensor	35
Figure 15:	Schematic of Optical Layout of the SLA500	38
Figure 16:	Typical Working Curve	44
Figure 17:	Line Width Compensation	44
Figure 18:	WINDOWPANE Part	45
Figure 19:	CHRISTMAS – TREE Part	46
Figure 20:	Stair Stepping Effect	48
Figure 21:	CAD Information Flow	49
Figure 22:	File Conversion Process	51
Figure 23:	Ramco Cleaning System	59
Figure 24:	Dadan & Sons Resin Extraction Unit	60
Figure 25:	Schematic of Engel 80 ton Tie-bar-less Injection Moulding Machine	67
Figure 26:	Injection Moulding Machine	67
Figure 27:	Injection Moulding Cycle	71
Figure 28:	Injection Mould	82
Figure 29:	Injection Mould Shot	83
Figure 30:	Plasma Arc Spraying	108
Figure 31:	Physical Vapour Deposition	109
Figure 32:	Reducing Corner Build-up	111
Figure 33:	Cooling Channel Placement	115
Figure 34:	Temperature vs. Time for Injection Mould Cycle of SLA without Cooling	117
Figure 35:	3D CAD Image of Modified User Part	118
Figure 36:	CAD Image of Assembled Tool with Inserts Fitted	120
Figure 37:	Tool Assembly Drawing	121
Figure 38:	3D CAD Images of Cavity & Core Inserts	122
Figure 39:	Engel Injection Moulding Machine	123
Figure 40:	Various Moulded Parts with AIM Insert	126
Figure 41:	Rib Thickness Versus Shot Number	132
Figure 42:	Curve Fits to Rib Thickness Measurements	133

Figure 43:	Overall Width Versus Shot Number	133
Figure 44:	Shot Size Calibration Curve1	134
Figure 45:	User Part Showing Warping and Cold Weld	139
Figure 46:	User Part Cavity Insert Showing Signs of Chipping	139
Figure 47:	User Part Filled 25% to 95%	140
Figure 48:	Material Flow Direction	141
Figure 49:	Material Temperature Versus Cooling Time	141
Figure 50:	Injection Pressure Curve	142
Figure 51:	Bottle Opener Parts	143
Figure 52:	Typical Configuration of Vacuum Casting System	147
Figure 53:	Sample Moulding in ALWA MOULD V	148
Figure 54:	Mould H Air Bubbles	154
Figure 55:	Fixed Half Insert Mounted in Injection Moulder	156
Figure 56:	Moving Half with Epoxy Plated Insert Mounted in Injection Moulder	156
Figure 57:	Un-Plated Aluminium Epoxy Inserts	160
Figure 58:	Surface Detail of an Un-plated Aluminium Epoxy Insert	160
Figure 59:	Plating and Epoxy Chip from Aluminium Epoxy Insert	162
Figure 60:	Surface Detail of Plated Aluminium Epoxy Insert	163
Figure 61:	Plating Cracks on SLA Inserts	165
Figure 62:	Chipping Around Sprue Bush	166
Figure 63:	SLA Bottle Opener Inserts Before Plating	166
Figure 64:	Chipping Around Gate Area	167
Figure 65:	SLA User Part Inserts	170
Figure 66:	Chipping from User Part Corner	170
Figure 67:	Cored Insert for Investment Casting Process	173
Figure 68:	Bottle Opener Width	178
Figure 69:	Hole to Hole Dimension for Bottle Opener	179
Figure 70:	Assembled Opener Showing Polished and Natural Finish	179
Figure 71:	Sample Transparent Silicone Mould	181
Figure 72:	QuickCast Patterns for Blow Mould	189
Figure 73:	Shelled QuickCast Patterns for Investment Casting	189
Figure 74:	Bottle Cap Component	191
Figure 75:	Create Adapter	192
Figure 76:	Rapid Tooling Processes	197

List of Tables

Table 1:	3D Systems – SLA500, Specifications	22
Table 2:	SL 5180 Liquid Resin Properties	26
Table 3:	Mechanical Properties of Cured SL 5180 Resin	27
Table 4:	Thermal Properties of SL 5180 Resin	27
Table 5:	Electrical Properties of SL 5180 Resin	28
Table 6:	Water Absorption of Liquid SL 5180 Resin	28
Table 7:	Part Parameters for SL 5180 Resin	29
Table 8:	Support Parameters for SL 5180 Resin	29
Table 9:	Recoat Parameters for SL 5180 Resin	29
Table 10:	Methodical Designing of Injection Moulds	70
Table 11:	SASOL Polymers – Polypropylene Comparison	103
Table 12:	Amorphous Versus Crystalline Properties	103
Table 13:	Moulding Fault and Description	106
Table 14:	ENGEL Injection Moulding Machine Specifications	124
Table 15.1:	Set-up Parameters	125
Table 15.2:	Set-up Parameters	126
Table 16.1:	Record of Shots Trial 1	127
Table 16.2:	Record of Shots Trial 1	128
Table 16.3:	Record of Shots Trial 1	129
Table 17:	Original Part Dimensions	129
Table 18:	Moulded Part Measurements	130
Table 19:	Optimum Machine Parameters	132
Table 20:	Trouble Shooting Table for Alwa Mould V Processing	150
Table 21:	Dimensional Deviation	151
Table 22:	Processing of ALWA Mould H	153
Table 23:	Dimensional Results of Un-Plated Aluminium Epoxy Inserts – PP	158
Table 24:	Parameters for Aluminium Epoxy Insert Using PP	159
Table 25:	Parameters for Un-Plated Aluminium Epoxy Insert Using ABS	159
Table 26:	Dimensional Results of Plated Aluminium Epoxy Inserts - PP	161
Table 27:	Parameters for Plated Aluminium Epoxy Insert Using PP	162
Table 28:	Dimensional Results of Plated Stereolithography Inserts – PP	164
Table 29:	Parameters for Plated SLA Inserts Using PP	164
Table 30:	Stereolithography Un-Plated User Part Test Record	168
Table 31:	Dimensional Results of Stereolithography Un-Plated User Part	169
Table 32:	Parameters for Un-Plated SLA User Part Inserts Using PP	169
Table 33:	Stereolithography Plated User Part Test Record	171
Table 34:	Parameters for Plated SLA User Part Inserts Using PP	172
Table 35:	Parameters for Cast Steel Inserts Using HDPE	176
Table 36:	Parameters for Cast Steel Inserts Using ABS	176
Table 37:	Dimensional Results of Cast Steel Bottle Opener Part Trials – HDPE	177
Table 38:	Dimensional Results of Cast Steel Bottle Opener Part Trials – ABS	178
Table 39:	Key Factor Table	199

List of Equations

E.1. Laser Exposure	30
E.2. Working Curve	43
E.3. Mirror Bits	53
E.4. Autocatalytic Plating	111
E.5. Shrinkage	131

1. INTRODUCTION

1.1. Historical Background and Research Justification

It is beyond dispute that today's business and manufacturing environments are becoming increasingly competitive. A Company wishing to survive needs to exploit the advantages that new technology provides. Any technology that can claim to cut new product costs by $\pm 70\%$ and time to market by $\pm 90\%$ [1] deserves serious consideration. As does a technology that allows prototypes of new products to be produced quickly without compromising complexity, thereby allowing product verification to be done throughout the development phase. As discussed by De Beer [7] in the context of Rapid Prototyping's impact on the product development process, it is in the conceptual phase of the design that most of the cost decisions related to the manufacturing process are made. This results in 80% of the decisions for downstream manufacturing being made in the first 20% of the process.

From Figure 1 it can be seen that for every stage in the design to manufacture process where the designer fails to identify the original errors in the concept phase, the cost of the corrective action increases by a factor of ten. This clearly illustrates the financial benefit of eliminating manufacturing complications timeously.

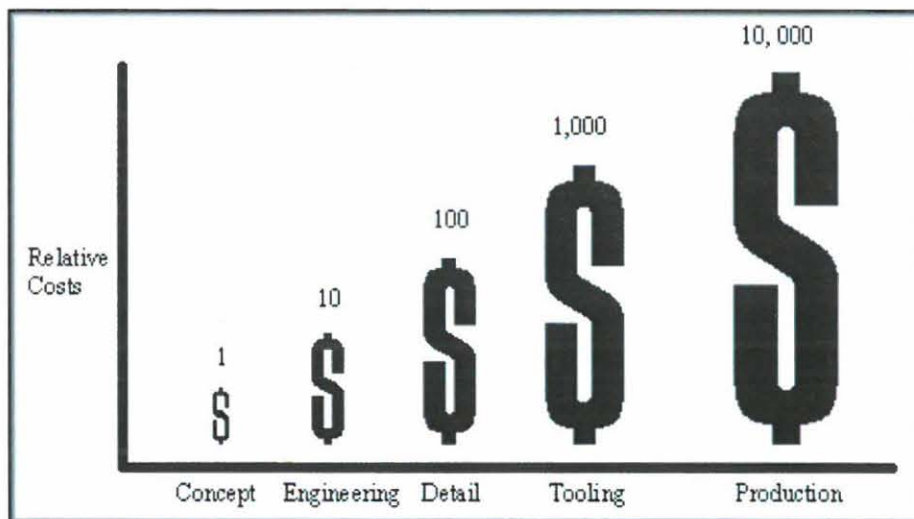


Figure 1: The Cost of Change (As used by De Beer [7])

As per De Beer [7] if a product is produced within budget, but six months late, up to 50% of the profitability window could be lost. If the same product is produced at 50% over the

budget, but on time, only 3% of the profitability window will be lost as illustrated in Figure 2.

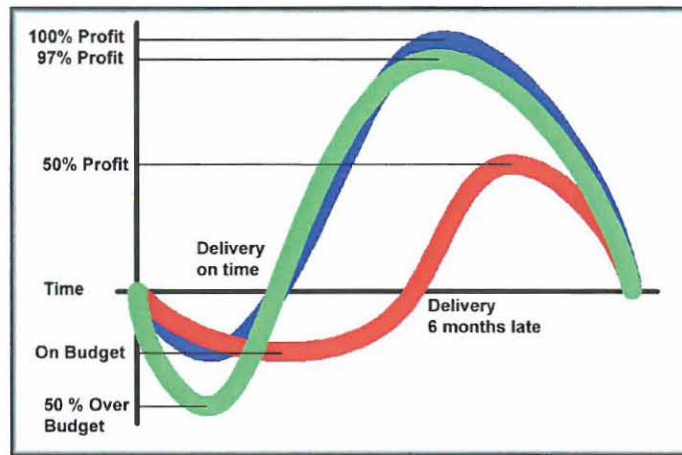


Figure 2: Time, the Competitive Weapon

One of these Time Compression Technologies that strives to reduce risk and time to market is known as Rapid Prototyping (RP). Hilton [11] defines RP as a technology that “...uses additive processes to create a physical geometry from a CAD file, replacing (conventional) methods that remove material”.

Conventional methods include Machining processes such as milling, turning, grinding and spark erosion. Machining methods are limited to cutter sizes, machining vibration, material properties and lengthy set-up times if machining is required from different angles on the work piece.

Rapid Prototyping can be categorised by material i.e.:

- **Photo-Polymer**

Photo-polymer systems start with a liquid resin, which is then solidified by controlled exposure to a specific wavelength of light – *Stereolithography Apparatus*.

- **Thermoplastic**

Thermoplastic systems begin with a solid polymer, which is melted and fuses upon cooling – *Fused Deposition Modellers*.

- **Adhesives**

Adhesive systems use an adhesive film to connect primary construction material to itself – *Laminated Object Manufacturing*.

- **Sintered Materials**

Sintered material systems locally heat powders, which fuse to produce a prototype. Metal powders, Polymers and foundry sand can be processed in these systems – *Selective Laser Sintering*.

Rapid prototyping systems are capable of creating parts with small internal cavities and complex geometry. The integration of rapid prototyping and casting processes has resulted in faster generation of patterns from which moulds are made.

Bridge tooling is the process by which injection moulds are produced directly from CAD models, resulting in moulded parts without the use of conventional machining to generate the cavities. Bridge tooling is a downstream development from rapid prototyping as industries stretch the boundaries of these emerging technologies.

Although SLS has the advantage of sintering metal powders into tool inserts, the shrinkage and surface finish of the post heat-treated part has been an inhibiting factor which still needs to receive further attention. Stereolithography, as the oldest and most wide spread rapid prototyping technology, has attracted most of the Bridge tooling attention. Good dimensional accuracy can also be maintained.

The use of bridge tooling allows a reduction in development time, thus gaining a competitive edge for companies. The main benefit is the reduction in lead-time, which for traditional machining techniques could range between 4-12 weeks. Bridge tooling allows a working model to be produced in 3 – 5 working days. The main purpose of bridge tooling is to produce a number of functional prototypes in the actual production material. These parts can be used to compare various materials under operating conditions, evaluate part behaviour, and eliminate design flaws in the part or the tool design, before investing in hard tooling. These parts are also suitable for marketing and consumer trials. If the process produces the quality required, this method can be used as a lead in to production, subject to the availability of production steel tooling.

Bridge tooling is primarily known as Direct AIM. The industry also refers to the process as Direct ACES (Accurate Clear Epoxy Solid) Injection Moulding and was pioneered in 1994 [18]. It has only recently been better understood and utilised. The idea of directly injecting molten plastic into Epoxy Cavities seemed unlikely to succeed. However, work carried out in this field proved otherwise. There are a number of companies that have researched this process. These include Plynetics Corporation, Knight Modle and Prototype, Compression Inc., Xerox and Mould Base Industries Inc., all based in the USA. No attempts to demonstrate or research this fabrication method, was done in South-Africa until now. (The technology is still in its infancy in South-Africa).

Direct AIM can be an exceptionally effective technique. Theoretically, entire projects, from CAD design to 100 injection moulded prototype parts can be accomplished in *five days*. If possible, this constitutes an enormous time saving – which in turn, will also realise a cost saving.

Epoxy insert material has poor thermal conductivity and should prolong the melt of the material flowing through the cavity. This could aid in reducing injection pressures. Trial materials can also be processed at the lower end of the operational spectrum, minimising the risk of degrading the moulding material.

Potential users of Bridge tooling include any fast changing industry. Clients seeking to reduce development risk and practice RCD (Reliability Centred Design) are the most likely users. In today's manufacturing environment, where there are moves toward full customisation [17], almost any manufacturing concern producing polymer components would benefit from this process. Theoretically bridge tooling, when successful, is especially applicable where a limited number, 100 – 200 prototypes, are required and when the cost of traditional tooling cannot be justified.

South Africa has been slow in adopting RP technologies. At present there are only a few operational facilities, with a select client base. All four Stereolithography systems in South Africa are from 3D Systems in the USA, with the largest capacity system at the CSIR in Pretoria.

Little data is available on exactly how many accurate parts can be produced on an injection-moulding machine using Epoxy inserts. The information published by the companies mentioned earlier is general and they are not willing to divulge test

results. Many companies involved in product development need information to assist them in making decisions on appropriate prototyping solutions depending on project requirements.

This in essence, forms the justification for this project.

As this process significantly impacts on the delivery time of prototype tooling and therefore actual compounds, the risk and time scales of product qualification is significantly reduced. This creates a strategic advantage to the company that employs these unique combinations of technologies. The risk in committing production capital alone is a decisive factor. With the economic position of South Africa, significant returns can be gained on the global market. The South African enterprise can however not afford to gamble its weak capital funds to enter the market on a trial and error basis.

1.2. Project Statement

This project investigated the use of bridge tooling for limited run injection moulding. Cost and time comparisons with conventional tool manufacture formed part of the feasibility evaluation. Tool life, quality of components and process risk was considered as part of the feasibility criteria.

Optimal processing parameters for each step in the design, manufacture and injection moulding process was required to ensure repeatability.

The project was conducted in a phased approach. The first iteration was to establish a baseline for the subsequent iterations. With every iteration, a limited group of issues was addressed to minimise process variables. This included part design and complexity, tool design and insert configuration, insert manufacture and finishing, as well as injection moulding process parameters.

1.3. Project Scope

The research consisted of a full Rapid Tooling cycles and involved:

- Gaining a thorough understanding of the underlying processes and equipment through a comprehensive literature survey and supported by training
- Attending Advanced user training for the Stereolithography equipment – 3D Systems, Valencia, USA
- Attending Basic Tool setting training – Plastics Federation of South Africa, Midrand, Gauteng
- Designing and modelling of the trial component on CAD
- The design of the injection mould tool – standard tool with replaceable inserts to reduce future time and manufacture costs
- The manufacture of the inserts via Stereolithography
- The manufacture of the injection mould tool
- Injection moulding of plastic components with the Stereolithography inserts. Selecting appropriate process parameters. Noting tool wear characteristics and component quality
- Investigating the temperature distribution through the inserts during the moulding cycle
- Investigating the effect of various release agents on the quality of parts and the ease of moulding
- Cost comparison of conventional methods versus Rapid Tooling Technologies.

The first study consisted of two iterations. The first inserts were produced with no shrinkage allowance. The second iteration accounted for shrinkage and corrected the mistakes made in the first iteration.

1.4. Objectives

The objectives for the research were:

- To gain a thorough understanding of Rapid Prototyping technologies (specifically Stereolithography), mould design for injection moulding and the operation of injection moulding presses.

- To design a mould for the part specified above. To reproduce the CAD model of the mould (cavity and core) as Rapid Prototypes on the SLA500 at the CSIR.
 - To obtain qualitative and quantitative information with regard to the life of the inserts under moulding conditions. To document the relationship between part dimensions, shot number and critical injection mould settings.
 - To compare the cost and time factors of producing the specific part via conventional and RP techniques.
- **Schematic of Workflow – With Case Study Iterations**

Figure 3 shows the cyclic iterations of the various experimental tooling cycles.

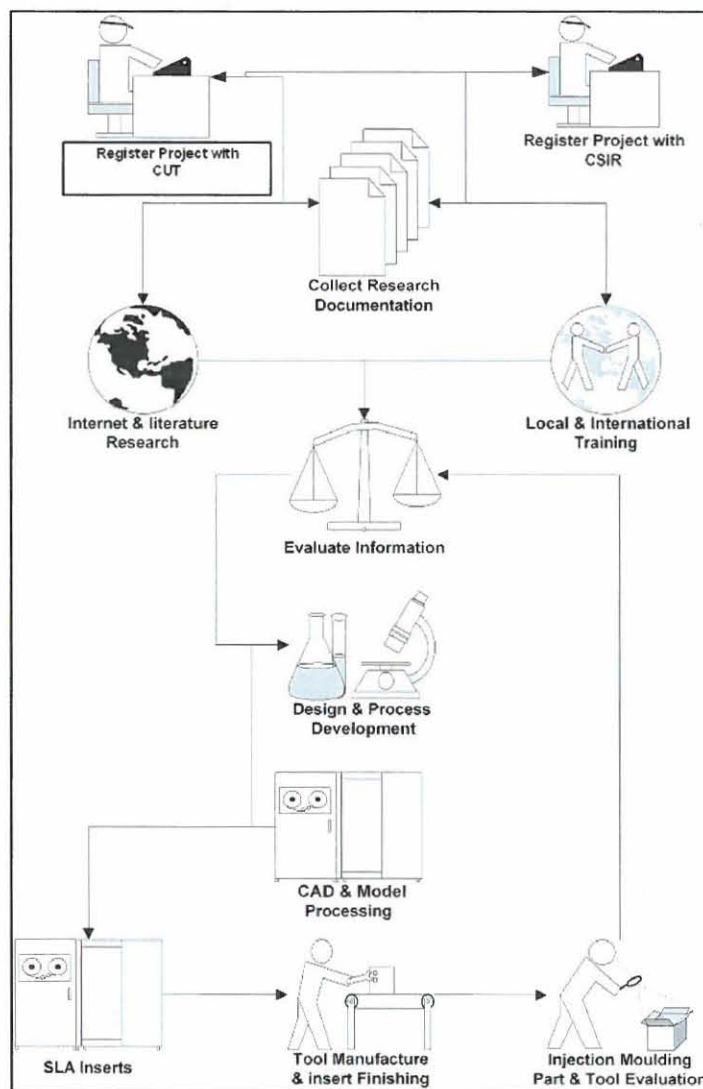
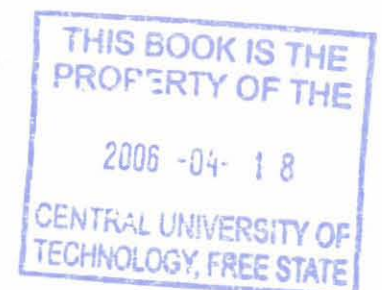


Figure 3: Workflow of Project



2. LITERATURE OVERVIEW

2.1. RAPID PROTOTYPING SYSTEMS OVERVIEW

These technologies have surpassed the point of being an experimental concept and are solidly entrenched as part of the natural product development route, even in the South African industries.

Unfortunately, the cost of establishing the equipment and the exchange rate of South Africa drastically limits the range of technologies available. At present these include Stereolithography, Fused Deposition Modelling, Sanders 3D printing, Selective Laser Sintering, LOM (Laminated Object Manufacturing), Z-Corp and Dimension 3D Printing.

A growing trend in the RP&M industry is toward multiple purchases, single companies investing in multiple technologies. This allows the user to select the appropriate technology, depending on the requirements or item specific criteria, e.g. mechanical properties required from the model.

The basic principles of the main systems appropriate for rapid tooling will be discussed briefly.

Rapid Prototyping describes the scope of technologies where a 3D CAD model of a solid object is converted into a solid artefact in an additive process. In most of the commercial processes the CAD model is sliced in thin cross-sectional layers. These layers are consecutively reproduced on top of each other to accurately reproduce the original 3D intent.

The following systems will be reviewed briefly, from an operational point of view:

- Fused Deposition Modelling
- Laminated Object Manufacture
- Selective Laser Sintering
-

Stereolithography is discussed in depth in Chapter 3.1.

Although RP has grown in popularity internationally as a production method for prototype and development masters, its application in the manufacturing arena has been far slower.

Patterns are used to develop jigs and fixtures or as a discussion tool between tooling and development departments. For investment casting and sand casting, RP components are used as master patterns. For the polymer industry, however, Rapid Tooling has not been widely accepted.

i. Fused Deposition Modelling

Fused Deposition Modelling (FDM), developed by Stratasys Inc. of Minnesota, uses spools of thermoplastic or wax to produce parts. The process is based on controlled extrusion, where the filament material (1.78mm in diameter) is fed into a heating chamber, melted at a controlled temperature and extruded through a specific size nozzle. A control system drives the melting head to deposit the material at the required X-Y location. The feed rate of the material is used to control the deposition rate. This process is illustrated in Figure 4. To obtain bonding between layers, the previous layer is kept at a temperature just below solidification as the next layer is deposited. As the delivery head is fixed in the Z-axis, a computer-controlled table is lowered by a layer thickness after each cross section.

A foam base is required to key the first layer of the support. Surface flatness is crucial for the foundation layers as this could result in warping or the head toppling the part during the build.

The material's physical properties, delivery speed, extrusion pressure and nozzle orifice sizes determine layer thickness of each layer. Surface finish is influenced by layer thickness, operating temperatures and can even cause de-lamination. Too high a melting point will cause degradation of the build material.

Wax and ABS thermoplastic has been used successfully as patterns for investment casting. A major problem is the drying out of filament material in storage. The material (especially the wax) should be sealed to prevent the material from becoming brittle. The material tends to break under the strain of feeding to the head resulting in the system only building a section of the model.

The FDM machine is quite simple to operate and safe apart from the elevated temperatures of the head. The amount of mechanical noise can be a disturbing factor in an office environment.

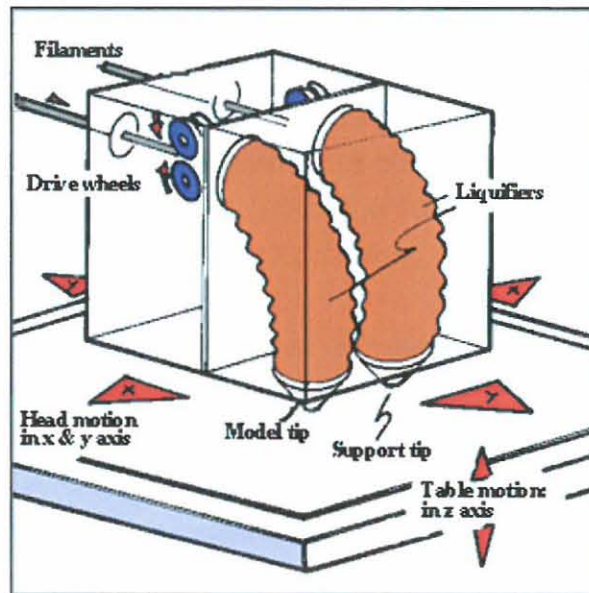


Figure 4: Schematic Diagram of FDM Operation

- **Conclusion**

ABS and Wax patterns for small parts (not high detail) can be used to generate tooling through investment casting. Post machining will have to be used to obtain the size and surface finish required. The ABS material is more suitable as better surface finish can be obtained in the pattern and it is not as fragile as the wax patterns. The ABS patterns can easily be joined to form larger patterns. As the support material is different in composition and colour from the part, support removal is easy.

ii. Laminated Object Manufacturing

Helisys, Inc in Torrance, California initially developed the laminated object manufacturing (LOM) process. The process is also layered based as the name implies. The LOM process fabricates parts by laminating sheets of material consecutively onto each other. Layers are joined using an adhesive that is both temperature and pressure sensitive. The individual cross-sections are cut using a 25 or 50W carbon dioxide (CO_2) laser, emitting infrared, at a wavelength of 10.6 microns.

The process also starts with receiving an ".stl" file. The file is sliced at exactly the same layer thickness as the laminating sheet material. (Typically adhesive-coated paper). The material is supplied to the working area as part of a continuous roll as per Figure 5. The unused material is rolled onto a take-up roller. A computer-driven platform is lowered by the thickness of the laminating material after each laser scan. The laser beam is directed onto the surface of the material and is driven in the x and y directions via focussing optics. A heated roller located above the laminate activates the adhesive to bond the next layer.

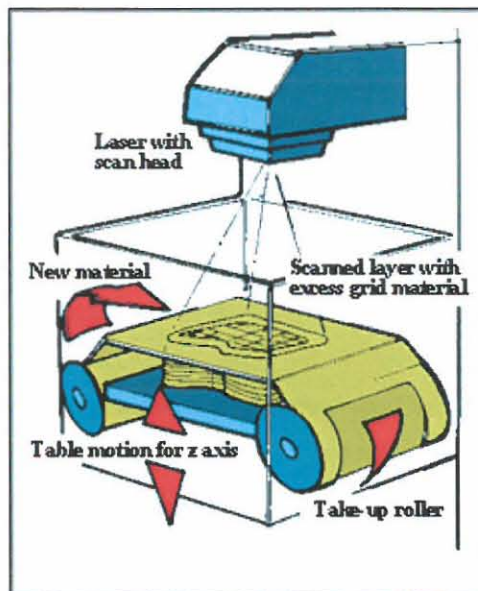


Figure 5: Schematic Diagram of LOM Operation

The laser burns a line through the working material, generating the boundary of the cross-section of the part. The depth and width of the cut depends on the laser power, scan speed and physical properties of the working material. Control of these parameters

affects part accuracy. To date, LOM systems do not compensate for the beam width and therefore this results in a consistent dimensional error on each part cross-section.

The whole working surface is re-coated with adhesive and material. One advantage is that the surrounding material generates a support system for the part. To facilitate the removal of this support material, the laser draws a block pattern to ease removal of the part from the block of laminated material. Removing large parts, typically foundry patterns is not a problem. However the removal of the support material from complex parts or small detail parts presents great difficulty. All cantilever surfaces pose a problem as these surfaces adhere to the support material below it. To alleviate this problem, the underlying layer is hatched with a close spacing to facilitate the removal of support material.

LOM parts made from paper resemble wood. The parts even look, feel, and smell like wood. It is recommended that parts generated with paper be coated immediately with a sealer to reduce the risk of water absorption. LOM parts can be modified or worked with traditional processes i.e. drilling, milling, turning etc. This process is ideally suited to sand casting patterns, as these geometries do not require fine detail or high tolerances.

The system relies on the thermal mass of the material to dissipate the heat of the laser. It has happened that the paper has burned beyond the desired layer cross-section.

Helisys has demonstrated that plastics, metals and even ceramic tapes can be used as build material. The most popular still remains paper. The paper parts have also been used in the investment casting process.

At present these systems still have the largest working area. A working accuracy of $\pm 0.25\text{mm}$ over the working envelope can be achieved in the X-Y plane. As the LOM system only scans the part boundary, it is considerably faster than other rapid prototyping systems. The speed of these systems is limited to the X-Y positioning system, as the lasers available will accommodate higher scan speeds.

- **Tooling Applications for LOM**

LOM is suitable for any system where wood or plastic moulds or patterns can be used.

The following secondary processes can also be used:

- **Investment Casting**

LOM is suitable for direct or indirect investment casting. One process used for low volume production of metal parts is the “lost paper” shell investment casting process. The master pattern is burned from the ceramic shell. The patterns have no expansion during the burn out process and the shell is less susceptible to cracking, unlike Stereolithography. Metal is poured into the ceramic cavity and a single component is produced. LOM is also used to generate two part tooling for wax injection to produce multiple waxes for mass production. This is called indirect investment casting. The mould must be sealed with a protective coating and can produce up to 100 parts. Where a larger volume is required a metal-filled epoxy tool can be produced from a LOM master pattern. Metal epoxy tooling can produce approximately 1000 wax parts.

- **Sand Casting**

Due to the large part size that can be produced on the LOM system and its wood qualities, it is commonly used to produce foundry patterns and cores for sand casting. For high volume casting, in the region of 1000 and more, the patterns can be converted into metal through investment casting or polymer parts through soft tooling.

- **Silicone Rubber Moulding**

This is a quick process to duplicate a master pattern. Room Temperature Vulcanising (RTV) silicone is poured over the master pattern and after setting leaves a cavity in which urethanes or epoxies can be cast.

- **Vacuum Moulding**

This process is similar to Silicone Rubber Moulding, but differs in that the casting is done under a controlled vacuum or pressure. This results in better mould and part quality. The risk of trapping air in the cavity is vastly reduced.

LOM patterns can also be used for traditional vacuum forming. Prototype parts can be produced in a wide selection of thermoplastic sheet materials. The LOM pattern withstands the compression forces of the vacuum process.

- **Spray Metal Tooling**

With Spray Metal Tooling, a low melting point metal is sprayed on the surfaces of LOM patterns. The resultant tooling is used for short run injection mould tooling. This type of tooling is capable of producing up to a 1 000 injection moulded parts. LOM split patterns are suitable for this application.

- **Prototype and Low-Production Injection Moulding**

LOM negative tool halves can be converted into aluminium or steel tool parts through the investment casting process. Post machining and finishing can be used to obtain the tolerances required. This is only applicable where no fine detail is required as this is a limitation of the LOM process. Figure 6 shows typical casting parts grown with LOM.



Figure 6: LOM Prototype Parts

- **Conclusion**

LOM can be used in two manners to generate prototype tooling. The first is through the use of the LOM pattern into investment casting and the second method for simple tools where metal sheet can be used to produce the cavity and core. In the latter an alternative adhesive to bond the layers should be used.

iii. Selective Laser Sintering

According to the EOS website the Selective Laser Sintering (SLS) process was originally developed at the University of Texas in Austin and was sold by DTM Corporation in the USA. EOS GmbH was founded by Dr. Hans J. Langer in Graefelfing near Munich, Germany in 1989 and sold their first system in 1991. In 2004 an additional licence agreement with 3D Systems gives EOS rights to all relevant patents formerly owned by DTM Corp. or licensed from the University of Texas. This has led to the **EOSINT M 270** shown in Figure 7, a Laser-sintering system for the direct production of prototypes and end products as well as tooling inserts for injection moulding and other tooling methods directly from steel-based and other metal materials. This system has a building volume of 250 x 250 x 215 mm and the system uses a Yb-fibre, 200 W laser.



Figure 7: EOS - EOSINT M 270 LS System

3D Systems Inc. has also branched out into the SLS market with their HiQ™ SLS system. Figure 8 is a picture of a HiQ™ SLS system.



Figure 8: 3D Systems - HiQ™ SLS System

The SLS process is based on selectively fusing small particles of materials together with a high-powered laser, at least a 50 - Watt CO₂ laser. As with the previous systems, this is also a layer-additive process and starts with reading in an “.stl “ file.

The major advantage of the above system is the wide range of materials that it is capable of processing i.e. Polymers, foundry sand, wax and metal powders. The layers are formed by depositing a thin layer of powder over the working surface. A feed roller that will deposit the material for the next layer removes excess material.

The laser, emitting in the infrared region at 10.6 microns, is directed by a pair of orthogonal mirrors and optically focussed onto the working surface. Depending on the materials' infrared spectral absorption characteristics, a portion of the laser energy is absorbed by the powder as heat. To minimise the laser output the material chamber, as illustrated in Figure 9 is kept at an elevated temperature, just below the fusing point of the particular material.

Furthermore, to avoid oxidation of the bonding surfaces and reduce the risk of combustion/explosion, the build chamber is operated in an inert nitrogen environment. The oxygen concentration is best maintained below 2%.

With amorphous materials, the laser causes the powder particles to soften and bond to one another at their mutual points of contact. This forms a quasi-solid or porous part. The density is dependent on the powder being processed. This also has a direct

influence on mechanical properties. The tensile strength of a SLS part is vastly lower than its injection moulded counterpart.

The slice of the SLS part is scanned in a raster fashion. Raster scanning causes X -Y errors known as horizontal aliasing. A diagonal line will be drawn in a zigzag fashion similar to a dot matrix printer. This contributes to the rough surface finish of SLS parts. The surrounding powder in the building chamber supports the part. For some geometry, anchors or supports need to be generated to minimise distortion. On removal, the part is contained in a cake of partially sintered material. This cake needs to be cooled down slowly to minimise shrinkage errors. The excess material is removed by cutting with spatulas, brushes, dental tools and compressed air. Final clean up is achieved by sandblasting with glass beads.

For metal components with the 3D Systems process, a metal powder coated in a binder is processed. The green part is cleaned and placed in an oven to burn off the binder and sinter the metal powder. The porous structure can be infiltrated under vacuum with a low melting point copper- tin alloy. During the burning off of the binder, a significant amount of shrinkage occurs.

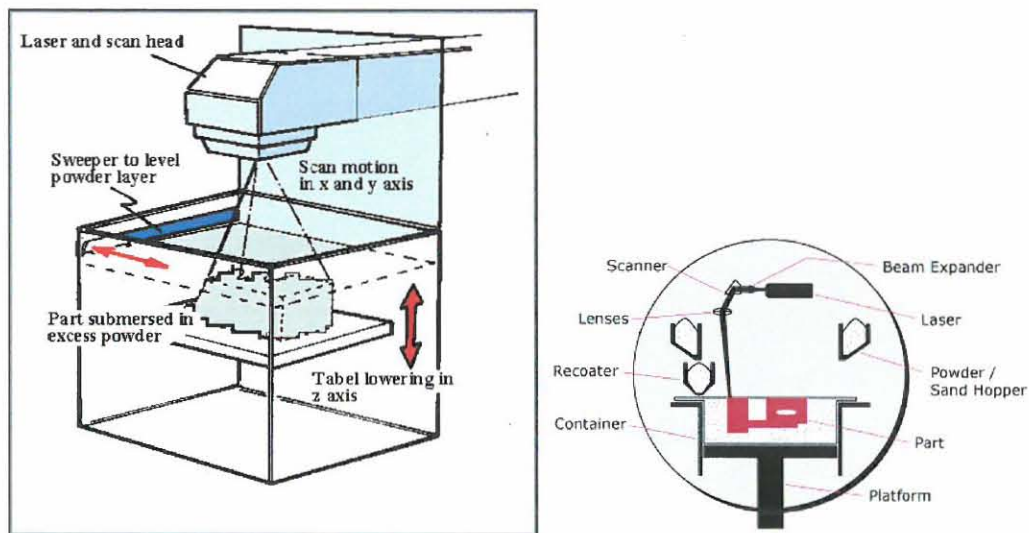


Figure 9: Schematic Diagram of SLS Operation

- **Conclusion**

Two possible methods to generate tooling with Selective Laser Sintering are: The first as a pattern for investment casting and secondly the direct sintering of metal powder as with the **EOSINT M 270**. This is the first direct method of producing metal components from a rapid prototyping system.

2.2. OTHER DEVELOPMENTS

i. KelTool – 3D Systems

This process allows the replication of a master in fused powdered steel. Irrespective of the advances made with lower volume tooling, industry continually seek alternative methods to reduce tooling time and cost.

KelTool, a patented process is suitable for the generation of complex geometry tool inserts. The size of an insert is still limited to a 150mm cube. This means the part size is limited to a 100mm cube.

KelTool is used in conjunction with SLA. The master pattern is produced in SLA and hand finished. The master is scaled up by 0.8% to compensate for process shrinkage.

A silicone mould is made of the master, similar to the RTV process. This is done in a temperature and humidity controlled environment to ensure calculated shrinkage factors. Similar to the aluminium epoxy casting process, an A6 tool steel and binder mix is poured into the silicone mould and cured.

This produces a “Green Part” which has sufficient strength to accurately maintain its geometric features through normal handling. The Green Part is de-moulded from the silicone tool and fired at $\pm 900^{\circ}\text{C}$ in a hydrogen reduction furnace to fuse the metal particles and eliminate the binder. This typically takes 3 – 4 days. This results in a porous part, 70% metal and 30% void. A combination of large and small particles is used to obtain this density.

The void is infiltrated with copper to increase the thermal conductivity of the insert.

Literature on trials has indicated that 10 million parts can be produced from a single KelTool set of inserts (with Tungsten Carbide material). For filled materials this figure is reduced to between 500 000 and 1 million. KelTool can also produce spark electrodes with a high copper content.

The typical time cycle for generating the inserts is 6 to 8 weeks depending on the size and complexity. Cost savings are estimated to fall in the area of 25 – 40 %. Cycle times can be shorter than those for conventional tooling due to the 30% copper loading.

The process is licensed by 3D Systems to technology partners. This could be the inhibiting factor as the total investment for the process could cost in excess of R 5 million over a four-year period. The process also requires stringent control, even to a specific RTV compound to be used.

Similar to the other RTV processes, the final tool is only as accurate as the master used for the process. Any surface defect will be replicated by the mould onto the final sintered metal insert.

ii. RapidTool – DTM

DTM Corporation builds Selective Laser Sintering rapid prototyping equipment. As previously discussed, one of the main advantages of the sinter technology is its capability to sinter a range of materials in the same machine.

One of the materials is tool steel with a binder. The difference between this process and KelTool is that the RTV tooling process is not required. The tool insert is grown directly in the SLS system. The Green Part is cleaned and finished before being fired in a furnace. The insert is also back-filled with a low melt alloy to reduce porosity and increase heat transfer.

The major difference is that multiple inserts would require a separate growth for each insert where-as with the KelTool multiple inserts are reproduced in the RTV tooling.

iii. Alternative Machining

Ciba's RenShape modelling board is widely used to machine master patterns for RTV and epoxy tooling. Newer materials are even being used to machine tools directly instead of AIM. The main reason for this is that toolmakers use the same equipment they will use to machine the final production tooling. They also verify CNC tool paths in the process. The disadvantage of this process is, although these materials machine faster than tool steels, tying up normal tool production on these machines.

New tool design and machining software is available that enables the designer to speed up the development process and to optimise the rapid tooling processes. Two companies that operate in this arena are Materialise (Belgium) and SolidConcepts (USA).

Both these companies provide a range of software tools to enhance the normal Rapid Prototyping and Tooling environments.

“Isopipe” heatpipes provide an alternative to cooling channels. These devices are fitted to areas where conventional water-cooling is difficult to install. The base of the heatpipe can be cooled by convection airflow or by water-flow. The main advantage is its sealed circulation that reduces the risk of cooling water leaking into the mould cavity.

3. MATERIALS AND METHODS

3.1. STEREOLITHOGRAPHY

Within the process various aspects contribute to the quality of the resultant part. Some of these aspects are so interdependent that a brief overview will highlight the significance of these aspects and their accumulative influence on the part being built.

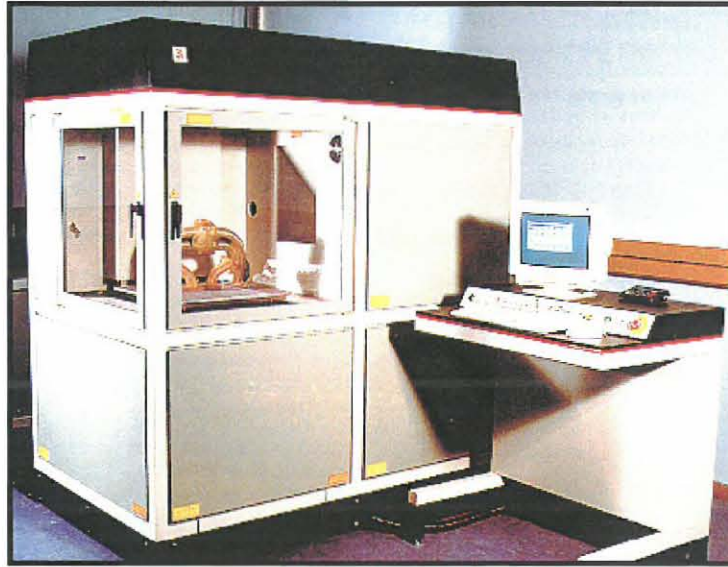


Figure10: SLA500 Machine Installed at NPDC, CSIR

Table1: 3D Systems – SLA 500, Specifications

Laser	Type	Argon Ion
	Wavelength	351 nm
	Power at vat @ 2000 hours (for epoxy resins)	264 mW
Recoating system	Process	Zephyr Recoating System
	Minimum recommended layer thickness	0.1 mm for both ACES and QuickCast
Optical & scanning		
	Minimum recommended part drawing speed	5 000 mm/sec
Elevator	Vertical resolution	0.00177 mm
	Position repeatability	± 0.013 mm
	Maximum part weight	68.04 kg
Vat	Volume	253.6 L
	Maximum build envelope	508 x 508 x 584 mm XYZ
Buildstation	Operating system	Windows NT
	Input data file format	.stl and .sle
Ambient Temperature	Temperature range	20 - 26° C
	Maximum change rate	1° C/hour
	Relative humidity	Less than 50%

Table 1's contents are described in more detail in the following text.

In 1987 Stereolithography or 3D Litho printing was the first commercial system to generate physical 3D parts directly from computer aided design (CAD) information. This is, like most prototyping systems, a layer based modeller. Various types of lasers are used in their range of machines, depending on the sensitivity band of the resins used. The laser is focused onto the liquid resin surface. Optical elements in the beam path, a scatter head in the small systems and Servo driven mirrors in the larger systems, direct the beam to trace out a layer boundary and scan over the solid areas. The light energy activates the free radicals in the resin, causing them to link and solidify. For each subsequent layer the part is lowered into the resin vat, allowing the laser to generate a new cured layer and thus building a 3 dimensional part. Figure 10 shows a SLA500. This unit has the capability to produce a layer thickness of 0.1mm. The SLA7000, as per Figure 11 can produce thinner layers by a factor of ten.



Figure 11: SLA7000 Machine (3D Systems, 1999)

A model can be solid, hollow or have a honeycomb type structure (QuickCast).

Stereolithography has predominantly found a niche in areas where prototypes of proposed designs are needed in a short time and the complexity rules out hand fabrication or machining. Prototypes are commonly used in the following engineering fields:

- **Concept Modelling**

Stereolithography in concept modelling is used by designers during the course of the design process to verify and validate a proposal. The speed of generating a model makes it an ideal communication and marketing tool.

- **Prototyping**

This process is ideal to verify assembly and manufacturing detail. It is common for design teams to grow iterations of parts as form, fit and function criteria are refined. As the tooling and production criteria become more evident, design changes are made to accommodate these processes and to reduce initial capital costs.

- **Masters for Metal Prototyping or Secondary Low Volume Production (RTV)**

Sacrificial masters can be generated for the investment casting process. These models are quasi-hollow in structure and has the process shrinkage incorporated before growing. Solid prototypes are used as patterns for sand casting as well as RTV (Room Temperature Vulcanising) moulding for polymer parts. (This process will be described in more detail in Chapter 5)

i. Basic Polymer Chemistry

UV-curable inks and coatings have been used in industry for the past 20 years. These include the printing industry, coating of electronic printed circuit boards as well as clear coatings for furniture. Stereolithography resins therefore only represent a small portion of this resin industry.

The main advantage of the Liquid Photo-curable resins is their energy efficiency. They require 50 to 100 times less energy than thermally cured coatings.

The Stereolithography resins share common features with the other application areas. The resin is always applied in thin layers. Spreading properties and viscosity are important and increased speed; improved toughness and reduced shrinkage are common objectives of all the application areas. The resistance to humidity factors is also a common obstacle. Although early development of the Stereolithography resins benefited

from these other applications, the laser light source used in the SLA requires a unique understanding of the resin properties.

Polymerisation is the process of linking small molecules (monomers) into larger molecules (polymers) comprised of many monomer units [15].

The *Vinyl monomers* are broadly defined as monomers containing a Carbon-carbon double bond. The early resins relied on the carbon atoms to form single bonds to form a single chain, while newer formulations form multiple links and are therefore far more stable. These are called *Cross-linked Polymers*. As this happens, many bulk properties change. With the increase in shear strength, the system changes from a liquid to a solid. The average distance between groups decreases, resulting in shrinkage or increase of density. The ideal is to make this transition with minimal distortion and at the lowest degree of reaction.

Acrylate monomers, during their polymerisation generate an exothermic reaction. The heat of reaction is nearly 85 kJ/mole. Despite this large driving force, the resins can be stabilised to remain liquid at ambient conditions. For acrylate resin systems, the usual catalyst to trigger the process is a free radical. The radicals can be generated thermally or photochemically. Using photons as a catalyst is extremely energy efficient. Each radical will result in the polymerisation of more than 1 000 acrylate monomers. The efficiency of this process allows productive use of relatively low-power ultraviolet lasers in rapid prototyping. Powder sintering requires approximately 1 000 times more laser power.

The radical polymerisation process has three phases:

- **Initiation**

As mentioned before, free radicals are formed by the photoinitiator (laser light source). On absorption, the photons react with the monomer to initiate a chain reaction.

- **Propagation**

In close proximity to the radical initiation, a transition to a cross-linked gel occurs. The rate of polymerisation decreases as the concentration of un-reacted monomer decreases and the viscosity of the gel increases (the Tromsdorff effect). The inflow of

free monomer is therefore steadily inhibited. This reaction is also the cause of gel forming on the outside of a part (side growth).

- **Termination**

There are three principal methods of chain termination. Two radicals joining to form a non-reactive molecule is called Recombination. Disproportionation involves the transfer of a β -hydrogen from one radical to the other, producing two polymer molecules. For laser-induced polymerisation, the reaction continues for one second in the dark, although no new radicals are produced. Occlusion is the entrapment of radicals within the polymer network. This could mean that polymerisation could still occur for months afterwards in the dark as un-reacted monomers and dangling double bonds are still present in the cross-linked polymer. Post curing in a PCA (Post Curing Apparatus) is used to speed up this process and prevent long-term distortion of the produced part.

- **SLA Resin Used for Trials**

Table 2 provides critical information to configure the SLA systems laser exposure. The resin is also susceptible to moisture contamination, effecting curing and layer bonding.

Table 2: SL 5180 Liquid Resin Properties.

	Method	Value
Boiling point	TA-1, (N ₂ -atm.)	> 240°C
Density (25°C)	DIN 51757	1.146 g/cm ³
Vapour Pressure (20°C)		< 4 Pa
Viscosity (25°)	Hoeppler	0.265 Pa
Viscosity (30°)	Brookfield	0.187 Pa
Solubility in Water		Partly soluble
Flash Point	Din 51758	> 120°C
Thermal Decomposition	Lütolf	150°C
Ignition Temperature	DIN 51794	360°C
Refractive Index (20°C)		1.4908
Storage Stability at RT.	Gel time measurement	> 6 months
D _p	3D Systems	4.4 mils (80 mW)
E _c	3D Systems	13.3 mJ/cm ² (80 mW)

Table 3 indicates the typical mechanical properties that can be expected of cured SLA resin tool inserts.

Table 3: Mechanical Properties of Cured SL 5180 Resin

	Sample	Method	Value
Tensile modulus	B	ISO R 527	2400 to 2600 MPa
Tensile strength	B	ISO R 527	55 to 65 MPa
Elongation at break	B	ISO R 527	9 to 11%
Flexural modulus	B'	3D Systems	1590 MPa
Flexural modulus	B''	3D Systems	828 MPa
Impact strength	B	DIN 52453	27 to 47 kJ/m ²
Shore D hardness	C	DIN 53505	84
Density	C	Buoyancy	1.216 g/cm ³

Comments:

- B Test specimens built with SLA (WEAVE™) or ACES™, post-cured 1h UV
- C Photocast between glass, post-cured 30 min. UV + 30 min. at 70°C
- B' Test bars built with SLA (WEAVE), dimensions: 80 x 4 x 2 mm, post-cured 1h UV
- B'' Test bars built with SLA (QuickCast™), dimensions: 80 x 4 x 4 mm, post-cured 1h UV

Impact strengths have been found to increase substantially over time. In 30 days the impact strengths of up to 66 kJ/m² have been recorded. Table 4 indicates that the cured parts have poor conductivity, this impacts the cooling cycle.

Table 4: Thermal Properties of SL 5180 Resin

	Method	Temperature (Range)	Value
Glass transition temperature	DMA	-100 to 200°C	85°C
Thermal Expansion Coefficient	DIN 53752	20 to 50°C	104.4 ppm/K
Thermogravimetric analysis (Weight loss in %)	TGA	265°C	2.2%
		460°C	84.5%
		539°C	96.1%
Thermal conductivity	VDE 0304		0.2089 W/m K
Oxygen Index	ASTM D 2863		20.1%

The electrical properties, as per Table 5 is poor. This impacts plating or surface coating processes.

Table 5: Electrical Properties of SL5180 Resin

	Method	Value		
Dielectric strength	IEC 243-1	20.9 kV/mm		
Volume resistivity	IEC 93	$1.44 \times 10^{15} \Omega \cdot \text{cm}$		
Surface resistivity	IEC 167	$5.9 \times 10^{13} \Omega$		
Dissipation factor, Tan δ and Dielectric constant ϵ_r	IEC 250	Freq. (kHz)	Tan δ	ϵ_r
		0.05	0.7	4.1
		0.1	0.8	4.1
		1	1.2	4.1
		10	1.6	4.0
		100	1.6	3.9
		1000	2.2	3.8
Tracking resistance	IEC 112 VDE 0303	CTI > 600 –0.0		

Not only is the polymers used for injection moulding susceptible to moisture, Table 6 indicates that the SLA resin can also be effected, causing swelling and softening of parts.

Table 6: Water Absorption of Liquid SL 5180 resin - % Water Absorbed by Resin. (Measured by Karl – Fischer titration).

	Ref	50% 25°C	50% 25°C	50% 25°C
	0 days	10 days	30 days	60 days
% H ₂ O	0.1	0.38	0.63	1.26
	Ref	80% 25°C	80% 25°C	80% 25°C
	0 days	10 days	30 days	60 days
% H ₂ O	0.1	1.38	1.87	3.32

As evident in Table 6, SL5180 is highly susceptible to moisture absorption. High humidity environments lead to a strong softening of SL 5180 parts independent of build style. Absorbed water may lead to dimensional changes, particularly in parts built in QuickCast. The recommendation is to store parts made of SL 5180 and especially QuickCast parts in a controlled atmosphere of 30 – 40 % relative humidity and at temperatures < 35°C.

Table 7 is a comparative table of the two build styles. QuickCast forming a hollow honeycomb structure with a higher hatch spacing that ACES.

Table 7: Part Parameters for SL5180 Resin

Description	QuickCast Values	ACES Values
Layer thickness	0.15 mm	0.15 mm
Hatch type	QuickCast	Box
Hatch spacing	3.80 mm	0.10 mm
Layer offset depth	2.50 mm	Not applicable
Double border compensation	0.18 mm	Not applicable
Skin type	X or Y	X or Y
Skin fill spacing	0.10 mm	0.10 mm
MSA	Not applicable	40°
Staggered Hatch	Not applicable	ON
Alternate Sequencing	Turn off alternate sequence	ON
Retracted Hatch	Not applicable	OFF or 0 start point and 0 end point
Border overcure	0.18 mm	0.18 mm
Hatch overcure	0.15 mm	-0.08 mm
Fill cure depth	0.30 mm	0.23 mm

As indicated by Table 8 there is no difference in the parameters for the support structure for both build styles.

Table 8: Support Parameters for SL5180 Resin

Description	QuickCast Values	ACES Values
Layer thickness	0.15 mm	0.15 mm
Support spacing	10 mm	10 mm
Border & hatch overcure	0.18 mm	0.18 mm

Notes: Do not use skin fill on supports

Use an MSA of 0° for supports

Do not use any of the STAR options for supports

The comparative values in Table 9 indicates that the ACES style requires longer and slower process parameters between layers. This affects the build cost.

Table 9: Recoat Parameters for SL5180 Resin.

Description	QuickCast Values	ACES values	Supports
Pre dip delay (PR)	45 sec	70 sec	15 sec
Z level wait	25 sec	25 sec	15 sec
Number of sweeps	1	1	0
Blade gap	180%	140%	Not applicable
Sweep velocity	100 mm/sec	50 mm/sec	Not applicable
Z dip velocity	Normal	Normal	Normal

Notes: The recommended QuickCast X and Y shrink compensation value is 0.998

The recommended QuickCast Z shrink compensation value is 1.000

The recommended ACES X and Y shrink compensation value is 1.001

The recommended ACES Z shrink compensation value is 1.0005

The recommended build temperature is 28°C
Do not sweep supports
Avoid building with trapped volumes if possible.

ii. Laser Exposure

In a typical coating or resist layer, the layer thickness is tuned to absorb only part of the energy. A sufficient amount of radiation is induced to cure the layer and to ensure adequate adhesion to the substrate. An increased exposure will only have a minimal increase in cure, but cure depth is still determined by the layer thickness. Figure 12 illustrates the typical beam focus to achieve correct cure depth and beam width.

In SL the process starts a build with the first support layer cured onto a perforated steel plate. The subsequent layers are drawn on the previous layer. Only when an overhang or a substantially larger area than the previous layers are exposed is the resin seen as a significantly deep volume. Laser Exposure E (mJ/cm²) will decrease exponentially with depth z in the following manner:

$$E(z) = E_0 \exp(-z/D_p) \text{ ----- } E.1.$$

Where D_p is the resin "penetration depth" at the laser wavelength and E_0 is the laser exposure at the resin surface ($z = 0$). The exposure where gel is created is slightly higher and is known as the "critical exposure" E_c .

Excessively high radiation layers therefore generate the phenomenon of bottom growth. This results in an uneven, wavy bottom surface requiring significant finishing.

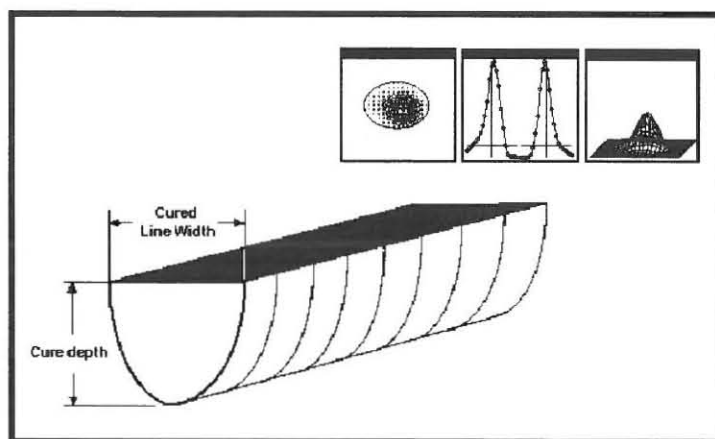


Figure 12: Cure Depth and Width by Laser Beam – Optimal Beam Shape

iii. Curl Distortion

“Curl” is a type of distortion that can occur in any layer based RP process. This is caused by the shrinkage of the successive layers while solidifying. It is most evident in areas where the bottom layers are not properly anchored, either to the platform or the lower layers as illustrated in Figure 13. A bending moment is introduced with the upper layer shrinking and thus inducing a tensile force on the lower layers. This could cause the upper layers to protrude above the resin surface. In small areas this will aid the part to correct itself as the model progresses, as these areas will not be wetted. In severe cases this will cause a sweeper stall as the part protrudes beyond the sweeper gap. Curl could also be the underlying cause of delamination or the distortion of upper portions of hole features. Marutani explains the origins of curl in a publication [16].

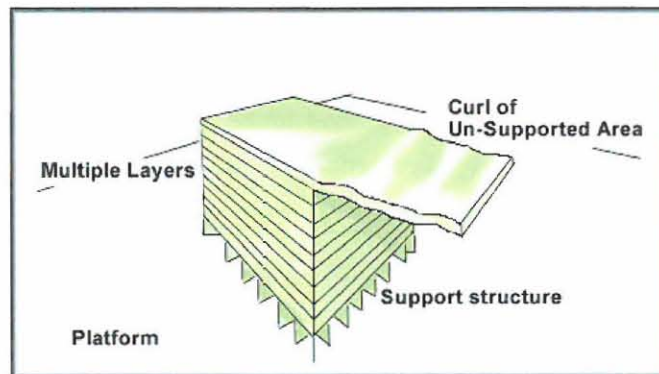


Figure 13: Curl Distortion

The effects of curl according to Marutani can be reduced by the following methods:

- Use high exposure and slow scan speed to such an extent that polymerisation is essentially completed under the laser spot.
- Use a resin with a faster rate of polymerisation.
- Decrease laser power to decrease scan speed for a given exposure.
- Use a low shrinkage resin.
- Increase layer thickness to increase the strength.

According to Jacobs the Marutani model is not accurate and concludes that curl will always increase with increased exposure, despite the increased shrinkage that may occur directly under the laser spot. He, however, concedes that the general form, lagging shrinkage after attachment, could still apply [13].

Thermal conditions have also been raised as a possible cause of curl. Initial expansion, induced by the heat of the top layer being exposed, would induce distortion on cooling. These measurements are experimentally complex and only recently test methods have been developed to address these effects over time.

- **Conclusion**

All of the more commonly used resins suffer from shrinkage and curl during the solidification process. This results in stress and subsequently causes distortions. Material suppliers are continually improving their resin characteristics to address this aspect. This is, however, only part of the improvements. System suppliers are also constantly evaluating new laser technology to control the energy induced into the resin as well as creating new build styles to allow for greater stress relaxation in each layer and to thoroughly cure the resin to minimise post cure shrinkage. Apart from special application resins i.e. biocompatibility or electrically conductive materials, general properties for heat resistance, brittleness, solvent resistance and greater accuracy, are all desired properties for the RP community.

iv. Rapid Prototyping Facility

A typical Rapid Prototyping Facility can be defined in various departments, concentrating on specific activities within the part generation chain. These activities follow in sequence to produce a component via RP.

- CAD Design Facility – File Preparation
- SLA / FDM growing Facility – Build Station
- Part Finishing Area - Finishing

These activities will be discussed briefly in the following sections.

v. Operator Requirements

Operational spaces can be divided in separate functional areas with specific human resource and facility requirements. For smaller operations two people are required. Depending on the throughput and workload, people can be assigned to specific operations, noting that part finishing is the most time-consuming and of great importance, as poor cleaning results in poor quality parts.

- **Part Preparation and SLA Machine Loading**

This person needs to be computer literate, preferably with a CAD background. The person is required to function within the UNIX as well as WindowsNT environments. A good appreciation for 3D space enables the operator to function within the growing area volume. A significant portion of this person's time is allocated to file transfers via FTP or E-mail. To obtain an accurate costing, the basic volume and part height for a platform need to be calculated. This in most cases requires that the operator first has to lay out the parts and find the best orientation.

- **Loading of SLA Machine**

This operation normally forms part of the file preparation function. It is still, however, important to document the parts contained on the platform, their slice height, growing style, re-coating parameters and specific growing conditions.

- **Finishing**

As the final deliverable depends on this person, hand / eye skills are just as important as full commitment to quality. Dimensional accuracy, aesthetic qualities and failure recovery all form part of each finishing cycle. This person should be creative with a combination of model building and pattern making skills. Most of the finishing is done by hand as most motorised tools are too aggressive in material removal. In larger operations, Green and final finishing functions are separated. The final finishing operators are even graded depending on the level of finish they can perform.

vi. Machine Levelling

The build stations set-up and calibration always start with this operation. It is essential that all mechanical systems be aligned. With all the sub systems, the only reliable source to calibrate from is the resin surface. Weight distribution in the system plays an important role. The system can only be levelled once a full vat is in place.

The SLA500 is mounted on three pads. Once the vat and the rim frame are calibrated to the resin level (X- and Y-axis), the Z-axis can be aligned. The Z-axis controls the platform travel. The Z-axis therefore needs to be calibrated in two axes to ensure it is truly perpendicular to the resin. The linear travel rails of the sweeper blade are mounted on the rim frame. To ensure parallel travel the blade gap has to be calibrated as well.

vii. Re-Coating System and Resin Levelling

The first SLA systems were made without a re-coat blade. This resulted in long waiting times between scans due to the settling time required for the resin. With trapped volumes and large flat surfaces this is a major problem and the 'Doctor' blade was introduced. This was purely a sweeping action and was replaced with a 'Zephyr' blade with the introduction of the SLA350.

viii. Zephyr Blade

The blade consists of a leading edge and a trailing edge separated by a vacuum channel. This enables the blade to deposit or re-distribute resin as required. A more uniform re-coat layer is achieved. The re-coating events are as follows:

After the laser scans a layer:

- The newly cured resin undergoes a short delay (pre-dip delay).
- The elevator lowers the part over a user-specified distance (for trapped volumes, one layer thickness). $\text{Clearance} = (\text{Gap}\% / 100\%) \times \text{layer thickness}$.
- Gap % should be 200% for 0.1mm layers and 167% for 0.15mm layers.
- The zephyr blade sweeps across the surface applying a thin coating of resin.
- If necessary, the elevator positions the part exactly one layer thickness below the resin surface.
- There is a short delay for fluid relaxation allowing the resin surface to become flat (z-wait).
- The laser then scans the next layer.

ix. Blade Gap

Blade gap is checked by building the gapcheck.bff file. It is important to ensure that the correct resin and zephyr blade are chosen. The auto drain function needs to be switched off as these parts are grown without sweeping.

The operations are as follows:

- Once these parts are complete, the vat is lowered to clear the parts from the resin.
- The blade is moved to the middle set of blocks.
- The elevator is then moved up by the gap value appropriate for the layer thickness.

- The locking screws of the sweeper blade are loosened. With a feeler gauge on the smallest value, lower the sweeper until it touches. Repeat this to the other side.
- Lower the blade by half a turn on both sides and tightly lock the blade.
- Check the clearance on the front and rear set of blocks.
- To check for tilt or twist in the blade check the leading and trailing edges.

x. Vacuum Setting

The vacuum setting should hold an amount of resin in the blade. This level should only be halfway in the viewing window. For large flat areas this may have to be adjusted to prevent excess resin being sucked into the vacuum pump

xi. Resin Levelling System

- Resin height is required to establish a home or starting position. This is done with the platform lowered to the start position. The resin should be halfway through the holes in the platform. This will ensure proper keying of the supports during a build. During a build start-up the system will prompt the operator to add or remove resin. This sub system reflects a light beam from a laser diode off the resin surface onto a large split photo diode. Depending on which photodiode is illuminated, resin needs to be added or removed as illustrated in Figure 14 [15].

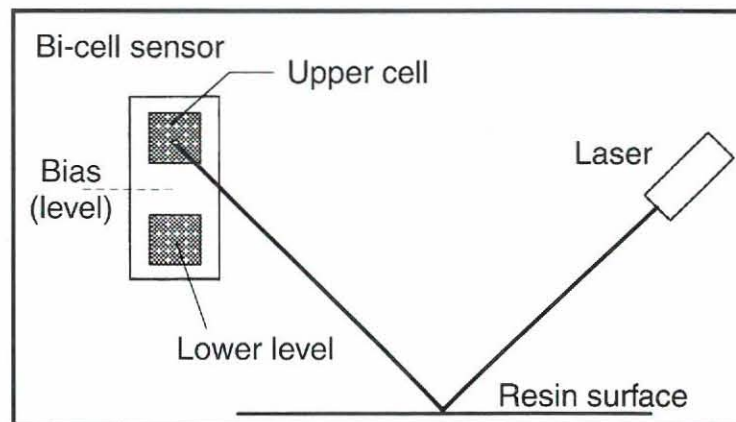


Figure 14: Schematic Diagram of Resin Level Sensor

xii. Re-Coating Issues

- De-wetting – Incompatibility between the liquid and the cured resin; liquid resin tends to flow away from the part
- This may be caused by:
 - Short pre-dip delay
 - Smaller layer thickness
 - Low blade gap %
 - Large blade gap
 - Long Z- wait
 - Blade derby
 - High resin temperature

- Leading Edge Bulge – bulge of excess liquid resin left by the blade on the first edge of the part; shear forces act on the resin meniscus.
- This may be caused by:
 - Low blade gap %
 - Smaller layer thickness
 - Increased resin viscosity
 - Fast sweeping

- Avoid
 - Even number of sweeps
 - Orientating long axes of part parallel to blade

- Mounding – liquid resin on the part is greater than the specified layer thickness.
- This may be caused by:
 - Insufficient Z-level wait
 - De-calibrated blade gap
 - Trapped volume
 - Increased resin viscosity

- De-lamination – non-attachment of vectors or layers to previously cured vectors or layers (difficult to diagnose)
- This may be caused by:
 - Low pre-dip delay
 - Mounding
 - De-calibrated laser power
 - Incorrect E_c and D_p

- De-calibrated blade gap
 - Trapped volume
 - Blade derby
 - Insufficient supports
- Trapped volume – a cup shaped part facing with the open end upward. (Done to minimise supports). Liquid layer does not relax flatly on top of trapped volume geometry.
 - This may be caused by:
 - Insufficient z- level wait
 - De-calibrated blade gap
 - Trapped volume
 - Increased resin viscosity
 - Wrinkled borders – borders are only partially attached to previously cured borders; effect is WAVY or WRINKLED borders.
 - This may be caused by:
 - Low pre-dip delay
 - Scan speed too high – fuzzy parts
 - Other possible issues
 - Bubbles
 - Humidity
 - Beam scatter

xiii. Lasers and Optical Elements in Stereolithography Exposure

The latest versions of Stereolithography machines differ significantly in the design of their optics systems. They are fitted with direct frequency double diode lasers and all the elements, apart from the scanning mirrors, are contained in the laser head.

As the SLA500 was used for this project, an overview of its layout and function will be discussed.

See Figure 15 for a schematic layout of the SLA500 system.

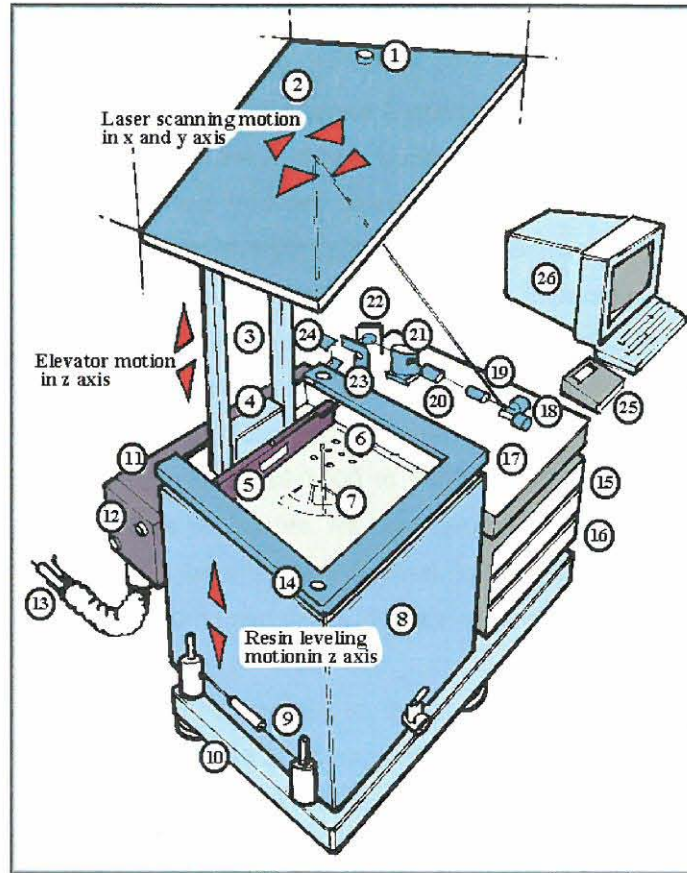


Figure 15: Schematic Diagram of Optical Layout of the SLA500

1. FAD Sensor (Saturation Sensor)	14. Sensor 1 and 2
2. 45° Mirror (Roof of Chamber)	15. Control Electronics
3. Z Axis Platform Arms	16. PC Build Station Software
4. Resin Level Sensor	17. Optics Table
5. Zephyr Re-coater (Sweeper Arm)	18. X and Y Axis Mirrors and Motors
6. Platform (Perforated)	19. Focus Optic
7. Resin	20. Pin Hole Optic
8. Vat	21. AOM (Acoustic Optical Modulator)
9. Vat Elevators	22. Corner Mirror – 45°
10. Levelling Frame and Feet	23. Safety Mechanical Shutter
11. Laser	24. Periscope Mirrors
12. Beam Adjustment Knobs	25. Laser Control Panel
13. Water Cooling, Power Supply, LAN	26. PC Monitor, Keyboard and Mouse

- **Laser**

The SLA500 is fitted with a Coherent Argon laser, radiating in the 351nm band (Ultra Violet). The laser head and its power supply require water-cooling. Low water flow or poor dissipation of heat from the closed loop system to the external cooling source will cause the laser and system to shut down. This mostly happens on machine start-up but can also be a cause of build failure. It is imperative that de-ionised water is used in the closed loop system to prevent build-up inside the tubes or corrosion. Due to the excessive heat dissipation and its deleterious effect on lifetime, argon lasers are typically operated at less than optimum values. Present Ultraviolet argon lasers have lifetimes in the order of 1000 to 2000 hours. Systems are often operated in excess of 400 hours per month. As tube failures are difficult to predict, preventative maintenance cannot be effectively applied. In most cases only the tube needs to be replaced but apart from resin this is the largest running expenditure.

The laser is mounted horizontally on adjustable feet. The laser can only be levelled after machine levelling has been completed (see machine levelling). The laser must be secured in a position where the beam will strike the centre of the bottom periscope mirror. On powering up the laser it might “laze” (radiate) but no focussed beam will show. This will require focusing the internal laser mirrors. This process is called “beam walking”. The mirrors are aligned with each other until a beam is produced. Thereafter micro adjustments are made to the tilt and jaw of the mirrors to optimise the laser output. This is a lengthy process as small adjustments can easily lose the beam. This process must be done without the systems auto beam tracking. This laser sub routine controls solenoids on the front mirrors. With a full shutdown or a power failure this information is lost and the laser needs to be re-aligned. An output power of 500 mW can be achieved.

The power output of the laser is normally regulated using the tube current, since the tube voltage is nearly independent of the tube current. During a build the laser is controlled to output a constant light output. Gas pressure is regulated due to the rapid argon pressure loss occurring at the higher tube currents needed for UV operation. To ensure a long operational life, gas-filling procedures must be followed as per manufacturer procedures. The laser output wavelengths depend on the choice of gas, the operational conditions, and the use of wavelength-selective laser mirrors. The next crucial element in the laser is the “aperture disc”. The openings in the disc determine the mode. For optimal operation in this application a single bright dot is

required. This is called a ($m=0, n=0$) TEM₀₀ or Gaussian mode. Other modes do not perform as efficiently e.g. Doughnut mode (dark centre spot). The aperture within the laser tube allowing performance closer to the TEM₀₀ mode introduces optical losses. It is therefore essential that the laser be finally focused with the correct aperture (setting 9) [13].

The following new advances contradict the presumed advances of greater laser power:

- Thinner layers, for better part resolution requires reduced laser power.
- New part building techniques have reduced cure depths.
- With the decrease in cure depth, laser power can be reduced.
- Higher laser power can only be used with thin layers if the scanning operation can be speeded up or if the photo-polymer sensitivity decreases.

The laser beam, emitting radiation of the correct power and wavelength, is sent through a pair of periscope mirrors, past a mechanical shutter, through the AOM, pinhole optic, expanded by the focusing optic onto the pair of cross-axis, galvanometer driven, and beam scanning mirrors. From here it enters the chamber through a duct onto the primary 45° mirror and is focused at a distance on the surface of the liquid resin. Beam diameter is typically less than 0.5mm. To obtain high speed, the scanning mirrors must be of small inertia and small in size. A power loss of 20 to 40% can occur as each optic induces a loss. This is easily measured with a laser power meter and is the only guide in cleaning optical elements.

Beam quality and focus is of primary importance to obtain accurate, reliable and well-finished parts. An oversized laser beam and standard beam width compensation could result in an oversized part. The minimum feature size of a part is determined by the diameter of the focused spot on the resin surface. The resolution of the part depends on the angular accuracy of the scanning mirror motors, the ability to control the intensity distribution, and the laser power. Results showed that calibration sensor saturation and beam quality are the most common causes of the system calculating the wrong exposure value and scan speeds. Apart from effecting part finish, this also effects part build times.

The time required to generate a part depends on the spectral responsiveness of the photo-polymer, speed of the galvanometer mirrors, power and wavelength of the

laser, and the re-coating time of each layer, which depends on the viscosity and surface tension of the photo-polymer and the characteristics of the re-coating system.

- **OPTICS**

- **Periscope Mirrors**

- These mirrors are adjusted to align the laser beam through the optical path. This is done with the aid of a cross hair tool instead of the focusing and pinhole optic.

- **Shutter**

- The Electro-mechanical shutter is linked to various interlocks in the system protecting the vat doors and system covers. This is a safety device to prevent laser exposure. If this safety system is bridged for maintenance purposes, appropriate safety glasses for protection at the wavelength of the system must be worn.

- **AOM – Acoustic Optical Modulator**

- A command string in the build file drives this optical device. The crystal is energised to distort the beam, effectively resulting in zero exposure at the vat. This is used for travel between scan points. Cobwebs in the vat are the result if this device is not properly set.

- **Pinhole Optic**

- The pinhole eliminates any secondary beams that may influence focusing. This is also the area where the highest loss occurs.

- **Focusing Optic**

- By rotating and adjusting the lens forward and backward, the beam is focused to obtain the highest peak possible with the smallest diameter. Care is also taken to keep the elliptical ratio of the beam as small as possible. This is done by setting the beam on the ½ mil pinhole of sensor 1 and watching

the graphic display of the beam profile in the field service window of the build station software.

- **Scanning Mirrors**

As previously mentioned, these are the primary drawing mirrors of the system and direct the beam in the x and y-axis.

- **Chamber Window and Cover**

During the build phase the resin generates vapours. This residue and dust is the main cause of the optics being contaminated. Windows and covers attempt to seal the optical elements.

- **Primary 45° Mirror**

This large coated plate is located above the vat. It is the last optical element before the resin. The main cause of contamination is vapour and resin droplets with careless removal of a platform.

- **Sensors 1 & 2 ; FAD**

These sensors compare the laser power to the laser power read in the laser head. The FAD or sensor 3 is a saturation sensor and is located next to the primary 45° mirror. This readily provides the operator feedback on the condition of the optical elements. Sensors 1 and 2 have four pinholes each. During the calibration process all four pinholes will be probed. This is to calibrate relative sensor position. All part exposure is done relative to the sensor location. Part of each scan cycle is a position check to each sensor. This ensures that the sequential layers are exactly aligned with each other. Horizontal shift in layers can be caused by power fluctuations, poorly secured platforms or the re-coater shifting the platform due to excess curl.

xiv. Working Curve

Layer thickness is directly related to cure depth. If a layer is not cured deep enough, it will fail to bond adequately to the solidified layer below it, resulting in part de-lamination. If the cure depth is too great, internal stresses can build up causing curl and other distortions.

Critical exposure, E_c and a corresponding radiation absorption or depth of penetration, D_p is known as the resin photo constants and is unique to each resin [13]. This equation is absolutely fundamental to Stereolithography and is known as the “working curve equation”.

$$C_d = D_p \ln (E_{\max} / E_c) \text{ ----- } E2.$$

C_d = Cure depth (mils)

D_p = Penetration depth of resin (mils)

\ln = Natural log

E_{\max} = Exposure (mJ/cm^2)

E_c = Critical exposure (mJ/cm^2)

This equation states the following points:

- The cure depth is proportional to the natural logarithm of the maximum exposure on the centreline of the scanned laser beam.
- A semilog plot of C_d versus E_{\max} should be in a straight line. This plot is known as the working curve for a given resin.
- The slope of the “working curve” is precisely D_p , the penetration depth of that resin, at the laser wavelength.
- The intercept of the working curve, specifically the value of the exposure at which the cure depth is zero, is simply E_c , the critical exposure of that resin, at the laser wavelength.
- Since D_p and E_c are purely resin parameters, both the slope and the intercept of the working curve are independent on the laser power. The points above are illustrated in Figure 16.

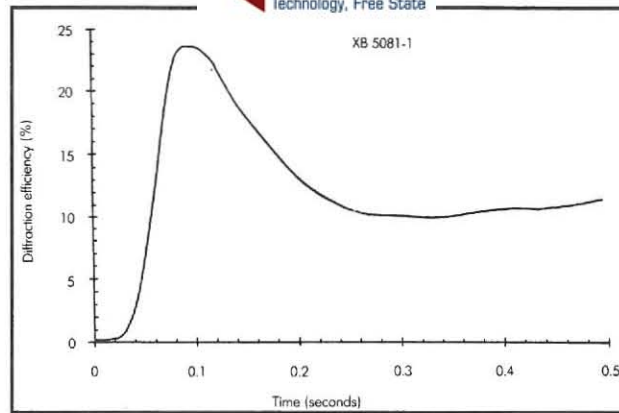


Figure 16: Typical Working Curve for Cibatool XB 5081-1 [15].

Critical exposure of the resin combined with the scan speed forms a line-width. This determines how closely to space scan lines for hatching to avoid internal stresses. Cured line width is also a factor in the overall dimensional accuracy of the Stereolithography part.

The line width parameter's influence is depicted in Figure 17.

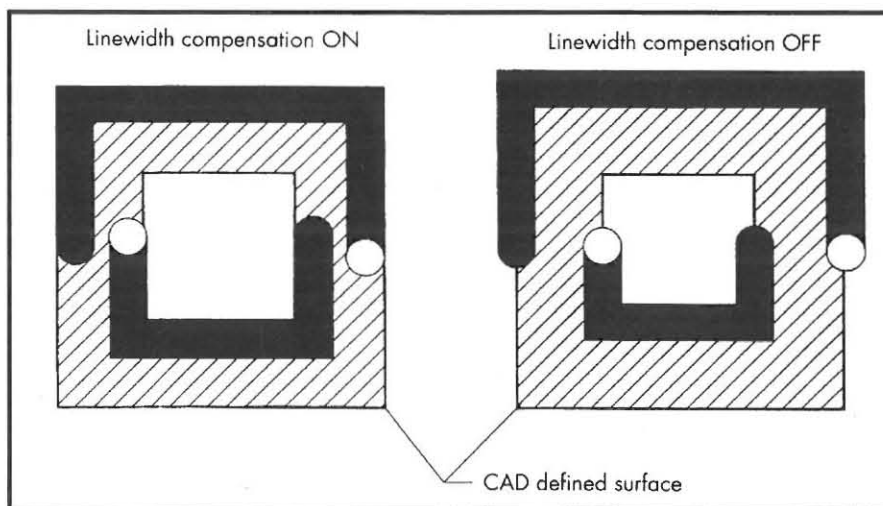


Figure 17: Line-Width Compensation

3.2. CALIBRATION PARTS AND PROCEDURES

i. AccuMax Parts

Line-width and drawing speed must be carefully controlled to ensure consistently accurate parts. Resin characteristics must also be known. The vat's character is constantly changing as it ages. The AccuMax parts were developed to address these issues. The WINDOWPANE™ part is used to calibrate the critical exposure and depth of penetration for the resin. The Reverse WINDOWPANE™ part is used to verify the critical exposure and depth of penetration values obtained from the WINDOWPANE™ part [13]. The detailed process is discussed in the AccuMax Procedure Manual from 3D Systems.

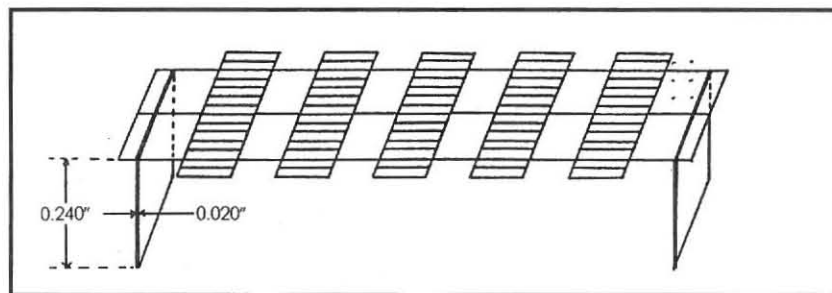


Figure 18: WINDOWPANE Part

The WINDOWPANE™ part, as per Figure 18, consists of a series of single-layer panels drawn at different scan rates to produce the panes of varying thickness. Faster scan rates correspond to thinner panels. The parts are removed, cured and analysed to determine the E_c and D_p values [13].

The same part is built again for the Reverse WINDOWPANE™ part. The calculated values are used and the resulting part is measured for accuracy. If the calculated values were correct, the pane thickness will match the specified values.

This procedure should be done when [13]:

- Different resin is placed into the SLA machine
- Every six months for routine performance check
- Laser power output changes become larger than 20%
- A new laser is installed
- As a diagnostic tool with unusual part building results

ii. CHRISTMAS-TREE Part

The purpose of the CHRISTMAS-TREE part is to determine line-width compensation (LWC) and X- and Y- axis shrinkage factors (SCF). To accomplish this, two test parts are built, twice. For each build, one part is aligned in the X-axis, and the other in the Y-axis. For the first build the LWC and SCF values are set to ZERO. After the parts are completed the AccuMax software calculates values for LWC, SCF(x) and SCF(y). These dimensions are compared to the nominal dimensions of the CAD model [13].

The second set of parts is grown with the values calculated. If the calculations were correct the new part dimensions will match the nominal CAD data to within 0.00127mm.

Figure 19 is a two dimensional representation of the test part. The horizontal bars also differ in the Z – Axis as well to add additional calibration parameters.

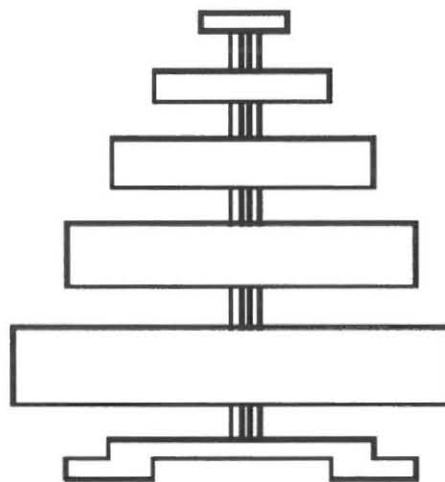


Figure 19: CHRISTMAS- TREE Part

3.3. THE PROCESS - SOFTWARE

i. Build Types

The Stereolithography preparation software supports several methods of building parts. These are known as *build types* and are styles in which the software forms the internal or solid area of the part. Also known as “hatch”.

These build styles are:

- **Weave**

This was the first accurate style developed by 3D Systems in 1990. Previous styles had large hatch spacing, resulting in residual liquid resin trapped within the part and surfaces suffered from curl distortion. (Rippled surfaces) [13].

- **Star Weave**

This was a refinement on the Weave build style introduced by 3D Systems in 1991. The three parameters can now be optimised:

- Staggered hatching
- Alternate spacing
- Retracted hatch

(Jacobs, 1992) [13].

- **ACES**

This stands for **A**ccurate **C**lear **E**poxy **S**olid build style. The laser scans the complete hatch surface. This creates a glass like finish on top flat surfaces and when polished provides the best optical transparency. This is also the build style with the highest density. This build style is most suited to models with thin walls and where polished finishes are required. Star Weave is faster and just as accurate if the part will only be finished to a level three finish [15].

- **QuickCast**

This was introduced in 1992 by 3D Systems. The aim of this style is to reduce internal mass. 70% of the parts internal volume is drained as liquid resin. The

remaining 30% form a honeycomb support structure to retain form and rigidity. This style is ideal for parts with large internal volume and is often used as sacrificial masters for the investment casting process [15].

Figure 20 illustrates the effect of different layer thicknesses. To retain part accuracy after finishing the software over compensates. Stair stepping is a direct result of the boundary calculation. The software takes into account the larger of the bottom or top profile of a layer to obtain a scan result. For this reason the parts are always oversize. The actual part surface boundary is at the inner corner of the staired surface. To obtain actual part size, sand the part till no lines appear on the surface. See Appendix A for SLA500 and Resin Specifications.

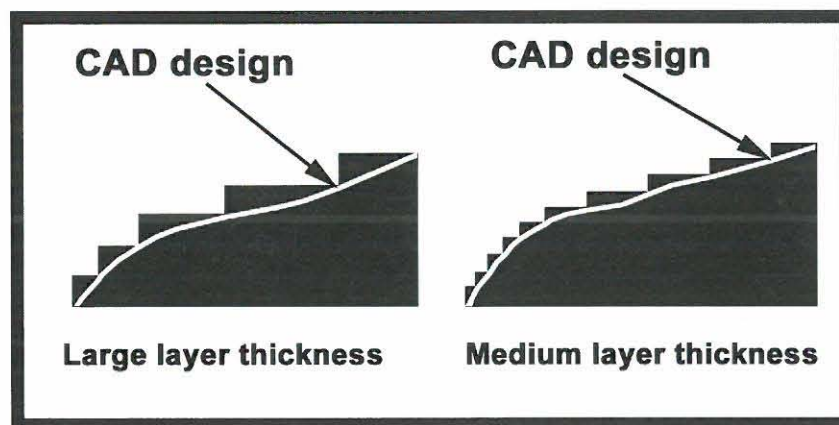


Figure 20: Stair Stepping Effect

ii. Build Errors

Build errors are a result of the complexity of the process. The system is made up of four sub systems. These cannot be seen in total isolation as their interdependence influence part quality.

These are:

- Optical system, including laser
- Mechanical systems
- Resin
- Control system

These issues are discussed in Chapter 3.1. STEREO LITHOGRAPHY.

iii. CAD - Process

The Stereolithography (SL) process starts with the generation of a solid 3D CAD model. A 'watertight' surface model can also be used. The surfaces of the model are tessellated - formed into a connected array of triangles. The triangle sizes are dependent on the curvature and angle of the surface. A flat square surface will only have two triangles where the triangles on a cylinder can be reduced to improve part accuracy. This naturally increases the file size. The file extension "filename.stl" distinguishes the file, generated through this process.

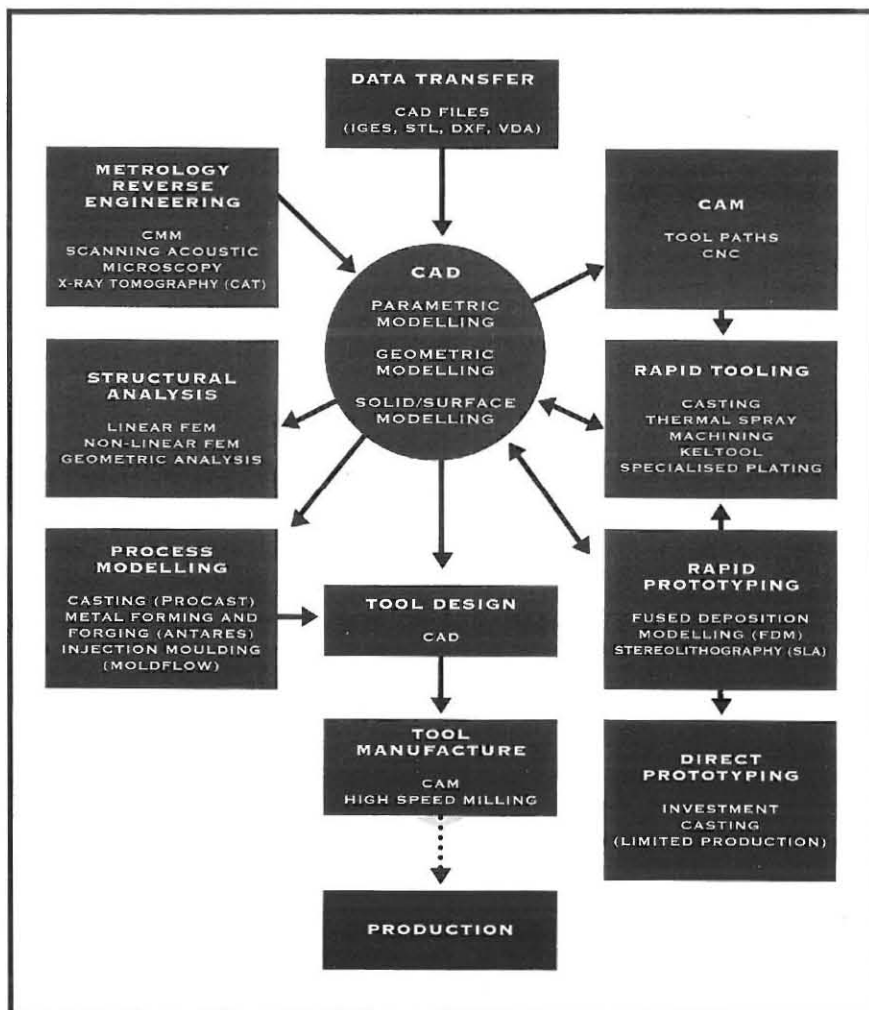


Figure 21: CAD Information Flow (After: du Preez, W [8])

As per Figure 21, 3D CAD models are the entry point to any of the RP&M processes. In fact it stands at the core of all concurrent engineering processes. To enable the user to

use any computer aided simulation of a process or the character of the part; a computer model of the part is required.

For a simple Finite Element analysis (FEM), a 2D sketch may be adequate. For more complex geometry a simplified 3D model becomes essential. In some cases such as Flow Analysis a mid plane model is generated from the part. The part is described as a model with no wall thickness. In these cases only parts with a limited cross section will give good results.

iv. Part Preparation and Building

For this project the EMS modelling package from Intergraph was used. This package is a hybrid modeller, allowing the user to model in line, surfaces and solids in 3D space. The software runs on a UNIX platform. The software does not have some of the sophisticated tooling capability of some of the newer packages, where a cavity and split line are easily generated by the software.

It is essential to determine design intent before starting the modelling process so as to avoid duplication of work or a model that will not evolve to the full extent. It is important to visualise the progress of the model and the steps that are required to achieve the desired model. Only then will the CAD modelling progress smoothly.

Two main methods of 3D CAD modelling exist today. The first being the ACES kernel. The engine of these CAD packages mainly model in surfaces and is driven by sketch geometry in 3D space. The para-solid kernel is only a solid modeller. Sketching on a predetermined plane generates 3D solids. These sketches can be extruded, revolved or subtracted from an existing solid. Added features of modern packages that improve productivity are:

- **Parametric Modelling**
This allows the solid model to be manipulated by changing dimensions on the sketch features. This process eases the modification of the solid without having to remodel from the start. Certain features can also be driven with relations to ensure fit of components or aesthetic proportion.
- **History Tree**
This allows the user to suppress some of the features to speed up regeneration processes or to change the order in which some of the features were created.

- **File Translation**

Most CAD systems can output a file in a format that enables other CAD systems to read its models. The oldest of the formats is DXF. This is typically used for 2D information. However, text and dimensions are lost in most cases. IGES (Initial Graphics Exchange Specification) is also a well-known format. As this format breaks the 3D model down to surfaces, the history of how the part was generated is lost. In some cases the model is so degenerated that the only alternative is to remodel. One of the latest advances in the para-solid arena is that the imported model can be regenerated during the translation phase to generate a model tree and the 3D model is broken down into features. This allows the new model to be driven and constrained parametrically.

v. The STL File

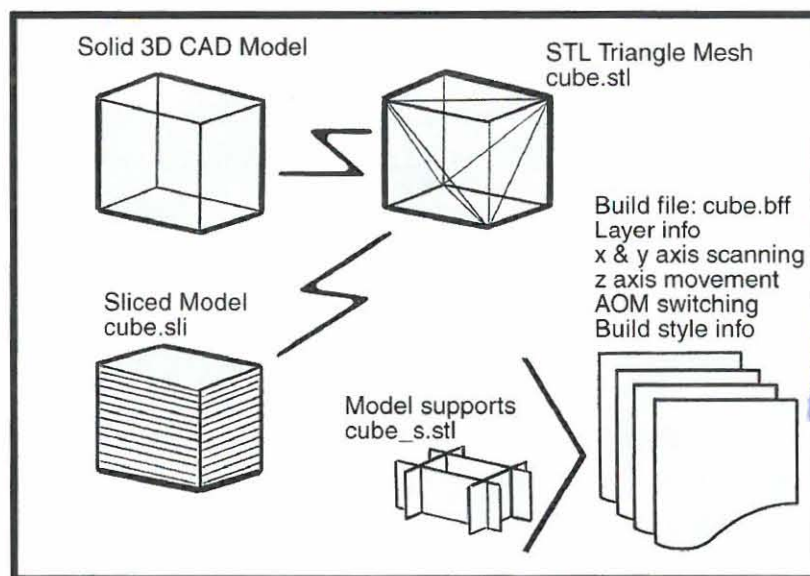


Figure 22: File Conversion Process

The file format required for Rapid Prototyping is the STL format. Figure 22 illustrates the conversion process of the 3D CAD model to the files required to build the part. An STL file is a mesh of triangles on the surface of the part [13]. Although a triangle is a 2 dimensional object, its vertices are located in 3D space. The process of generating the triangles is called tessellation. Triangles in a STL file must all mate with other triangles at the vertices, resulting in the 'vertex to vertex' rule. The triangle information also contains

THIS BOOK IS THE
PROPERTY OF THE
2006 04 18
CENTRAL UNIVERSITY OF
TECHNOLOGY, FREE STATE

a surface normal. This indicates which side of the triangle contains mass. For complex shapes, the higher the triangle counts the higher the object resolution.

The most common problems encountered with STL files are caused by gaps between triangles and adjoining triangles indicating opposite surface normals. These problems can be seen when the STL model is shaded. Missing or reversed surface normals leave visible holes in the model. To assist in this the suppliers have incorporated an analysis program. With gaps the system will generate the smallest number of triangles to close the volume and will swap around the surface normals where required.

The Stereolithography file consists of x-y and z co-ordinates of the three vertices of each surface triangle as well as an indicator of the surface normal orientation. This is to distinguish between outer and inner surfaces.

Since its inception by 3D Systems Co., it has become the de facto standard of the RP&M industry. Most CAD systems now support this as an export format.

It is the front-end software that generates control information for the build station. The software allows the user to manipulate the position, scale, orientation and build style.

The build station consists of a laser system and optical elements that direct the beam perpendicular to the surface of a vat of liquid polymer. The beam and platform in the vat is controlled by the information contained in the build file.

The polymer selectively cures where exposed to the laser beam. The part is finally removed from the vat, washed to clean the part of uncured resin and after removal of surface roughness i.e. Stair stepping, is post cured to obtain a stable prototype.

vi.Reduction of Information

A minimum of three triangles meets at a vertex. Each triangle describes the vertices in x, y and z values. Only one value is required. To reduce the duplicate information, the software generates a ".ctl" (compress_stl.ctl) file. This removes these common vertices and the file size is generally eight times smaller than the original.

vii. Statement

For this project the ACES build style will be used predominantly. Therefore this route will be dealt with in detail. The QuickCast build style will be used for investment casting of tool inserts but is not the main focus of this project.

viii. Conversion of “.stl “ to Buildstation Operations

Vista, the support generating software, reads the “ctl2odf “ information to identify regions to support. These would be all the down facing triangles in that particular orientation. If the part is rotated these triangles will change.

Small triangles or thin sliver triangles could cause problems and it is therefore important to View and Edit supports where thick support ribs will be generated (Cause problems in cleaning the part).

The resolution of the part as mentioned is determined by the facet sizes of the triangles. Stepper motors drive the X and Y scanning mirrors. The movement of the mirrors is counted in mirror bits.

(2 000 mirror bits = 1 CAD unit) _____E3 [13].

This translates in slice resolution = mirror bits / CAD unit.

A layer is described by a “up boundary“ and a “down boundary“ and the “layer boundary “ or hatch. On an angled face the up and down boundary exceeds the part geometry. This is the cause of “STAIR STEPPING “

ix. Viewing the Various Files

The viewing function of the software enables the operator to rotate, position, scale, copy and identify the items before the final build station preparation starts. Objects can be viewed as “.stl“ wire frame models, volume blocks or shaded objects. The volume block mode speeds up the positioning of the parts on the platform but shading reveals most of the part specific details and errors.

Faceting is clearly visible as well as surfaces with missing or reversed surfaces. The Verify software will change around surface normals and will even patch up missing triangles. These patches are however the shortest distance fix and detail could be lost.

For QuickCast applications the wire frame mode is important to position vents and drains to enable the internal resin to escape.

The slice files can also be viewed to verify part boundaries, especially in very thin detail areas. Hatching can only be viewed for the SLA250 machine as the hatching parameters for the larger systems are only generated at the build station.

x. Supports

As the parts are located in positive space and a gap of +/- 10mm is left underneath the part in the Z-axis, a support is required to anchor the part to the platform. All overhanging or down facing surfaces also need to be supported. This prevents part distortion as well as aids in part removal. Generating a simple block, slightly penetrating the part can generate supports in the CAD system. The support geometry STL file is saved with an identifier after the filename " filename_s.stl " There are typically five types of supports:

- **Gussets**

Gussets are used to support overhang areas. Gussets attach to a vertical wall near the overhang and thus provide surface for the overhang area to attach during building. Gussets provide the optimal support for overhang areas as minimal resources are required during building and supports are easily identified during the cleanup. The gusset spacing parameter is used to control gusset spacing. The gusset length parameter is used to control the maximum gusset size.

- **Projected Feature Edges**

The edges of unsupported areas and overhang areas where gussets cannot reach are projected to provide support. Projected feature edges support to actual edges of the part, optimally controlling curl and providing the most accurate results. The minimum projection extent parameter is used to control the projection of small feature edges.

- **Single Webs**

A single web support is a wall projected from the centre of a narrow feature or along a sharp edge feature. Cross members are added to provide stability. The support spacing parameter controls the spacing.

- **Webs**

Webs are intersecting walls, which provide support for the interiors of large unsupported areas. Webs also connect to the projected feature edges to provide a stable support for the area. The Vista support generator in some cases generates supports, which intersect or are closely spaced to vertical walls, making these supports difficult to remove or even to distinguish. The support spacing parameter controls web spacing.

- **Columns**

Columns are used to provide support for islands and other small-unsupported areas. A column support consists of two walls, which form a plus shape that is large enough to build on its own. The column width parameter controls the size of a column.

xi. SolidView – Software

This company supplies third party software to view “.stl” files and generate supports. In some cases this software seems more robust and reliable than the VISTA support generator from 3D Systems.

SolidView Features include:

- Real-time rendering.
- Support for STL, VRML, 3D DXF, and OBJ CAD files.
- 3D dimensioning of edges, faces arcs, points objects and assemblies.
- Easy to learn, intuitive user interface.
- Collaborative engineering review tools.
- Cross-section display and measurements
- Options for IGES, VDA/FS, Rapid Prototyping.
- Bridgeworks – for slicing and support generation.

xii. Slicing the Part

This process generates a series of closely spaced horizontal planes; these are mathematically passed through the triangulated surfaces. Layer boundaries are generated - describing the part as two - dimensional cross-sections, each spaced at its own Z co-ordinate value.

The most common layer thickness is 0.15mm for solid parts and 0.1mm for casting patterns. With advances in resin and machine technologies a layer thickness of 0.01mm can be achieved. This advancement is a great improvement as it reduces the phenomenon of stair stepping dramatically. Also during this step the intended building style, cure depths, desired hatch spacing, line width compensation value and shrinkage compensation factors are selected.

The following parameters have a combined influence on the quality and accuracy of the parts built:

Line-width compensation of the final part: This function operates at the borders of the part to allow for the cured laser line-width. The laser must be offset by half the line-width toward the part mass to draw accurate borders. If not, the part will be oversize. This value is usually overridden after the machine is installed and the true line-width compensation is determined. The default is "0" and the range is 0.025 to 0.5mm.

X hatch spacing: controls the separation distance between each X hatch vector, which forms the internal structure of the final part. The default value is 0.28 mm and the range can be 0 (deactivates the drawing of X hatch vectors) or 0.025 to 25.0 mm. Values in the upper region of the acceptable range are sometimes used with equally large Y hatch spacing to build support structures using the bottom borders of the part projected downward to the build platform.

Y hatch spacing: The same as for X hatch spacing, but in the Y direction.

60/120 hatch spacing: This controls the separation distance between 60°, and 120°, cross - hatch structure. This parameter applies to the Tri-Hatch build style. The default value is 0 (deactivates drawing 60/120 crosshatch vectors) and the range is 0 or 0.025 to 25.0 mm.

xiii. Build File

This is the accumulation of all the parts that will be grown together. The first step is to locate the parts in positive space and ensure that parts do not overlap one another.

xiv. Buildstation and Preparation Software

For the SLA250, four separate files are transmitted to the build station. Each file contains the parameters for a specific sub system i.e. scanning & shutter, z-axis control etc. For the SLA500 and larger machines these files are combined into a single file with the file extension “.bff”

This file contains information pertaining to the build style perimeters, resin type, scanning parameters and system speed parameters.

At the build station, the operator has the opportunity to verify the build and even override some of the selected parameters. This is also the first time that an estimate of build time is generated. This can only be done after the system has verified available laser power that affects the scan speed that the system can build at.

The software also enables a skilled operator to recover an aborted build. This could happen due to sweeper stalls, laser malfunction, power failures or insufficient cooling to the laser system.

The field service section is a critical interface to obtain maximum efficiency with the laser and optics.

3.4. THE PROCESS – BUILT PARTS

i. Growing environment

For QuickCast it is essential that the area for growing and finishing be regulated for temperature and humidity. Variations in these parameters could adversely affect the pattern during its pre-shelling phase.

ACES finishing differs only in as far as no TPM wash bath is required for QuickCast. Apart from this, the same tools and equipment is used.

ii. Finishing – GREEN STATE

- **RAMCO – Green part Washing**

This devices' name in Figure 23 has become a household name in the SLA industry in the USA. This wash unit is a pneumatic actuated device that rises and lowers a platform of parts while in a TPM bath. This action is the most effective in cleaning uncured and gel-state resin from the part surface. It is also safer for handling of green parts as the finisher is not exposed to excessive liquid resin. As this is an automated device the finisher is free to spend more time on cured parts in the cue rather than hand washing the parts. As most of the resin is removed, hand tools and work area remains more resin free. Supports also tend to soften slightly and are easier to remove. Iso – Propanol is used to wipe the part down during hand finishing. As can be seen from the image the unit operates in a sealed mode, making it more environmentally friendly requiring less fume extraction.



Figure 23: Ramco Cleaning System

- **Trolleys**

To transport the platform from the SLA machine to the cleaning facility, a flatbed polyethylene trolley is used. The base of the trolley is covered with an absorbent paper-towelling pad. Resting the platform at an angle inside the chamber of the build station drains off excess resin. There is thus minimal resin draining from the platform as it is transported. This is a great plus for keeping equipment clean.

None of the draining resin is recovered as this has been activated and cannot effectively be used again.

- **Waste Bins**

In all the rooms, red waste bins are used to collect all green resin soiled materials. This includes clothing, gloves, paper towels etc. these materials are classified as toxic waste and are disposed of in the same manner as liquid resins. After the resin has been post cured it is safe to be handled and can be handled without wearing Nitrile gloves.

- **DADAN & SONS – Resin Extraction Units**

These are centrifugal systems used to extract the liquid resin from QuickCast parts. The perforated sidewalls of the DADAN unit illustrated in Figure 24, eases

orientation of the platform. With the system at the CSIR consideration must be given to drain hole location and part orientation to ensure good drainage.

Liquid resin is allowed to escape from the part by strategically locating drain holes (resin accumulation areas) and vent holes (first drained areas). As this resin is not recovered it is best to drain as much of the resin from the part as possible while still in the SLA growing chamber. Care must also be taken to clearly mark vent and drain holes to ease the sealing process. This will be discussed as part of QuickCast trials.



Figure 24: Dadan & Sons Resin Extraction Unit.

iii. Support Removal

To assist in support removal, it is important for the person preparing the build to check the supports that were generated for the part. In some cases the supports must be edited to facilitate the ease of removal or prevent supports being co-incident with the part (effecting the surface finish and obscuring part – support boundaries). The depth that the supports penetrate the part will also affect the easiness with which they are removed. A good support style is the sierra angle steep, allowing a smaller distance between contact points but less contact surface area. Various lengths of spatulas or putty knives are used to loosen the supports from the platform. The blades of the knives should be flexible enough to stay parallel with the platform during operation. Levering could snap thin parts. Work at the supports from a 45° angle to the growth line to ensure minimal part chipping. Always work towards the centre of the part to prevent chipping. After the part has been removed from the platform, scrape the down facing surfaces to remove pips remaining and also the over-cure gel. Sand the down facing surfaces with water paper wetted with

Iso-Propanol to get a good finish before placing part in the PCA. Remember all finishing done in the green state is less hard work done when the part is post cured.

iv. Protective Gear

Each operator should have the following:

- Overcoat Protects clothing and bare skin from resin
- Safety glasses Splashing of resin or cleaning solvents
- Safety goggles Used for dusty operations if no down vacuum table is available
- Nitrile gloves With every operation where resin is handled in its green state a single, or with support removal, a double layer
- UV laser glasses These are used with the light gun for part repair or for field Servicing the SLA machine

v. Post Curing – PCA

In some cases transparent supports can be used to ensure that the parts are illuminated evenly. Large or thick walled parts should be rotated during the process – (eliminates warping).

The reflective base of the turntable should be kept as clean as possible as this helps in the curing (wrap tin foil over the surface, it can be removed when soiled)

The platforms are also post cured to neutralise the activated resin remaining on the platform. This also dries the platform. QuickCast parts should not be on a platform in the PCA as the moisture on the platform will affect the parts.

3D Systems supplies a calculation chart to determine the post curing time for a part dependent on the cross sectional thickness of the part.

vi. Finishing – Post Cured State

QuickCast parts should never be submersed in TPM or other solvent. To clean the parts, they are wiped with Iso-propanol swabs until they are tack free.

- a. Place a pile of lint free paper towels on the cleaning tray.
- b. Soak the first few layers with Iso-propanol.

- c. Wipe the part and frequently use a new swab until all stickiness is removed.
- d. Liquid resin on gloves should be avoided as this makes part cleaning difficult.
- e. For multiple parts gloves may have to be replaced. For large parts, wearing multiple layers from the start helps as soiled gloves can be peeled off without stopping.
- f. Sanding and repair work should be left till after post curing.
- g. Place the parts in the PCA. If the parts have large overhangs, support these areas as they may sag.
- h. After post curing, QuickCast parts are lightly sanded with 150-grit sandpaper. All support pips or burrs are removed by sanding. Do not use files. Cracks, holes and joints can be repaired using resin and a light gun. A third party that supplies different viscosity resins in a syringe format is Aptek (Valencia). The following items can be used to define edges, curves or for alignment: magic tape, acetate sheets, microscope slide covers, styrene tubes etc. it is better if the item is transparent to illuminate through if no other angle is open.
- i. For sanding large flat areas, a sheet of sandpaper glued to a flat surface works well. Even sandpaper glued to a putty knife with spray adhesive works well.
- j. Forceps are used to hold sandpaper or paper and former to sand in difficult spots e.g. Cavities and holes.
- k. To remove stair stepping a hobby knife blade works well. Scrape along the lines to prevent gouging. A knife blade can be shaped on a small desktop belt / disc sander to the required shape to get into blended corners.
- l. When joining parts for a single casting, check each part with vacuum for good sealing. To check a part for sealing, plug all vents and drain holes with resin. Choose a strong area of the part and attach a chimney. Use resin and a light gun. Only then drill a hole through the opening. Attach the hand vacuum pump hose to the chimney and pump to 25 psi. If the part holds the pressure, it is sealed. If not, attach an air supply hose to the chimney. Run low-pressure air through and feel or listen for air escape. This process may have to be repeated numerous times to seal a damaged pattern.
- m. A part should be purged by drilling a small hole in the furthest area from the chimney and running Nitrogen through the hollow part. Marking the hole, assists in sealing later.
- n. The part must be coated by spraying it with clear quick drying epoxy to give a good finish and avoid moisture damage.
- o. In some cases the pattern is shipped with the chimney to allow the foundry to check sealing. For in-house foundries the chimney can be removed and the holes sealed with resin.

- p. New holes need to be drilled in the areas where the gates are attached to facilitate air escape during burnout.

ACES parts should be finished in the same manner except that the parts are washed in a TPM bath prior to removing them from the platform. This replaces the wiping procedure. On final sanding of the part, the part is sandblasted with silicon powder to obtain an even finish. This should remove all sanding marks. Depending on the level of finish required, finer grits of paper can be used. Wet sanding gives better results. Frequently wash the part to remove grit that can scratch the part surface. To ease the sanding process, a guide coat can be painted onto the part. The part is sanded until only thin paint lines are visible. – Rather remain slightly oversized.

Buffing with a soft wheel and talc-like compound can produce a polished finish. It must be ensured the part does not heat up as this could cause damage. A second wheel without compound can be used to clean the part.

- **EFOS – Light Guns**

These devices are essential for complex part finishing. The advantage for QuickCast parts lies in that minimal patching wax is used to repair a part and this improves burnout. It is also ideally suited to join parts as the light exposure is focused and more intense than the PCA and better alignment is achieved.

- **APTEK – Joining Resins**

This company supplies three grades of resin varying in viscosity. The thin resin is to seal or repair thin cracks whereas the thick resin is used for larger gap filling applications. The SLA resin can also be used. The best method of application is with a syringe fitted with a large bore needle.

vii. Tools

The following tools and consumables will be required during the cleaning and finishing process:

- Sand paper – start at 150 grit to 1200
- Putty knives – more flexible blades to remove the part from the platform – long bladed putty knives.

- Dremels – cordless and table model with sanding bobbins and drills. (motorized hobby tool)
- Knives – hobby knives various blades – stiff blades (not scalpels). Grind blades to a specific shape for scraping.
- Steel rules – check flatness and for large are scraping.
- Bench top belt / disc sander – shaping of blades.
- Styrene hobby stock – tubes, flats – to reconstruct damaged parts – fill and cure with light gun.
- Radius gauges – used to check and scrape corners.
- Files – not used often – fine files on well-cured parts.
- Post-curing jigs – Transparent material to maximise part exposure
- Bead Blaster – fine ceramic powder – to obtain a uniform finish after hand finishing.
- Buffing wheels – soft linen wheels and fine buffing compound.
- Spray adhesive – to mount sandpaper
- Sanding blocks – table surface, putty knife, rubber pads, and forceps.

viii. Colouring

A frequent method of finishing is to spray the SLA part with quick drying epoxy enamel paint. Certain paints however contain ingredients that soften SLA parts.

An alternative process that still retains the translucent quality of the SLA part is to use fabric dyes.

A concentrated solution is prepared by dissolving fabric dye in boiling water. The SLA part is submersed in the solution until required colour density is achieved. Parts do soften during the process but can be countered by rinsing the parts immediately afterwards in cold water. The dye penetrates the resin surface therefore not effecting part fit.

This process can be used to identify parts i.e. differentiate parts in an assembly (QuickCast chimneys) or for aesthetic reasons.

ix. Quality Inspection

Apart from the aesthetic inspection before a part is delivered, a dimensional inspection should be performed. It is preferable that the client should supply the critical dimensions on a marked-up drawing. For in-house purposes the parts can be compared to the CAD file. The normal SLA software is not adequate for this purpose. Standard instruments

should include a sound measuring table, height, radius, and bore gauges, digital verniers, and steel rules (used to check flatness).

3.5. INJECTION MOULDING

i. Introduction to Injection Moulding [3].

- The basic process of injection moulding is to force or inject a material into a cavity of a mould. To achieve this, certain practical considerations must be met. These are:
 - The material must be able to flow and reproduce the mould cavity and then be allowed to harden.
 - The mould must then open in such a way as to allow ejection of the hardened article without distortion or damage to the article.
- The objectives of injection moulding are to mass-produce articles of consistent shape, dimensions and quality. Therefore the cycle of the injection moulding process must be optimised to yield:
 - Complete articles
 - Accurate dimensions
 - Consistent quality
 - Highest output rate possible within the constraints of the above
- There are two types of polymer materials used for the injection moulding process, namely thermoplastics and thermosets.

Thermoplastic materials are materials that behave similarly to candle wax. When heated, thermoplastics soften, when cooled it hardens again. This heating and cooling cycle may be repeated a limited number of times, providing scrap thermoplastic is kept dry, is not degraded by overheating and is kept free from dirt.

Thermosetting materials are materials, that soften when heat is applied, but continued heat causes the material to set and harden. A comparison may be made with a boiled egg. Initially the egg is soft and fluid, when heated it sets hard and cannot be softened again. Thermosets therefore cannot be re-used.

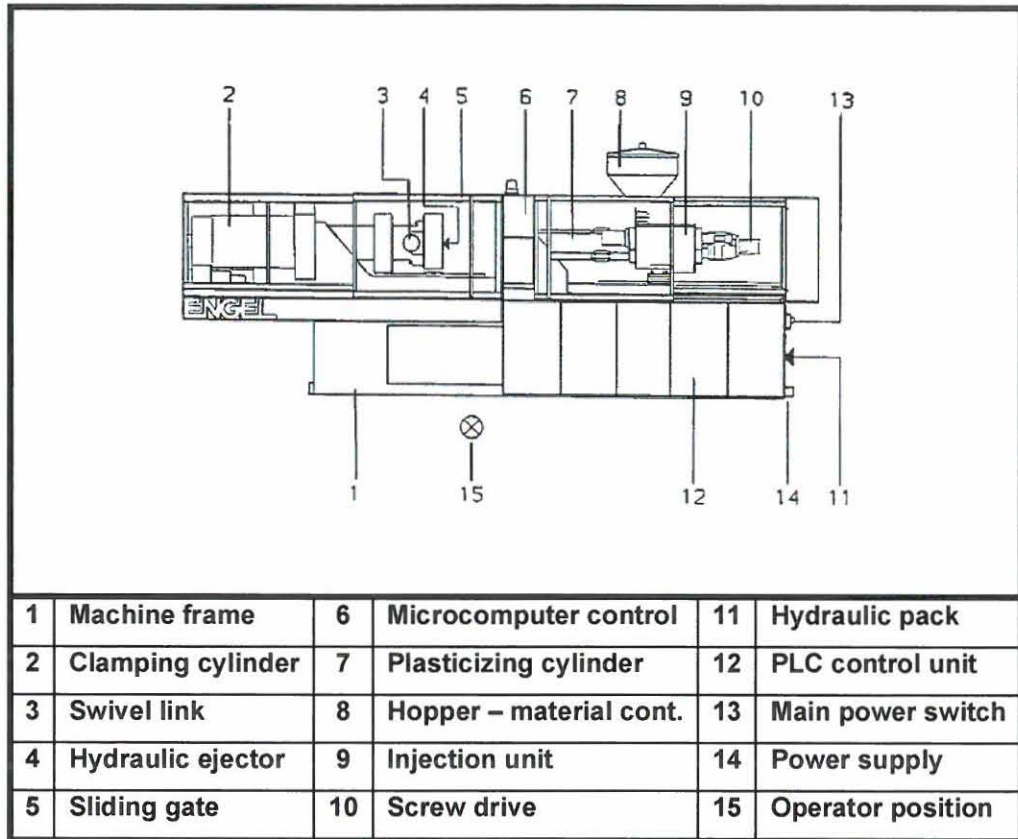


Figure 25: Schematic of Engel 80 Ton Tie-bar-less Injection Moulding Machine

The injection moulding cycle revolves around three basic features. Two are moulding machine specific and the third is customer defined: (clamping – mould – injection). Figure 25 illustrates the layout of the moulding machine used during trials and is typical of modern machines depicted in Figure 26.



Figure 26: Injection Moulding Machine

- **Mould Clamping Unit**

The mould clamping unit's primary function is to keep the mould closed during the injection moulding and curing cycle. Therefore these systems can exert closing forces of 5 or even over 2 000 tons clamping pressure, depending on the type of the machine and the requirements of the mould. Injection moulding machines are classified by the "clamp-force"; therefore projected surface area of a cavity determines the machine size. The secondary function is to open the mould, depending on the part and mould design these could also be high forces. The clamping of the mould can be done mechanically, hydraulically or through a combination of these two. There are even new machines on the market that are fully electrically operated.

- Depending on the type of injection moulding machine, the ejection system is incorporated into the clamping unit. It enables the part to be freed from the mould. This is the primary function that enables a tool to operate without human intervention.

- **Injection Unit**

The injection unit's primary function is to heat and soften the material and secondary to inject it into the mould. Heating is normally done by electric heater-bands around the barrel of the injection unit. Temperatures are divided into several zones and are regulated within a specified band by the system's control unit. There are three basic injection units.

They are:

- Plunger injection moulding machines
- Pre-plasticiser injection moulding machines
- Screw injection moulding machines

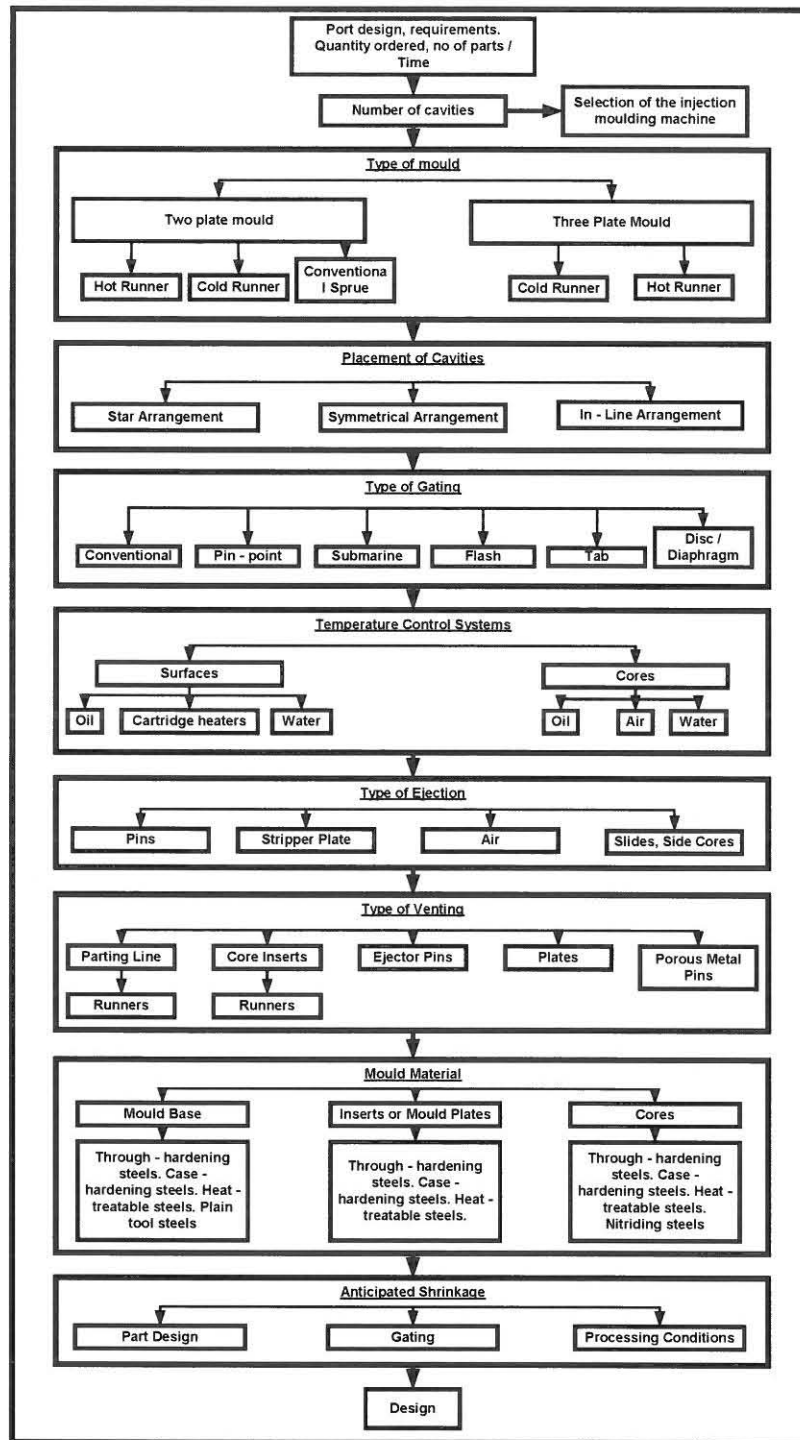
Screw injection is the most common type of system. When the screw rotates the material is fed closer and closer (tapered screw) to the inner surface of the heated barrel. As the material comes off the front of the screw the screw retracts to permit the "shot" to accumulate. Injection is achieved by the screw acting as a plunger, moving forward, forcing the material through the injection nozzle and into the mould. The size of the "shot" is regulated by the amount of material allowed to accumulate in front of the screw and the screws' set travel distance.

- **Mould**

This customer-defined element is the core of the process. All the injection moulding machine functions are geared to support the mould and related process requirements. The mould defines the final Shape and Finish of the part. The mould also incorporates runners to deliver soft plastic from the injection unit to the cavity. After the mould has closed, vents enable trapped air to escape. Cooling (thermoplastics) or heating (thermosets) systems are incorporated and finally Ejection and Movement systems allow the part to be removed from the mould.

There are numerous configurations of tools. These are mainly defined by the part cavity and part specific requirements. Table 10 provides a roadmap to select the appropriate design solutions for the various functions of the injection mould tool.

Table 10: Methodical Designing of Injection Moulds



The clamping, injection units and mould operate in harmony during the injection moulding cycle to form an injection-moulded part. The sequence of events during a moulding cycle is as per Figure 27:

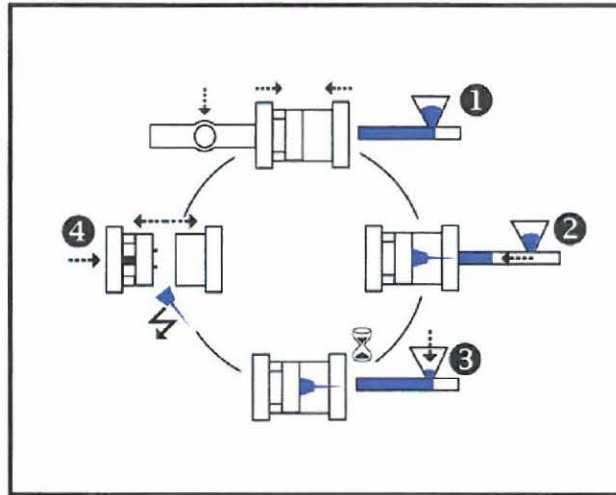


Figure 27: Injection Moulding Cycle

1. The mould is closed and locked by the clamping unit.
2. The plasticised material is injected into the cavity via the runners.
3. The mould is held closed while the material solidifies and cools.
The system plasticises the next "shot" of material during the cooling period
4. After the cooling cycle, the mould opens and the part is ejected and the cycle starts again.

ii. The Injection Unit

Most of the new generation machines are closed loop microprocessor controlled. Sensors measure actual parameters at the time of operation. This enables the systems to regulate the parameters to stay within the defined operational tolerances. E.g. Barrel temperature is regulated to constantly stay within $\pm 5^\circ$ of the specified temperature for the specific zone.

The injection unit consists of the following sub-elements:

- **The Hopper**

The hopper feeds the raw material into the barrel. It consists of a funnel section fitted with a sight glass to monitor material level. A lid prevents dust or other foreign objects from falling into the material. Newer machines are fitted with other safety devices, e.g. magnets to stop metallic objects. At the bottom, the hopper is fitted with a slide gate. This allows the operator to remove material from the hopper without spilling material.

For mass production machines, which use large volumes of the same material the hopper is replaced with vacuum suction out of drums or centrally fed piping systems from huge silos.

- **The Barrel**

The barrel is a tubular steel section, which houses the plasticisation screw and conducts the heat to the material. The outer body also acts as the piston sleeve for the injection process. The feed section, directly underneath the hopper is water-cooled. This prevents “bridging” – melt from flowing from the barrel back into the hopper. Heater bands for thermoplastics or water jackets for thermosets are warped around the outside of the barrel and are normally divided in three zones. Thermocouples provide a feedback loop to the control system to regulate the melt temperature.

These zones are as follows:

- Feed section underneath hopper
- Feed zone 1st section after hopper
- Compression zone mid section of barrel
- Metering zone closest to nozzle and mould

- **The Screw**

There are various screw designs available on the market depending on the material being processed or compounding requirements.

The functions of the screw are to:

- Transport material forward;
- Compress the material against the barrel wall where it's heat forms the melt;
- (Feed zone – deep flights, pickup material and feed into barrel);
- Mixes and compounds the material;
- (Compression zone – shallow flights);
- As a plunger – injects the material into the mould.

The screw consists of the following:

- The root, with increasing diameter towards the tip.
- The flights, which carry the material forward

- The check valve, which prevents a backward flow of the material during injection, but allows the material to pass through during plasticising.
- The screw tip, which together with the check valve, acts as a piston during injection.

- **The Nozzle**

- The nozzle is the tip section of the barrel that directs the molten material into the mould.

It consists of the following:

- The body
- The orifice
- The radius tip – this radius must match the sprue bush radius for good shut-off.
- In some cases shut-off nozzles are used to close off the orifice in the nozzle during plastification to prevent drooling of low viscosity melts. This is even more critical if “sprue break” (pullback of the barrel during the cooling cycle) is used. Continuous contact of the nozzle with the sprue bush of the tool can elevate mould temperatures. These types of nozzles are not used for heat sensitive materials e.g. Nylon, PVC or POM.

- **Controls and Limit Switches**

- Controls for the manual operating of the injection unit are:
 - Injection unit forward towards mould
 - Injection unit backward from mould – sprue break
 - Screw rotation start of feed operation
 - Screw rotation stop of feed or plasticisation
 - Screw forward injection of melt – piston action
 - Screw back suck back or plasticisation start

Limit switches – Automated functions

Limit switches control machine movements. Their function is to initiate or stop a particular function.

Limit switches on the injection unit are:

- Screw movement backward: Controls the amount of material picked up for each shot (shot weight – including sprue and runners).
- Screw movement forward: Switches the machine from the first injection stage to the second stage (from injection to hold-on-pressure or additional speeds and pressures).
- Suck-back (optional): Short retraction of the screw after rotation has stopped to relieve the pressure on the material in front of the screw.
- Injection initiation: Start the cycle
- Sprue break (optional): Travel of injection unit backward.

Newer machines with computer control panels has significantly enhanced the setting of these values. Older machines are fitted with slide scale stops for each set of limit switches. An allowance must always be made for a cushion of material at the end of the injection stroke to minimise shrinkage and back flow of material from the mould and prevent damage to the screw tip and check valve or ring.

iii. Clamping Unit

As with the injection unit, various clamping systems are incorporated in injection moulding machines. The basic functions of all these systems are the same:

- To open the mould
- To close the mould
- To clamp (lock) the mould before injecting (prevent flash, prevent thickened parts)
- To activate the ejection of the part once the mould has opened.

The functional elements of the clamping unit are:

- Clamping system
- Platens – fixed (injection unit side) and moving (attached to clamping system)
- Ejector system
- Gates and guards
- Limit switches and movement controls
- Hydraulic cores and other optional movement equipment

There are three clamping systems:

- **Mechanical Toggle:** Mechanical links activated hydraulically. Can accommodate large forces.

- Hydro-mechanical system: Mould opening and closing by mechanical system. Mould clamping by hydraulic piston
- Hydraulic system: Mould is opened and clamped by the movement of a hydraulic piston.

Before any clamp settings can be made, the mould height must be set. This is the total gap between the fixed and moving platens while the mould is in the closed position. On all toggle type clamping systems, the mechanical links must be in a linear position when locked, i.e. no force should be transmitted to the hydraulic system during injection.

- **Platens**

Platens are sturdy plates and form the foundation onto which the mould halves are mounted. Numerous threaded holes or T – slots provide for variable tool dimensions and tool orientation. The platens are normally guided by Tie-bars in each corner. These ensure that the platens stay parallel to each other. Newer machines are called “Tie-bar-less” as the moving platen slides on two bottom rails and the clamping unit compensates for the misalignment during clamping.

The major differences between the fixed and moving platen is the size of the central hole. On the fixed half a large diameter hole allows for mould alignment to the injection nozzle. This is called the locating ring hole. The hole in the moving half is for the ejector bar.

- **Ejector System**

This system releases the part from the moving half. Only in extreme cases will a mould be designed with ejector links to the fixed half for part stripping. There are three main ejection systems used:

- **Mechanical** - These are length-adjustable bars, fixed to the injection moulding machine. On ejection the bar will press against the mould's ejector plate through the hole in the moving platen. These systems have only one ejection stroke and the ejector pins are only moved to the rear during the closing operation via pushback pins.
- **Hydraulic** - In these cases the ejector bar is fixed to the mould's ejector plate as the system moves forward and back with the moving platen. This means the ejection operation can be repeated to shake the part from long protruding pins

(deep cavities). The ejector also retracts the ejector pins before the mould closes and prevents accidental damage if a part is not properly clear from the tool.

- **Air** - A compressed air blast is used to dislodge the part and is typically used in thin wall production e.g. margarine containers. This system can be fitted to either tool halve.

- **Guards and Gates**

Newer machines enclose all moving actions and sources of heat. Numerous accidents occur when operators override the safety features. During the semi-automatic operation, closing the gate of the mould area signals the start of a new injection cycle.

- **Movement Controls for Manual Operation**

- Close mould
- Open mould
- Initiate high pressure system - Mould set-up switch off
- Deactivate high pressure system - Mould set-up switch on
- Activate optional equipment
- Deactivate optional equipment

- **Limit Switches**

- Mould opening stroke – Minimum opening required to allow full ejection
- Low pressure activation – Mould safety. Prevents mould damage on closing if object is between die faces
- Mould close damping – To slow down the platen movement after high speed closing. Prevent mould halves banging together
- Mould open damping – To prevent high impact on mechanical ejector and prevent opening over-stroke
- Ejector deactivation – to prevent damage to mould surface by closing on a locked ejector (only on hydraulic ejectors)
- Initial mould slow opening – Minimises part distortions due to pulling of the fixed halve.
- Optional equipment activation and deactivation

iv. Drive Systems and Process Controls

- **Introduction**

These are all the controls that regulate the injection and clamping units so that the process will be executed at the right temperature, correct volume, speeds, pressures and the right sequence. With the development of solid state devices in sequence control systems, an improvement was made in that the system would detect a variation from the set parameter and alert the operator to take the necessary corrective action. This is called an open loop system.

Recent developments in technology has made it possible to fit a pressure transducer to the cavity. By measuring cavity pressure during the moulding cycle the systems can even regulate themselves to switch over to the next phase in the sequence. These analytical systems can vastly reduce set-up times and improve part quality.

- **Drive System**

Most of the moulding machines used today use electrical power to drive hydraulic systems.

- Electrical power is supplied to the hydraulic pumps, heater bands, optional equipment and the process control circuits.
- Hydraulic oil pressure and flow is used for most of the movements required. To control the oil, three types of valves are used.
- Pressure valves reduce system pressure to the required pressure for the particular movement.
- Flow valves reduce the flow of the oil and regulates the speed of the movement.
- Directional valves direct oil into a circuit to activate a movement.

The machine can operate in three basic modes:

- Manual – used to set the machine. A function can be repeated until optimal setting is obtained.
- Semi-Automatic – the cycle is continuous until the mould opens. The gate must be opened and closed to repeat the cycle. This process is commonly used for non-automatic tools where operator intervention is required.
- Automatic – the cycles follow on each other and will only stop if the system detects a fault.

- **Process Controls**

There are five types of process controls. They are:

- Pressure
 - Clamping unit – Clamping (high) pressure
 - System pressure (injection and clamping)
 - Ejector pressure (hydraulic units)
 - Optional equipment (cores, slides, etc)
 - Air pressure (air ejectors)
 - Injection unit – Injection first stage
 - Hold-on
 - Following stages (if selected)
 - Backpressure
 - Injection unit (pressure of nozzle against the sprue bush)
- Timers
 - Clamping unit – Pause time (end of each cycle)
 - Ejector timer (blowing time for air ejectors)
 - Optional equipment
 - Other pause times to delay machine movements or functions
 - Injection unit – Injection first stage
 - Hold-on (second stage and following stages)
 - Cooling time
 - Plasticisation delay
 - Injection unit back (sprue break)
 - Backpressure
 - Injection unit (pressure of nozzle on the sprue bush of the mould)
 - Cycle control timer
- Speeds
 - Clamping unit – Mould closing
 - Opening speed
 - Ejector speed
 - Optional equipment
 - Injection unit – Injection speed (screw speed forward)
 - Hold-on

Screw rotation (plasticising)
 Injection unit forward (high pressure on clamping unit)
 Injection unit back (sprue break)
 Fast injection speed (for thin walled/ long flow path parts)

○ Temperature

- Clamping unit – Thermoset moulds (heater cartridges in insulated tools with external controls).
 Hot runner moulds (heater coils for long flow path to cavities, to prevent mould freezing).
 Normal moulds (oil heating or water cooling to minimise warping and control shrinkage).
- Injection unit – The barrel is divided in zones for heating and cooling
 Material intake / hopper mouth (water cooled)
 Zone 1 – Feed zone (lowest temperature)
 Zone 2 – Compression zone (higher, enough to plasticise)
 Zone 3 – Metering zone (highest temperature)
 Nozzle – Slightly lower (material should not freeze)

This profile is material and screw dependent for optimal performance.

○ Strokes

- Clamping unit – Mould opening stroke (maximum distance required to eject part)
 Ejection stroke (maximum distance required to dislodge part)
 Optional equipment (distance to clear undercuts and features)
- Injection unit – Injection stroke (distance screw travels forward for shot filling)

• **Typical Injection Moulding Cycle**

- Mould closes – Timer times out (auto). Gate closes and makes switch (semi-auto)
- Mould closing slows – Limit switch activates low pressure and mould safety
- Mould is locked – Limit switch activates high pressure
- Injection unit forward – Follows on high pressure on mould lock
- Nozzle unit forward – Limit switch initiates injection
- Injection – Timer count down for shot 95% of shot

- Hold on pressure – Limit switch activates screw rotation to fill last 5% of shot
- Screw rotation – Timer starts for plasticising
- Screw rotation stops – Screw at the rear, end of plasticising
- Suck-back (optional) – To prevent drooling from the nozzle
- Injection unit back (optional) – Limit switch stops movement for sprue break
- Mould opens – Cooling timer times out
- Ejector operates – Limit switch determines distance and timer regulates speed
- Mould opening stops – Limit switch stops maximum opening
- Mould closes – Timer times out (auto). Gate is opened and closed by operator (semi-auto)

3.6. MOULD CONSTRUCTION

i. Functions of The Mould

The whole injection moulding machine and process revolves around supporting the mould requirements to produce quality parts. Within the mould the cavity or part shape is the central focus of all the movements, gates, runners, vents, cooling and heating.

The functions of the mould can therefore be defined as:

- To be clamped to the fixed and moving platens of the injection moulding machine
- To convey and distribute the polymer melt to the cavities
- To shape the product
- To vent the air from the cavities and runner system
- To cool the part (thermoplastic) or heat the part (thermoset)
- To open the mould and allow the part to be removed

ii. Identification of Mould Parts and Mouldings

A simple mould consists of two main sub assemblies:

- The fixed half – attached to the platen on the injection units side
- The moving half – attached to the moving platen and ejection side

Figure 28 illustrates the various parts of a typical injection mould.

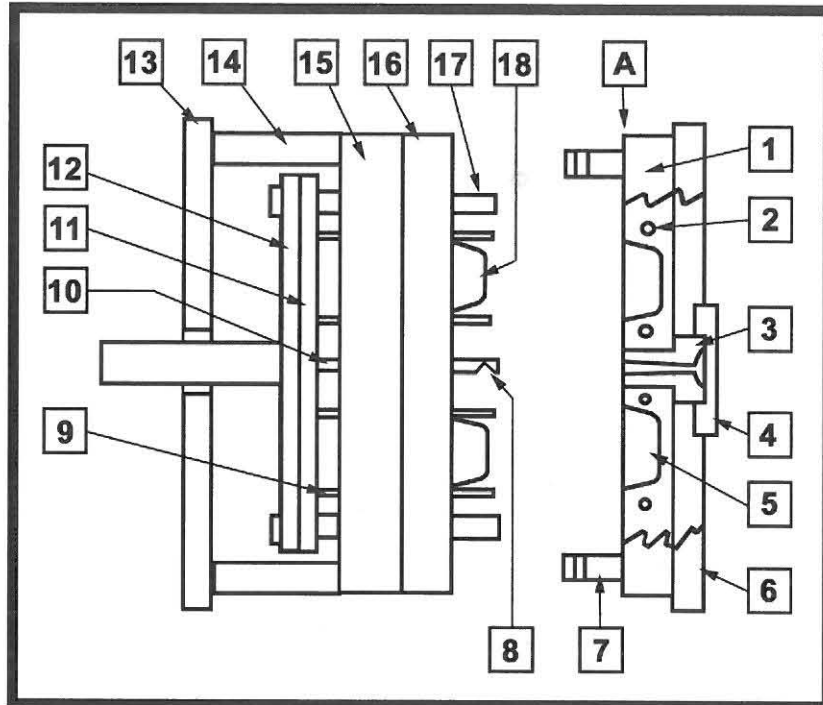


Figure 28: Injection Mould

Fixed Half		Moving Half	
1.	Cavity plate	8.	Sprue Puller Grip
2.	Cooling Channel	9.	Ejector Pins
3.	Sprue Bush	10.	Sprue Puller
4.	Locating ring	11.	Ejector retainer plate
5.	Cavity	12.	Ejector plate
6.	Clamp Plate	13.	Clamp Plate
7.	Guide Pillar	14.	Risers
A.	Split Line *	15.	Support Plate
		16.	Core Plate
		17.	Push Back Pin
		18.	Core

* Note: Not always on a singular plane

iii. A Moulded Shot

The shot is called a tree. This is the total melt required to fill the cavity runners and sprue. For clarity Figure 29 indicates the various parts.

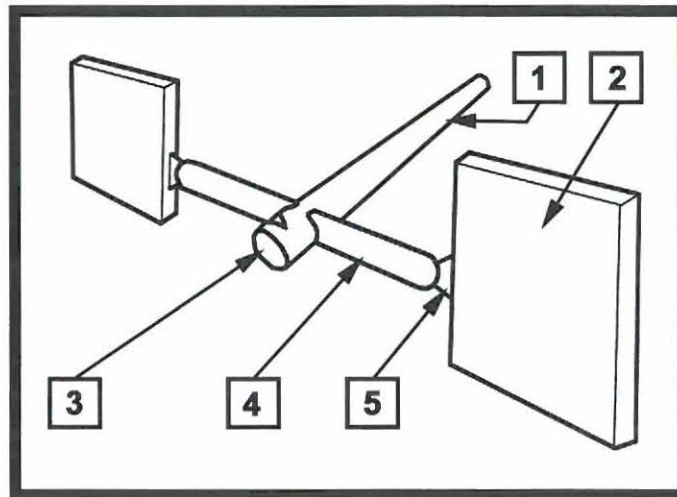


Figure 29: Injection Moulded Shot

- | | | | |
|----|-------------------------------|----|--------|
| 1. | Sprue | 4. | Runner |
| 2. | Part | 5. | Gate |
| 3. | Cold Slug Well / Sprue Puller | | |

iv. The Functions of The Various Mould Parts

- To convey and distribute melt from injection unit to cavities

- **Sprue Bushing**

The sprue bushing connects the nozzle of the injection unit with the inside of the mould. The sprue has a concave radius. This should match the radius on the nozzle. If the radius of the sprue bushing is smaller, flash is formed in the space between the nozzle and bushing. This could cause the part to remain in the fixed half and will not be ejected from the cavity. This part will have to be removed manually. For the same reason, the sprue cavity widens toward the part.

- **Cold Slug Well**

The purpose of the cold slug well is to divert the cold material at the tip of the nozzle out of the flow path for the melt to flow freely down the runner system into

the cavity. A secondary purpose is to form a holding device called a sprue puller. This has directly the opposite effect as the flash at the sprue bush. With the mould opening, the pull force is directly onto the sprue puller and minimises distortion due to bending of soft runners.

- **Runner Systems**

The runners divide the melt and direct flow to various injection points or separate cavities. To facilitate ejection this normally lies on the split line of the tool. For multiple cavities hot runners are recommended. These runners are heated to minimise material waste due to large runners.

- **Gates**

- This is the small transition area from the runner into the cavity. Variations in gate design is used to facilitate the following:
 - Direct the material into a particular part of the cavity (injecting a solid ball).
 - Pressurise the melt to achieve high filling speeds (thin walled parts).
 - Reduce pressure to provide slow even filling (long flat shapes).
 - Provide an even flow of melt to all parts of the cavity (parts with holes).
 - Allow for fast freezing of material in gate area so that injection time is minimised (hot runner systems).

- **To Shape the Part**

The negative shape of the part in the tool is called the cavity.

- **Cavity and Core**

The cavity forms the outside shape of the part (normally on the fixed half). A core (normally on the moving half) forms the internal detail of the part. More complex parts require additional moving sections to release the part.

- **Vents**

As the mould closes air is trapped inside the cavity. To enable the air to escape, vents are used.

If air is not vented the following could result:

- Air will be absorbed in the melt and minute bubbles will be observed on the part surface – streak marks.
- Burn marks or holes could be formed as the compressed air heats up.
- Short mouldings, as the air pressure equals the injection pressure.

To prevent this, air can be vented:

- At the mould split line or cores by leaving rough finish or venting grooves
- Past ejectors or vent pins with venting flats machined to aid air escape.

- **Opening Mould and Removal of Part**

- **Split Line**

To control surface detail on all the part surfaces and material packing, the part is fully encapsulated in the tool. The two mating surfaces of the moving and fixed halves of the tool form a parting line. This parting line is in most cases visible on a moulded part. This is called the split line. The split line follows the outer part boundary from where the part tapers to facilitate release in the tool. Any obstruction that will prevent the part from naturally releasing in the primary direction is called an undercut.

- **Cores and Slides**

Secondary motions withdraw tool material in the form of Cores and Slides to release undercut detail. These actions can be actuated mechanically on opening the tool (limited to the opening stroke of the tool) or with hydraulic or electrical sub systems. (Screw threads turned by collapsible cores or revolving cores).

- **Ejectors and Strippers**

As the tool opens the ejector system moves the ejector plate forward. The various ejector pins protrude from the moving half surface, so forcing the part from the core. For fully automatic production the parts fall free between the mould halves and into the collection chute. For elastomer parts and parts that require operator removal, the gate is opened and the operator removes the parts manually. (Semi-automatic).

- **Clamping of Tool Halves**

As previously mentioned, the tool is aligned with the nozzle of the injection unit via the locating ring. The protruding flanges of the two clamping plates allow the tool to be secured to the machine platens with bolts, spacers and clamp blocks.

- **Cooling or Heating of the Tool Cavity**

An even distribution of cooling or heating minimises warping and distortion of the moulded part. For thermosets, heat is required to achieve a thorough cure of the material. To facilitate this process, heater cartridges or coils are fitted into the cavity plates. An external control unit regulates these. In some cases heated oil is pumped through channels in the tool.

The cooling system in a thermoplastic tool removes heat from the moulding to facilitate solidification of the material. Cycle times can be optimised and surface finish is improved. The material structure and characteristics are stabilised. Mechanical properties are improved (tensile, etc).

Cooling channels are designed to distribute the cooling as evenly as possible. In cores for example, cooling could be in the form of spirals to keep water flow close to the whole part. Most injection moulding machines are fitted with multiple flow manifolds to regulate water flow.

3.7. CONVENTIONAL TOOL MANUFACTURE

i. Introduction

There are a number of methods in use for manufacturing the parts of a mould. Besides various techniques for making the cores and cavities, there is a need to create gates, vents, sprues and establish the proper fits, clearances and drafts in the tool.

The core or insert, being a male form, is usually turned on a lathe or milled from plate or bar-stock material – or a combination of both. The cavity is simple, and a rectangular cavity, providing it can have radiused corners, is easy to mill. However, a rectangular cavity with sharp corners all round is impossible to mill.

One method of producing a cavity with sharp corners is to machine mould inserts and fit these within the cavity pocket to produce the sharp edges. Alternatively, often more desirable methods of producing these sharp corners, as well as other complex configurations, include Electrical Discharge Machining, hobbing and casting.

ii. EDM – Electrical Discharge Machining

EDM (Electrical Discharge Machining) operates on the principle of removing metal with electrical energy. An electrode having either a male or female shape designed to produce a corresponding cavity or core is positioned into the EDM machine. The electrode is then lowered into a work tank filled with dielectric fluid and to within a few microns of the work piece (mould plate). Electric arc travelling across the gap then “erodes” away the cavity material.

The electrodes are commonly made of EDM graphite, brass, or other conductive alloys such as copper, silver and tungsten. The electrodes must be dimensioned to compensate for the over-burn (spark gap) that occurs during the EDM process and also to allow for the plastic shrink factor. For very complex mould cavities or where several of the same electrodes are required, electrodes can be purchased from companies that specialise in producing moulded electrodes (usually copper tungsten) from models of the finished parts.

Any conductive material or metal – tough, hard, soft, brittle – can be eroded with EDM. Many conventional machining applications are now being replaced by EDM because it is

more accurate and more reliable. Also configurations that were thought to be impossible or very difficult to machine a few years ago are now being produced by EDM. Micro slots, burr-free holes, intricate dies and contours make excellent EDM projects. The recessed contours and square corners of cavities are ideal applications of EDM. For difficult shapes in carbide, exotic metals, hard or soft tool steel, aluminium or other conductive materials, it is difficult to match the economics of electrical discharge machining.

This process is however time consuming as electrode manufacture and the eroding process requires skill, accuracy and time to obtain the finish and fit required.

iii. Hobbing

To produce this cavity, it is necessary to produce a male form in steel with the shape of the desired cavity. The hob can be turned to the required diameter, or milled to produce the features. Hob tools are commonly produced by oil hardening drillstock. Next the cavity is prepared for hobbing by machining the cavity to near fit size. Finally, after being coated with white lead – an effective non-galling lubricant – the hob is forced into the cavity in a hydraulic press. It can also be impacted into the cavity. It is possible to hob cavities in aluminium, kirksite and soft low-carbon steel.

It is normal practice to hob a cavity to an over-depth condition. The parting line of the cavity is machined or surface ground to size to obtain sharp edges and reduce the risk of flash on the splitline.

iv. Casting

This same over-depth requirement exists when a cavity is to be cast. First, a model is made of the required part with the dimensions suitably increased to allow for shrinkage. From the model, a pair of epoxy or silicone rubber moulds are cast. From these moulds, plasters are cast and thoroughly dried by baking at 390° C for some hours. Finally, aluminium or kirksite is poured into the plasters and the resulting cores and cavities will be a fine detailed reproduction – in reverse – of the original model. This method of producing moulds is used when the article to be reproduced is difficult to duplicate by machining as for example a sculpture or carving.

v. Fits and Clearances

When plastic is forced into a mould, considerable pressure is involved. The material will flow into all fine corners, edges and cracks. If a clearance of 0.1mm is allowed between a recess and the insert in it, the space will fill with material. Mould tolerance is also polymer dependant as some materials flow more readily e.g. Silicone tools generally have a tolerance of 0.01mm on splitline faces to prevent flashing. It is essential in producing a good mould to carefully size and fit all internal parts. For slide-fit dowels or ejector pins, a reamer of which the size is plus 0.02mm or 0.05mm should be used.

vi. Draft

When machining a cavity or core, a tapered mill cutter could be used or lathe turn with the compound slide set at an angle. The cavity should decrease in size as it moves away from the parting line. A core should decrease in size from its base toward its highest point. The draft in a cavity should be at least 0.5° per side; the core should be drafted a minimum of 1° per side. During moulding the part will shrink away from the cavity and onto the core or insert.

vii. Location of Mould Sections

In order that the desired accuracy be maintained in a part, it is necessary to locate the mould sections relative to each other. In lathe turned moulds, location diameters can be matched during the making of the tool. Moulds made from square or rectangular platens are aligned by doweling the two matching pieces. The drilled and reamed holes should be a close fit to ensure proper alignment and prevent any binding. Sidewalls of the blocks must be finished to establish good edges that can be used for marking out the cavity. This preparation is a necessary step and will subsequently result in more accurate cavities and finished parts.

Any of the following operations will aid in relocating the mould halves: The use of different size dowel pins, stamp alignment marks or milling of a flat on one corner.

viii. Gates

The gate should be cut only after the cavity and core is completed. It is recommended to start with a small gate and increase the size until no signs of knit-lines remain in the moulded part. A large gate will produce a better quality part than a gate, which is too

small. Ease of removal, aesthetics, material flow and material properties also play a role in gate location and type.

ix. Sprue

The size of the sprue at the nozzle end must be larger than the size of the nozzle orifice. The finish of the sprue hole must be smooth, free of chatter or scratches. Various sizes tapered reamers are available commercially.

x. Vents

One of the most important features of a tool is the vent system. Air must be allowed to escape as the material enters the cavity. Vents should be cut at the parting line in various locations around the cavity. Occasionally it is necessary to vent a large cavity at locations other than the parting line. Core pins and inserts can be designed to provide this added venting.

If during sampling, it is found necessary to increase the gate size, it should also follow that the venting may have to be increased. The size of the cavity and the rate of fill will determine the width and number of vents. Over-venting is rarely a problem since the resulting flash on the moulded part can easily be trimmed. Under venting is a common fault and causes burn spots on the moulded part.

xi. Tool Size

The projected surface area and size of the part will regulate to some extent the size of the finished tool. For a small mould, the surface at the parting line should be at least 30mm larger all round the part size. The plate thickness should be no less than 30mm greater than the maximum cavity depth.

When mould halves are bolted together, adequate size bolts should be used as small bolts tend to shear or the threads strip under pressure. The bolts should be positioned to evenly distribute load and create effective sealing.

Support material and bolt sizes will increase proportionally to the tool size.

xii. Mould Finishing

Every mould, core or cavity requires some finishing. First and foremost among finishing operations is polishing. The idea is to have a smooth surface as well as high lustre on the mould working surfaces. First, all machining marks must be rubbed away, and all undulations or ripples in the metal surface removed. Only then will polishing be effective.

The tools used are as follows:

- For removing rough machining marks a light sanding with emery or carborundum cloth should be followed by rubbing with a rough polishing compound (approximately 280 grit) on balsa or hard wood sticks. Felt pads used with motorised hand tools can also be used with compound.
- For a finer finish, polish with a 600 grit compound, finishing with a metal polish on cloth. The part will directly reflect the finish obtained.

Polishing may account for 10 to 15% of the total mould making time. Protective coatings such as chrome or nickel plating, hard anodising or case hardening should only be applied after thorough polishing. Likewise, surface texturing, for example, and blasting to remove lustre, or photo etching to produce a pattern, must be applied over a smooth surface to achieve the desired quality. It is common practice to leave the spark-eroded texture as the final tool finish.

3.8. TOOL MAKING MATERIALS

i. Aluminium

The most widely used material for prototyping and short-run tooling is aluminium. It is readily available, lighter to handle than most other metals, and machines easily. It will take and hold a high polish, and the harder grades wear well. It is resistant to corrosion by most moulding materials and the fumes that they may generate. Aluminium is not highly resistant to erosive or abrasive effects. However, it will easily take hard chrome plating or hard anodising as surface finishes. These finishes are necessary when parts are needed in such materials as glass-filled nylons, which are abrasive. Aluminium grades typically used for tooling are 2024T4 or 7075T6 [4].

ii. Beryllium

This is normally used as a copper-based alloy with a hard, low-friction surface. It will machine and polish well and is highly resistant to abrasion. Because of its high cost, it is used mainly for inserts or cores where aluminium does not have sufficient strength. It requires no heat treatment. Some moulding compounds, especially those with chlorine content such as vinyl, may cause rapid corrosion to beryllium. Beryllium may also require special handling during machining due to toxic fume emissions.

iii. Kirksite

This is a low-melting point, non-porous alloy, rather soft and free cutting. It will cast easily, capture detail and is usually used to produce moulds of sculptured or detailed parts. It may be cast into well-dried plaster moulds. The resulting castings are used as moulds for plastic moulding. Mould life may be extremely short, often well below 100 pieces; however, the mould can be easily made with intricate machining.

iv. Steel

When strength, resistance to wear, and resistance to accidental damage are factors, steel is an obvious choice for mould making material. Tool steel is easy to machine, readily available, inexpensive, and can be moderately casehardened at a minimal cost. Sprue bushings, cores, inserts and thread forms can be made easily in tool steel and then casehardened if necessary. To avoid the problems of heat treatment, tool steels or drill rods are highly recommended. These materials, although partially hardened, can be

machined and polished and are favourites for sliding cores and loose inserts. Large hand operated moulds should not be made out of steel due to the weight. A steel plate that is 150mm X 150mm X 55mm weighs approximately 10kg. A piece of aluminium of equal size is only 3kg. In many applications it is better to have an aluminium mould base with steel inserts for ease of handling.

Other frequently used materials come in the form of ready-made components. They include hardened steel dowels used for location pins and cores, and ejector pins that are available in many sizes may be used as core pins.

3.9. MOULD INSTALLATION

i. Preparation

It is important that the mould will match the injection moulding machines' specifications.

The following areas must be taken into consideration:

- Clamping unit must be able to deliver sufficient force to avoid flash
- Daylight (free travel area) between tiebars to fit tool through
- Overall size of the platens
- Minimum and maximum mould height
- Mould open stroke
- The position and size of securing threaded holes in the platens
- Ejector system of mould and machine is compatible
- Facilities and programs are available if electrical or hydraulic systems are fitted to the tool
- Injection capacity is sufficient to fill the cavity
- The locating ring of the tool will fit the locating hole in platen
- The sprue bush radius matches the nozzle radius

The following tools and equipment is required to install a tool:

- To transport the tool from the tool rack to the machine – trolley or forklift
- To lift the tool – Eye bolts, locking bar to keep mould halves together
- Lifting equipment – gantry, hoist, slings and shackles
- To secure the mould in the machine – clamps, bolts and spacers
- Ejector spacer bar
- Auxiliary equipment – for heating, cooling or core pulling

ii. Lifting and Machine Preparation

To protect the tiebars or in the case of a tiebarless injection moulder, the slides must be protected from damage when loading a tool. Aluminium, PVC or rubber sheets should be used.

The approximate tool height is set. This is especially important with older machines where mould height is set manually.

It is preferable to lift and fit the two mould halves together. This will prevent damage to the cavity, ejector pins or slides. To ensure that the tool remains closed, a lifting bar is bolted to the tool halves. The lifting eyebolt is normally fitted to this bar. Webbing slings can also be used for smaller tools. Care should be taken not to damage water-cooling fittings.

Tool setters and helpers must wear protective clothing and communicate their intentions as injuries can be sustained easily.

iii. Securing Mould

Some moulds are designed for specific machines. It is best if these tools are made with the correct mounting holes in their clamp plates. For the others clamps must be used. The fixed half is secured first. The locating ring is positioned to slide into the locating hole in the platen. The mould should be oriented into the optimal position where the part will fall free in ejection and where cooling hoses will not interfere with operation. Some tools have loose running slides - care should be taken that they don't fall free during mould opening.

The following is important for the use of clamps:

- The bolt should be equidistant between the spacer and mould clamp plate
- The spacer should be the same height as the mould clamp plate
- The clamp bar should be thick enough not to bow under tightening load.
- The bolt threads should penetrate a minimum of twice their diameter

Cooling hoses and connections should be checked for leaks. To prevent damage during operation, hoses should be secured with only the required free play and safe routing. The ejector bar should be connected and set. This should be followed by connecting the electrical, hydraulic and pneumatic systems if required. Lastly the mould slings, eyebolts and lifting bars should be removed.

On removing the mould, the following must be checked:

- Residual plastic material should be removed.
- All moving parts should be cleaned and greased.
- Any defects should be noted to generate a tool room work order.
- Any leaks or corrosion should be noted and repaired.
- Heaters or other auxiliary systems should be checked for defects.
- Mould parting faces should be protected with anti – corrosion.

- Water needs to be blown from cooling channels with dry air to prevent corrosion.
- The last moulding should be kept with the tool for identification and comparison purposes.
- Only soft metals should come in to contact with cavity faces.
- Mould documentation should be kept up to date for audit purposes.

3.10. RUNNING OF AN INJECTION MOULDING MACHINE

There are five main areas in running an injection-moulding machine

- Mould installation
- Setting of machine movements
- Start-up and shut down of the machine
- Purging – for changes of material
- Optimisation areas – to obtain a smooth running machine producing acceptable quality products at the highest optimum rate.

i. Start-up and Shut-down of the Machine

Before start-up the following must be checked:

- Ensure that the mould and other equipment have been correctly fitted and are in good condition.
- Turn on the main switch and set the specified temperature profile.
- If running with a hot runner mould or a hot mould, the temperatures should be set.
- Start the pump to allow the oil to heat up as well.
- Ensure that the feed section and hydraulic oil cooling is open.
- While the machine is heating up, assemble all the things required to run the product.

ii. Procedure

- Ensure that the barrel, mould and hydraulic oil have reached their set temperatures.
- In the manual mode, ensure that the machine has been correctly set and that mould safety is operative.
- Fill the hopper with the required material to correct level.
- With the injection unit in the retracted position, fill the barrel in short rapid shots.
- Check the melt and mould temperatures with a pyrometer to ensure instruments are reading the correct temperatures.
- Commence moulding

iii. Determine Pressure-Changeover Position From First to Hold on Stages

- Set shot weight limit switches
- Set hold on pressure to zero
- Set hold on limit switch very close to shot weight limit switch
- Mould (it will be a short shot)
- Move hold on limit switch further from shot weight limit switch
- Mould (will be less short)
- Repeat until cavity has been nearly filled. This is the position for the changeover to hold on pressure.
- Apply procedure 3.10.iii. to determine hold on pressure

iv. Determine Hold on Pressure

- Set pressure very low, with long hold on time
- Mould and measure/weigh component (note pressure gauge reading)
- Increase pressure slightly and repeat first two steps
- Set the hold on pressure when dimensional tolerances and weight are correct.
- Apply procedure 3.10.v. to set hold on pressure time

v. Determine Hold on Pressure Time

- Reduce time to a minimum
- Mould and weigh component without sprues and runners
- Increase time by 1 second (it's best to allow a few shots for the machine to stabilise)
- Weigh component and record
- Repeat until component mass does not increase. At this stage the gate has frozen off and optimum hold on time has been achieved.

If the machine is to be stopped for any length of time, for example for repairs or overnight, the material must be removed from the barrel before the machine is shut down.

vi. Velocity

This aspect will be of particular importance for the use of epoxy tooling. In order to extend the mould life the velocity of the injection will need to be kept at a minimum.

Injection speed – the velocity of the advancing screw, acting as the injection plunger, is responsible for this effect. This can also be expressed as Injection time.

During this period of the injection cycle dynamic forces are unevenly distributed on the cavity walls. This is therefore a critical period for damage to fragile cavity faces.

3.11. POLYMERS RELATED TO TRIALS

i. General

The most significant rules in part design and material selection is to keep the wall sections constant, and use adequate draft on all vertical surfaces. If “no draft” is called for, it may be necessary to add additional material on the part and remove this excess material in secondary processes to generate the parallel surfaces.

Wall thickness on moulded parts are typically 0.7mm to 3mm. Excessive pressures are needed to force material into cavities with less than a 0.7mm wall. Sections over 5mm will tend to cool too slowly and stresses and sink marks will result.

It is bad practice to have extremes of wall thickness or localised heavy sections on a plastic part. Differences in cooling and chilling rates will cause warpage in the finished part. When a heavy section is required, it should be used as a filling point for the cavity.

ii. Tolerances

A common error made by designers is to expect tolerances similar to precision machining. Although the tool is manufactured with accuracy and tight tolerances, the moulded parts will not all necessarily be the same size.

All plastic parts will shrink when cooled from a plasticised to a chilled part. The shrinkage will depend on the mould temperature and the material temperature change. A cavity produced at a different temperature than those during operation will also expand (if heated) and have an influence on the final part size.

Additional factors that influence variations in size are ambient temperature and humidity or changes in injection pressure and speed.

Material suppliers include general shrink factors on the material data sheets. These are however a guideline only. In addition to the spark gap and non-linear shrinkage due to geometry constraints, the only way to achieve higher accuracy is to wait until after part sampling and only then make final adjustments as required. This is especially true for multiple components clipping or sliding together. Careful design is the only alternative to minimise the cost of high tolerance components.

iii. Polymers for Experiments and Trials

The most important criteria for the material selection for the experimental trials were:

- The material should have little abrasive impact on the tool.
- The process temperature should be as low as possible.
- It should be a common engineering plastic being used by industry.

Two materials were selected namely, Polypropylene (PP) and Acrylonitrile-Butadiene-Styrene (A.B.S).

- **A.B.S. [2]**

A.B.S. is a thermopolymer – a mixture of acrylonitrile (which gives it chemical resistance), butadiene (a rubber which improves impact strength), and styrene (a rigid, high lustre, low-cost and hard base). It colours well, resists straining and can easily be bonded with solvents. This is a relative low cost material and is commonly used for consumer products. The molecular chains must not be thought of as straight lines. The chains are more like coiled springs and in addition lie in all directions, even turning back on themselves. This material forms part of the amorphous family. In these materials the chains are randomly distributed and there is no order. The reason for the amorphous state of certain polymers lies in the structure of the chain; polystyrene has large side groups (benzene groups) on the chain. This benzene ring is attached to every second carbon atom, making it difficult for the chains to lie close to one another or for the backbone of the chain to blend or fold back on itself.

- **Polypropylene [2]**

This is the lowest density commodity polymer. It is manufactured as a homopolymer or as a copolymer with ethylene. Manufacturers commonly mix both types with fillers and other additives to obtain specific properties. These blends are called copolymers. Polyprop floats easily, can be sterilised by boiling, has a high lustre surface, moulds easily and is fast replacing other plastics in the electronics industry as a component material. Polyprop will not absorb water, and it resists most chemicals and solvents. (Ideal for experimentation with various release agents). The material is flexible, but has poor wear resistance and is also commonly used for integral hinges with the added advantage of low cost.

Polyprop is part of the crystalline polymer family. In these polymers the molecular chains pack closer together and form regions where the molecular chains are ordered as the material cools. When molten it is clear, indicating that there are no crystalline areas. But as it cools down it starts to become hazy – these are the molecules packing closer together – until it becomes opaque when fully cool. The cooling process is critical to the formation of crystalline areas and in some materials it may continue for up to 48 hours after de-moulding. Crystalline areas in materials have a reinforcing (stiffening) effect on the polymers. Even with heating these materials will remain stiffer for longer (used in the appliance industry for kettles). These materials are susceptible to differential shrinkage if moulded with variable wall thickness. This causes warpage and even stress cracking in some cases. Table11 shows the general properties of the various grades of material obtained for tool trials where as Table 12 compares ABS versus Polyprop under various conditions.

Table 11: SASOL Polymers – Polypropylene Comparison Use for Trial Mouldings

Properties	Units	1100N	1102K	2340PC
Physical properties				
Mass density	g/cm ³	0.908	0.908	0.906
Melting point DSC	°C	162	162	162
Melt flow index MFI 230/2.16	g/10min	11	3.5	15
Mechanical properties				
Tensile strength at yield (50mm/min)	MPa	33	34	26
Elongation at yield (50mm/min)	%	10	10	8
Ultimate elongation	%	>50	>50	>50
Modulus of elasticity in tension (1 mm/min)	MPa	1500	1450	1300
Izod notched impact resistance 23°C	kJ/m ²	2.3	3	5
Charpy impact resistance 23°C	kJ/m ²	NB	NB	NB
Charpy impact resistance 0°C	kJ/m ²	25	NB	NB
Charpy impact resistance -20°C	kJ/m ²	14	18	NB
Shore D hardness after 3 seconds	-	71	70	60
Shrinkage	%	1.4	1.5	1.5
Thermal properties				
Heat distortion temp. HDT/A (1,8N/mm ²)	°C	47	55	55
Heat distortion temp. HDT/B (0,45N/mm ²)	°C	82	89	94
Vicat softening point A/120 10N	°C	150	152	150
		High flow Short cycle times	Low flow	High flow Short cooling time Thin walled parts

Table 12: Amorphous Versus Crystalline Properties [2]

Amorphous	Crystalline
During cooling	
<ul style="list-style-type: none"> Density remains constant Little shrinkage Clear 	<ul style="list-style-type: none"> Density increases Shrinks Translucent to opaque
During heating	
<ul style="list-style-type: none"> Wide softening point Wide melt temperature 	<ul style="list-style-type: none"> Short softening range Sharp melt point
During moulding	
<ul style="list-style-type: none"> Can be over-packed 	<ul style="list-style-type: none"> Can not be over-packed
Properties	
<ul style="list-style-type: none"> More permeable to gasses Better stress crack resistance Better dimensional stability Better welds, joints 	<ul style="list-style-type: none"> Stiffer Better chemical resistance Better lubricant properties Better adhesion Better wear resistance Improved surface hardness

3.12. Fault Identification and Rectification – Moulded Parts

This may be a lengthy process since it requires consideration of material, machine, mould and process. The following guidelines are suggested:

i. Material

The grade or type of material should be checked. Material should be examined for contamination and if it complies with the manufacturer's specification.

ii. Machine

Functioning of all parts of the machine in accordance with the recommendations given should be checked, especially anything that could influence pressure, temperature, rate and time.

iii. Mould

The mould parameters should be properly set as well as the correct temperature and all the parts should function smoothly and correctly.

iv. Process

The pressure, temperature, rate and time should be set according to the material parameters as recommended by the material supplier.

v. Services

Cooling / heating of the mould should be set at the correct temperature as well as air pressures should be set correctly, and no excessive fluctuation in electricity supply should occur.

vi. Moulded Component

Visual clues as per the following table are the indicators of underlying faults that need to be addressed. In addition to these, components need to be weighed for consistency, colour compared to a set standard and critical dimensions measured. For the purposes of this project the injected components will be measured with a digital vernier. This comparative process is similar to the evaluations done by 3D Systems [14] and also

Taguchi [5]. Results in these two references show dimensions like diameters and lengths measured to accuracies of three decimal places, which is possible with a vernier. The dimensions will include overall lengths, boss diameters and rib thicknesses.

Table 13 clarifies common terminology used in the plastic moulding industry to describe defects in parts. These defects are used as indicators for fault finding and implementing corrective action.

Table 13: Moulding Fault and Description [2]

Fault	Description
Burn mark	An area of degraded or oxidised polymer in a moulding
Cracking or crazing	Fine cracks on the surface of a moulding which sometimes turn into deeper cracks when stress is applied
De-lamination	Surface layers of the material which separate from the main section of a moulding in appearance rather like the skin of an onion
Distortion	The moulding is of a different shape from that required, generally apparent immediately after the component is removed from the mould (see warping)
Flash	Unwanted thin web of material on the edges of a moulding or at mould mating surfaces where gaps should normally be too small for material to penetrate
Flow marks	A mark on, or in the surface of a moulding which shows the flow path of the material, especially where the stream of material has become divided (see weld line)
Mica mark	See splash mark
Poor surface finish	Undesired dullness or ripple on the surface of a moulding
Scuffing	Surface marks on the walls of a moulding which run in the direction of mould opening
Short moulding	An incomplete moulding
Silvering, silver streak	See splash mark
Sink mark	An unwanted depression in the surface of a moulding, especially on the face opposite to where the section thickness increases (e.g. At a rib)
Splash mark	A mark on a moulding having an appearance similar to mica. Splash marks generally (but not invariably) radiate from the point of entry of the material into the mould. Also known as mica mark, silvering or silver streaking
Splay mark	Surface marking on the moulding, generally near to the gate and similar in appearance to the grooves of a gramophone record.
Staining	Areas of a moulding (or Mould), which take up a dull, discoloured appearance.
Sticking	The mounting tends to stick in the mould by mechanical or vacuum adhesion of the moulding to the mould surface, making ejection difficult. Sometimes this fault only occurs at the sprue
Voids	Only obvious in transparent moulding, voids and unwanted cavities within the thickness of the material. They occur also in opaque mouldings, when they can be detected either by ultrasonic means or by density determination (or by destructive test)
Warping	The moulding becomes bowed or distorted, generally some time after cooling (see distortion)
Weld lines	A mark on the surface of a moulding at the junction of separate streams of materials
Window	An area of transparent material in an otherwise translucent moulding
Witness mark	A mark on a moulding where different parts of the moulding come together or "mate"

For corrective actions refer to the "Injection moulding fault finding chart" attached as Appendix A, published by the Plastics Federation of South Africa. This chart describes the Fault, Causes associated with the categories mentioned above and their related corrective actions.

3.13. Coating Techniques

Many techniques for coating onto plastics and resins have been developed. The part to be coated is defined as the *substrate*, and the coating material as the *consumable*. Coating techniques are categorised as fusion or non-fusion. Non-fusion processes have porosity as an inherent property.

i. Metal Impregnation

This technique is a method for incorporating metal powders into a plastic or resin moulding material. It causes a dull, lustreless surface finish and the part tends to become brittle. The main reason for using metal impregnation is to enable the part to be electroplated. Electroplating requires the plastic part to be conductive. However metal impregnation causes an uneven dispersion of metal powder. This results in uneven plating onto the plastic part [9].

ii. Hot Metal Dipping

Hot metal dipping involves coating a plastic substrate by the melting of solder. The solder should be of a low melting point to prevent melting or damage to the plastic part. This is followed by quickly dipping the substrate in a bath of molten metal. A deposit of the metal is fused to the solder coating [9].

The technique is restricted to plastics that can withstand high temperatures, and produces an irregular, thick metallic surface. This technique is more suited for industrial purposes and would not be applicable to this project.

iii. Thermal Spraying

Thermal spraying is the application of a consumable to a substrate by melting the consumable into droplets and impinging the molten droplets on a substrate, to form a continuous coating. The molten droplets cool on impact with the substrate, such that the coating is essentially formed by overlapping splats of metal [6]. To optimise the adhesion process, abrasive blasting or a bond coat is applied beforehand. The most common thermal spraying processes are:

- Flame spraying
- Electric arc spraying
- Plasma arc spraying
- Detonation gun spraying
- High velocity Oxy-fuel spraying

Many of these techniques use Oxy-fuel torches to melt powder, causing excessive heating of the part. They are thus unsuitable for coating on to plastics.

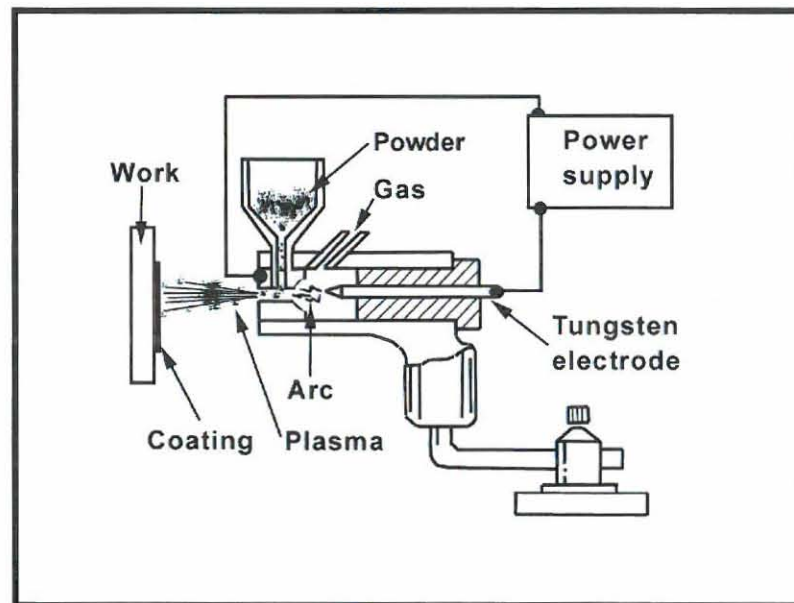


Figure 30: Plasma Arc Spraying [6].

Plasma arc spraying, as per Figure 30 uses a powder melted by arc-generated plasma within a spray gun and can be used on plastics. There is very little heating of the substrate with part temperatures rarely exceeding 150°C. Under the right conditions; this temperature can be reduced to below 100°C. The deposit has a grained structure forming a rough irregular surface finish. It can be used for the initial step of electroforming.

iv. Physical Vapour Deposition

An extremely thin deposit of metal, usually aluminium, is vaporised in a vacuum and deposited onto the surface of the substrate. Pre-treatment is necessary to provide an adhesive surface. An electric charge is placed through a thin aluminium wire or film in a crucible, vaporised into a gas cloud, and subsequently deposited onto the part. The part needs to be rotated so that all areas are in direct 'line of fire' of the metal film. Recesses or undercut surfaces are not coated. The surface needs to have a lacquer applied directly after the deposition to keep the metal deposit sealed onto the part. The technique is also known as vacuum metallising [6]. The set-up is illustrated in Figure 31.

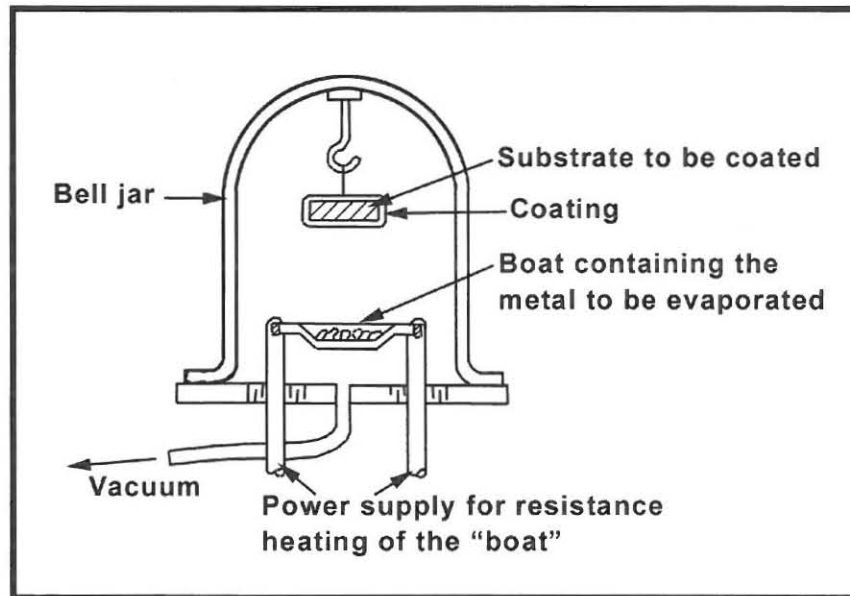


Figure 31: Physical Vapour Deposition [6].

The process is very sensitive to environmental impurities such as dust and only non-recessed parts can be processed. The surface finish can be very even and accurate provided the procedure is well controlled. Coating thickness of $0.5\mu\text{m}$ can be obtained, but this would be too thin for wear or thermal transfer processes. This technique is sometimes used to deposit a mirror finish onto transparent plastic parts [9].

This process could be used to evenly coat an epoxy mould and therefore would be relevant to the project. Careful control over the process is necessary to ensure an even finish on slightly recessed areas of the mould.

iii. Immersion Plating

The part to be plated is placed in a plating bath without electrical or external energy. The chemical process is ion substitution. The coating is not very strong and is used often as a pre-treatment for electroplating or electroless plating.

iv. Electrolytic Plating

Electrolytic plating is a process whereby metallic ions in solution deposit onto an oppositely charged substrate. This requires that the substrate be electrically conductive. The metal ions originate from the electrolyte. The electrolyte is usually a water solution of a metal salt of the metal to be plated (e.g. CuSO_4 , where copper is the metal to be plated). Adhesion on to the substrate is part mechanical and part atomic bonding. Atomically clean surfaces (no absorbed oxide layers or films) are needed for electroplating and are created by acid pickling or electrochemical cleaning immediately prior to plating. Before plating, plastics need to be made conductive by metal impregnation, immersion plating or autocatalytic metal deposition.

Electroplating does not level rough surfaces, but corner build-up of the plating occurs as per Figure 32. This occurs due to a high current density on corners, causing an increase in the number of ions to be deposited. Plating thickness should be limited to $25\mu\text{m}$ to maintain dimensional accuracy. Plating into recesses requires widening of the recess opening or using electroless plating technique to plate into the recess.

Redesigning the part using the following guidelines can reduce the effects of corner build-up:

- Radius all corners
- Provide an area for electrical connection to the part such that build-up does not occur at the connections.
- Avoid small holes and openings.
- Large flat surfaces should be made convex.
- Flat edges ending in corners should be tapered.

[6].

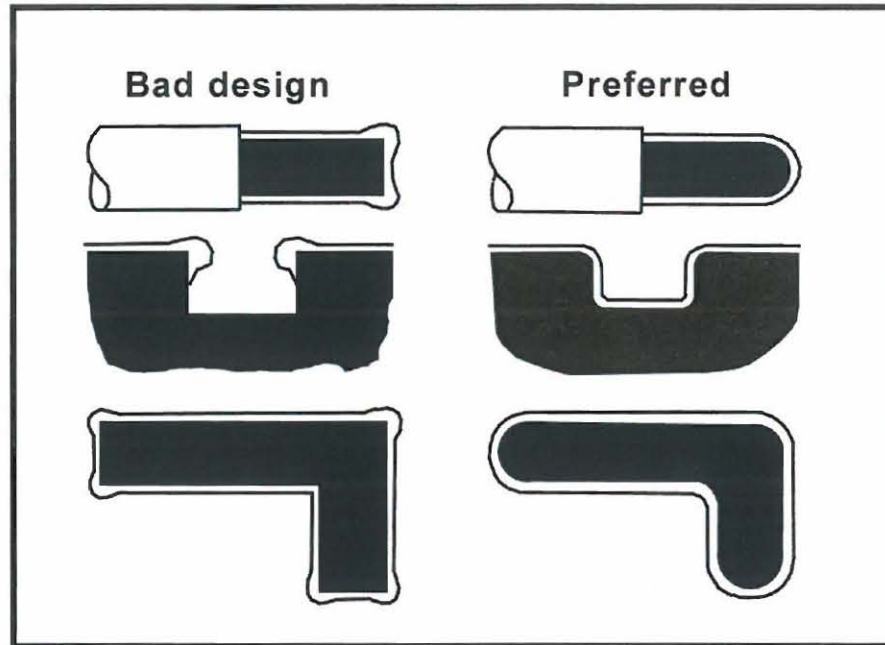


Figure 32: Reducing Corner Build-Up [6].

v. Electroless Nickel Plating

Electroless nickel plating was first developed in 1945. The part is immersed in a plating bath and an adherent coating develops. The mechanism used is the catalytic reduction of metal ions onto the substrate. Electroless nickel is deposited from an aqueous solution of nickel salts, a reducing agent, pH buffers and catalysts. When the part is placed in the bath, the nickel deposited on the substrate's surface acts as a catalyst, causing the nickel ions in solution to be reduced by the reducing agent. The technique is also called *autocatalytic plating*.

The reaction in a nickel sulphate bath with a reducing agent of sodium hypophosphite is:

$$\text{NiSO}_4 + \text{NaH}_2\text{PO}_2 \xrightarrow{\text{heat / catalyst}} \text{Ni plating} + \text{NaHPO}_3 + \text{H}_2\text{SO}_4 \quad \text{E.4.}$$

The plating does not stop when the surface is completely covered with nickel. Coating rates range from 12.5 to 25µm per hour. Unlike electroplating, electroless nickel plating does not form corner build-up and the surface topography remains relatively unchanged from small deposition thickness (<25µm) [6].

The plated surfaces are usually semi-bright in appearance. The appearance depends on the smoothness of the substrate, as a rough surface will not produce a bright finish.

Usually the plated surfaces are ground or polished after plating to increase appearance. Different bath formulations can produce bright, semi-bright or dull deposits.

The uniformity of the deposit depends on ion concentration throughout the solution. If there is circulation of the solution over all areas of the part, then a uniform deposit occurs. This is difficult to achieve in thin, deep grooves.

A disadvantage of electroless nickel plating is that the chemical bath is kept at a temperature of 90°C, which causes "burning" of the stereolithographic epoxy surface. Electroless copper plating is similar to electroless nickel plating except that copper salts are used instead of nickel salts. Also, the bath temperature is approximately 60°C. A thin surface coating (5-10µm) serves as a good undercoat for electroless nickel plating. A nickel coating has the advantage of increased hardness compared to a copper coating. Copper coatings have better heat transfer than nickel coatings.

The plating facility at the Atomic Energy Corporation (AEC) was subcontracted to plate the mould inserts. Electroless Nickel Plating and electrolytic Nickel Plating were the chosen techniques due to their accuracy and surface detail reproduction.

Three sets of inserts were plated. The User Part and Bottle Opener SLA inserts were plated using electrolytic nickel plating. The AEC was not able to perform electroless nickel plating on the Stereolithography parts. To enable electrolytic plating, the surface needed to be made conductive. The pre-treatment of the inserts included:

- Mechanical polishing
- Chemical etching
- Surface activation

Mechanical polishing and surface etching are processes to prepare the surface for plating. The surface activation process makes the outer surface of the insert conductive. The AEC was not forthcoming with further details of these processes as they have been developed in house and are a competitive advantage.

The nickel plating occurs in a chemical bath at 40°C. This causes the nickel to cover larger area of epoxy than at room temperature. As the insert cools down, the nickel contracts with it and forms thin ridges that detach from the surface. This was noticeable on large flat sections. The nickel plating that was deposited onto the insert had a

thickness of between 10 – 25 μ m. The inserts were jugged along the cooling channels so they had silicone oils on their surface, deposited during the silicone moulding process. This caused trouble with the plating process and the plating had to be repeated several times.

The User Part was plated to test whether the process could plate into thin ribbed sections. This was successful although corner build-up occurred, despite the smoothing of the corners that was done by hand.

The aluminium epoxy inserts were initially plated by electrolytic copper plating, followed by electroless nickel plating. The undercoat of electrolytic copper plating was required to cover all areas of exposed epoxy. The electroless nickel process does not plate well onto non-metallic substances. The undercoat developed from the point of electrode contact on the cooling tubes and propagated outward to the rest of the part. Thin layers of copper were deposited, sanded down with emery paper to ensure even plating and re-plated. This resulted in a thick, consistent layer of copper deposited on the inserts. The epoxy part was difficult to cover completely. The parting face of the insert ended with a copper layer approximately 100 μ m at its centre. This layer gave an excellent adhesion to the underlying aluminium epoxy substrate.

An electroless nickel coating was deposited on top of the copper coating. The plating bath had a temperature of 90°C and this caused discoloration of the epoxy as could be seen after testing. The electroless nickel coating had a thickness of 10 – 20 μ m.

3.14. Temperature Distribution and Mould Cooling

The temperature distribution in an injection mould is difficult to quantify due to the complex geometry; temperature gradients and cooling rates which all exist in an injection mould.

The problem can easily be broken down into three distinct stages:

- Heat energy added to the system through plastic injection.
- Conduction of heat through the mould.
- Heat removal from the mould by cooling water and air convection.

The temperature cycling compounds the heating and cooling conditions experienced in the mould.

- **Heat Energy Added**

Plastic is initially injected at the highest temperature of the entire cycle. This temperature depends purely on the material process specifications. The heat of the plastic is conducted from the plastic to the surface of the mould. The rate depends on the enthalpy of the plastic material. Enthalpy is not a linear function and working curves for plastic are temperature dependent.

The heat transferred to the surface is localised to the area in direct contact with the plastic part. Furthermore, the heat is concentrated where higher volumes of plastic are present and so the surfaces near to these large volumes experience more heat transfer than other areas.

- **Conduction Through Mould**

The heat is then removed from the mould insert face by conduction to an area of lower temperature by the principle of temperature gradients. The rate of conduction depends on the thermal conductivity of the material. If a series of different materials with distinct interfaces occurs, such as in plated mould inserts, the heat transfer depends on the conductivity of the contact faces, thermal build-up within each layer and heat absorption of the materials.

As can be seen in Figure 33 the heat is transferred concentrically from its point of origin. To promote even heat transfer, cooling channels should be placed 2 – 3 times the channel diameter from the surface.

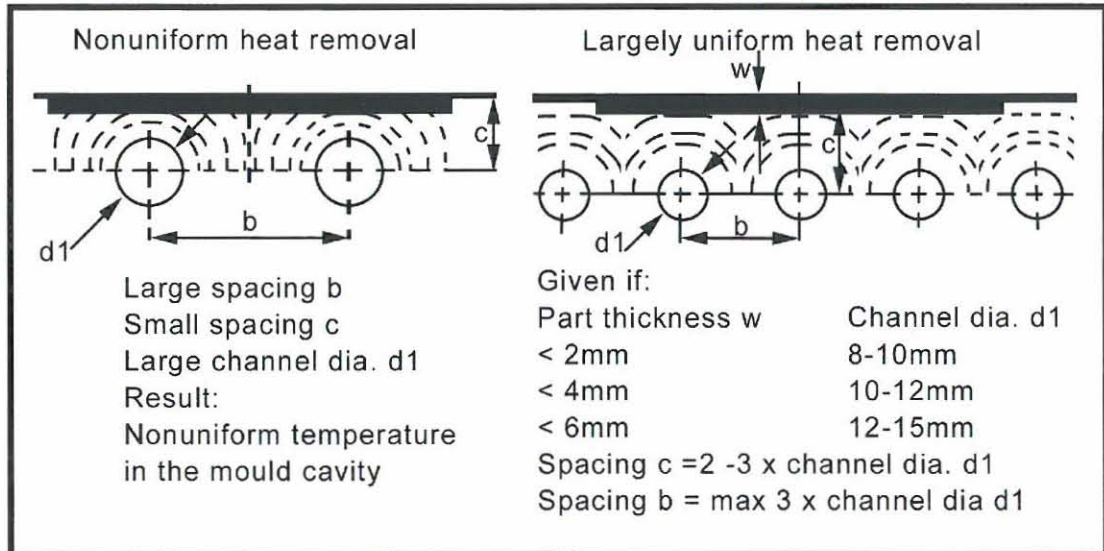


Figure 33: Cooling Channel Placement [10].

- **Heat Removal**

The heat removal process occurs by three means:

- Cooling water circulated through cooling pipes in the mould.
- Natural air convection and radiation around the mould.
- Forced air convection and radiation through compressed air blown onto the surface of the mould.

- **Cooling Water**

This is the primary method of cooling of the majority of moulds. Cooling water circulates through tubes or machined channels in the cavity plates. The heat is transferred by convection from the mould to the cooling water in the tubes. It is important that good surface contact exists between cooling tubes and the mould material. Ineffective conduction between the mould material and the cooling tubes can occur, such as air gaps between the tube and mould material. This will drastically reduce cooling rate. The mechanism of heat convection from the cooling

tubes to the cooling water is best obtained under turbulent flow of the water. This is assured for Reynolds numbers > 6000 and partially assured for Reynolds numbers between 2320 and 6000.

- **Natural Air Convection**

Air circulates around the mould as a natural form of air convection. Air near the surface of the mould is heated by convection and is subsequently displaced by cooler air from beneath. This form of convection is unpredictable due to natural drafts and the enclosed space typical of injection mould machines. There is also radiation removal of heat from the surface but this is negligible in comparison to conventional effects.

- **Forced Air Convection**

Heat removal can be effected by forcing air convection on the faces of the tool. This is most frequently done to the parting faces of the moulds after ejection and before the next cycle is initiated.

The complex nature of the problem requires some simplification and assumptions to be made to enable analysis of the problem by analytical techniques. It is sometimes more useful to use experimental results on similar work to evaluate the temperature distribution within the mould. Many of the parameters required for the analytical analysis need to be determined experimentally and some parameters have large ranges.

In an experiment described by Rhamati [19], a Stereolithography bridge tool was tested without water-cooling. The temperature was recorded throughout the injection moulding process as seen in Figure 34. The mould was cooled to 45°C before a new cycle began. The temperature was necessary to produce complete mouldings. The cycle time was 4.3 minutes with the freeze time of the plastic being increased from 15 to 40 seconds. The experiment produced parts free of warpage and cavity temperature did not exceed the glass transition temperature of the Stereolithography resin.

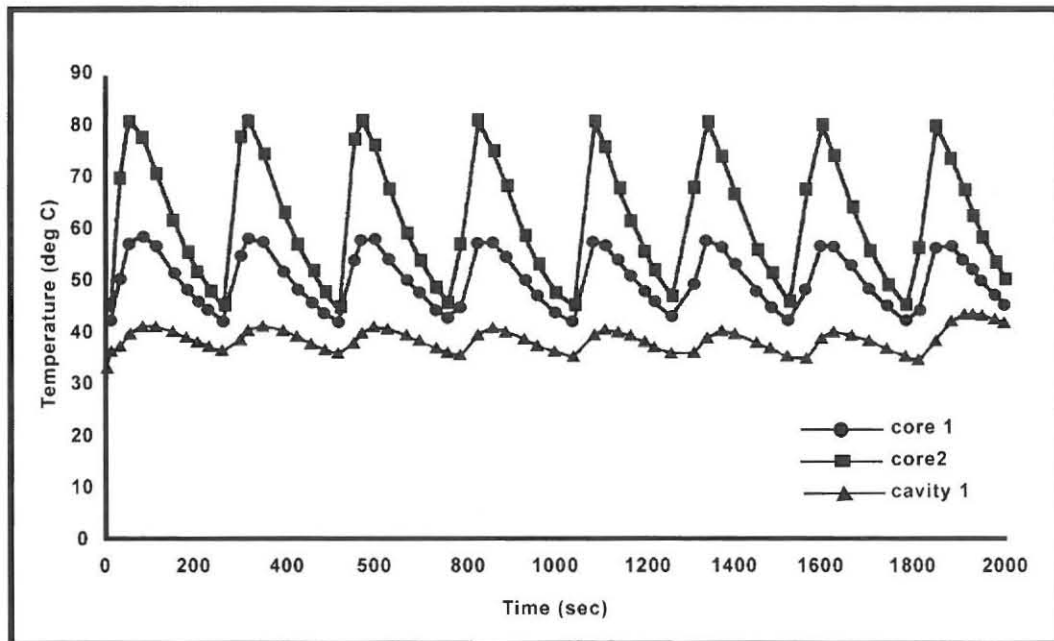


Figure 34: Temperature vs. Time for Injection Mould Cycle of Stereolithography Mould Without Cooling [19].

A second experiment involving air jet cooling of the moulds was performed. This resulted in the cycle being reduced to 2.2 min.

Stereolithography resin has a thermal transfer rate of 300 times less than that of steel. Thus the rate of cooling within a mould is slower and hot spots develop. These hot spots are concentrations of heat on the mould surface caused by large volumes of plastic, which contain more heat than other areas with small plastic volumes. These hot spots can cause the mould to exceed its glass transition temperature. This results in damage to the mould and reduction of mould life. Hot spots can adversely affect the plastic parts. Slow cooling of a spot results in different material properties to the other areas of the part.

4. EXPERIMENTAL RESULTS

i. Study 1 - User Part

The initial investigation in conventional tooling methods highlighted the fact that tools typically suited to EDM were the candidates for rapid tooling. The time-consuming task of breaking the part up into multiple electrodes, the machining of complex shapes and the alignment of electrodes with the work piece for the sparking process, generally takes too long. Parts requiring thin slots to be produced in a tool, generally smaller than 3mm in diameter and deeper than the cutter diameter, are also fair candidates.

As trials published by 3D Systems, did not test these conditions, (flat circular discs etc.) a modified “user part” was selected.

This part consists primarily of the above mentioned features. Initially it was intended to core out the corner pillar sections, but the core pins were omitted in fear that the part will stick to the fixed half of the tool.

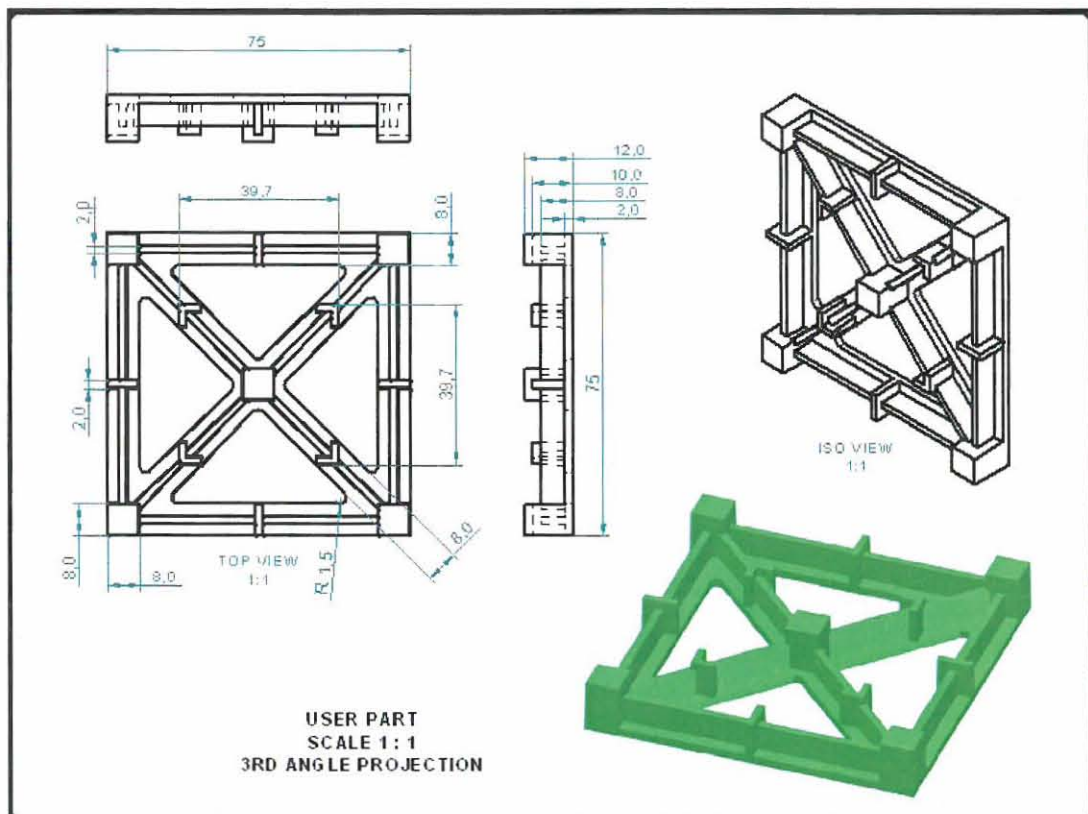


Figure 35: 3D CAD Image of Modified User Part

This part is used extensively by the RP community to determine accuracy and tolerance criteria of various RP systems.

As per Figure 35, the part was modelled as a solid 3D model with Intergraph's EMS CAD modelling software. A general draft angle of 1° was used and no shrinkage compensation was added. This part was later subtracted from the insert models to produce the two mould cavities.

ii. Tool Design

Various tool configurations were investigated.

The following constraints were imposed on the design:

- The tool size and height had to be compatible with the injection-moulding machine available in the Polymers Section of MATTEK at the CSIR.
- The tool would be used for various tool configurations.
- The SLA inserts had to be kept to a reasonable size to minimise growing time.
- Parts of the tool had to be interchangeable to adapt the tool to experimental requirements.
- The cost of tool manufacture had to be kept to a minimum.
- As the tool would invariably be fitted and removed from the moulding machine numerous times during an experiment, the tool had to be a manageable size and weight.

Initially an aluminium tool with the inserts mounted from the front of the die plates was considered. The complexity and ejector configuration however ruled out this option. As this tool would not be standard, new configurations would require specific design and machining.

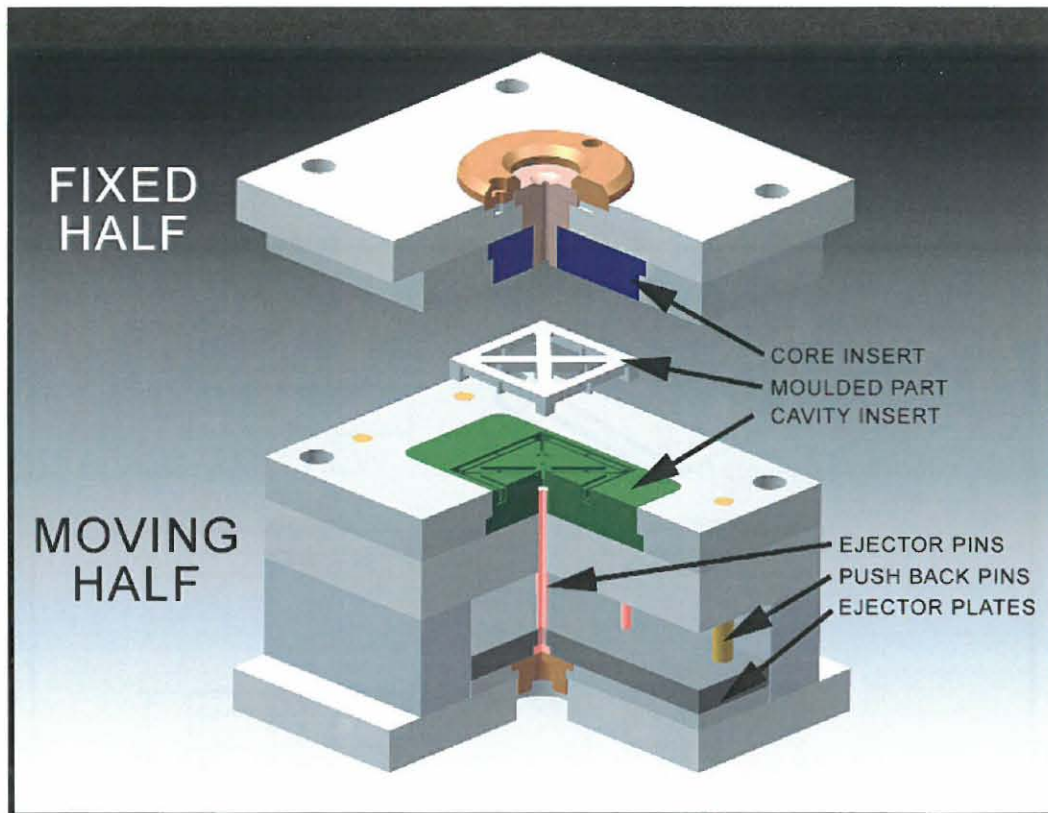


Figure 36: CAD Image of Assembled Tool With Inserts Fitted.

A standard 246mm X 196mm die-set with 26mm thick die plates was ordered from Form Mould Services. As per Figure 36 the only modification requested to the die set was the two insert pockets. The inserts of 160mm(length) X 92mm(width) X 26mm(height) would be retained in the tool by a 5mm wide shoulder. The inserts would be fitted from the rear of the die plates to ensure that no movement occurs during the trial process.

Considerable tool face remained to minimise the direct clamp force on the insert shutoff faces.

The die set was delivered within a three-week window. During this time the SLA inserts were produced on the SLA500 with SL5180 resin. Figure 37 shows the assembled tool with overall sizes and maximum ejection stroke of 35mm. The mould height is used to set the clamp height of the injection moulding machine.

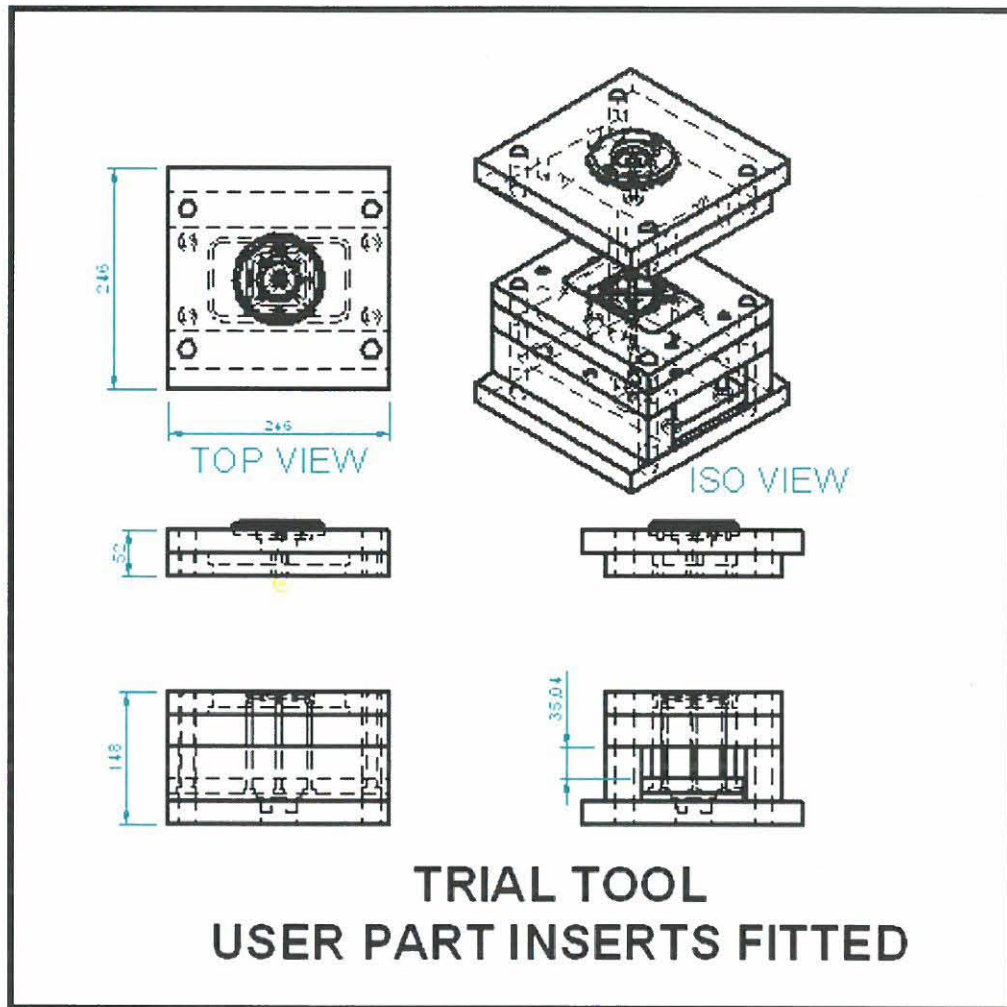


Figure 37: Tool Assembly Drawing.

iii. Insert Generation and Finishing

Other features apart from the cavity were added to the CAD models. These include the ejector pinholes, sprue bush hole core pinholes and water cooling channels. These features are indicated in Figure 38. The inserts are 160mm long, 92mm wide and 26mm high. The total volume for the cavity insert is $319\,750\text{mm}^3$ as opposed to $321\,243\text{mm}^3$ of the core insert.

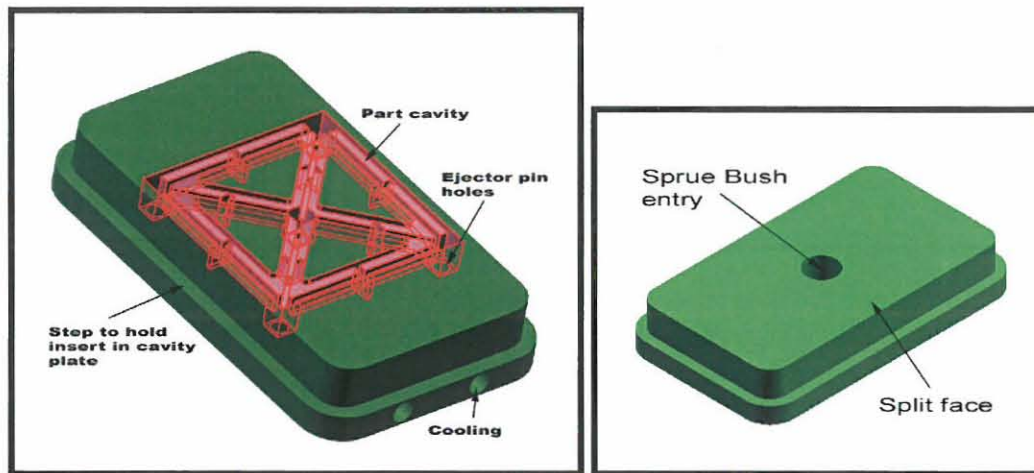


Figure 38: 3D CAD Images of Cavity & Core Inserts.

STL files were generated with a cord height tolerance setting of 0.01mm and exported to the Maestro™ software. The inserts were positioned in the centre of the platform with a provision of 10mm support. The split line faces of the inserts were aligned parallel with the platform and the inserts were rotated to reduce the risk of the sweeper arm colliding with a straight edge. Layer thickness was set to 1.5mm. The remainder of the parameters were left on default settings. Estimated growing time was calculated to 24 hours for the two inserts.

iv. Tool Assembly and Specific Machining

On inspecting the grown inserts the split line surfaces did not align properly. Both sides had a meniscus with a maximum deviation of 1mm. The inserts also measured 0.5mm oversize and had to be sanded down to fit into the die plate pockets. The edges of the inserts were aligned with the front of the die face and the additional material was sanded down to obtain proper die closure. The support structure was removed from the cooling channels and the spiral pockets were sealed off with plugs grown for this purpose. Extension tubes with quick release connections were fitted to the inserts. The ejector pin holes and the sprue bush hole were reamed to size to ensure proper fit.

At this stage it was decided to change the standard sprue bush design and to provide a shoulder for the bush to press onto the mounting plate. This would reduce the risk of the injection unit exerting excessive force onto the fixed half insert.

This concluded the tool assembly. The tool was mounted into the injection-moulding machine for trials.

v. Tool Trials

- **ENGEL Injection Moulding Machine**

The trial was performed on an 80 ton ENGEL injection moulding machine at the CSIR, similar to the unit in Figure 39.



Figure 39: ENGEL Injection Moulding Machine.

The machine specifications are as follows:

Manufacturer:	ENGEL
Type:	ES 330/ 80 HAS
Serial no.:	29 253
Year of construction:	1996

More detailed specifications for this machine are in Table 14.

Table 14: ENGEL Injection Moulding Machine Specifications

Injection Unit				
Screw diameter	mm	30	35	40
Metering stroke	mm	160		
Screw speed	min ⁻¹	400	400	320
Plasticising rate	g/sec	14	19	22
Injection rate	g/sec	80	108	142
Max. stroke volume	g/sec	113	154	201
Max. shot weight	cm ³	103	140	183
Specific injection pressure	g	2400	2000	1530
Nozzle stroke	bar	250		
Nozzle contact pressure	mm	47.1		
Heating capacity	kN	9.2		
Heating zones	kW	4		
Clamping Unit				
Clamping force	kN	800		
Opening stroke	mm	450		
Ejector force	kN	40		
Ejector stroke	mm	100		
Mould height min.	mm	250		
Mould fixing plate size	mm	660 x 360		
Drive				
Pump drive power	kW	15		
Oil filling	l	140		
Weight				
Net weight	kg	4900		

Ambient conditions at the place of installation of the injection moulding machine was:

- Ambient air temperature:
Min: +10 degrees C max: +40 degrees C
- Relative humidity:
Min: 20% max: 80%
- Measurements were taken using a Mitutoyo CD-6"BS digital vernier; by Mitutoyo Corporation, Japan
- The material used was Polypropylene 1102h by Polifin. The material has a density of 0.90g/cm³.
- Various release agents were used and consisted of:
 - "Sunlight" Dishwashing liquid
 - Q10, a penetrating oil by Triton-Leo Group
 - WD-40, produced by WD-40 Company Ltd.

These release agents had no noticeable effect on the inserts.

vi. Methodology

- **Machine Set-Up and Parameter Selection**

The die set is lifted into place using an overhead crane. The locating ring is located into the hole in the fixed die platen. This half of the tool is secured with clamps. The gate of the moulding machine is closed to move the moving half forward in set-up mode. The ejector bar is connected to the ejector plate of the tool and the moving half of the tool is secured to the platen. The cooling hoses are connected and tied back to ensure they will not be damaged during mould operation. The protective gates are closed and the set-up can begin. A full list of the parameters used in the experiment is listed in Table 15.1 and Table 15.2. Adjustment of all the parameters is done on the electronic console on the ENGEL machine, which uses an EC88-A02 microcomputer.

The first parameter to be set is the mould height. Second is the ejector stroke. The stroke needs to be long enough to eject the part off the insert, but should be short of hitting the back of the support plate.

The initial parameters used for this experiment were based on experience with steel tooling. Pressures and speeds were decreased to compensate for the decreased strength of the epoxy tool.

Table 15.1: Set-up Parameters

Settings	Value
General	
Clamping force	400 kN
Injection pressure	50 bar
Cycle time	Varied
Release agents	Varied
Temperatures	
Nozzle temperature	190
Zone 2	200
Zone 3	190
Zone 4	180
Mould closing	
Opening stroke	300mm
Mould protection	10mm
Mould protection pressure	45%
Mould protection end	0.1mm
Mould protection time	5 sec
Injection	
Max. injection speed	130mm/s
Actual injection speed	Varied
Injection time monitoring	5-10 sec

Table 15.1: Set-up Parameters

Post injection pressure	
Post injection pressure	Varied
Post injection pressure time	5 sec
Cooling time	Varied
Plasticisation stroke	Varied
Plasticising	
Stroke / (shot size)	Varied
Back pressure	Varied
Sprue break	Off
Ejection stroke	35mm
Cooling	
No cooling of inserts	

The process was run in semi-automatic mode. Each cycle was stopped after part ejection to allow the operator to intervene. This enabled the inspection of each part to determine setting changes. It is the authors' opinion that a skilled tool setter is required to optimise the process and minimise the risk of accidental damage to the inserts.

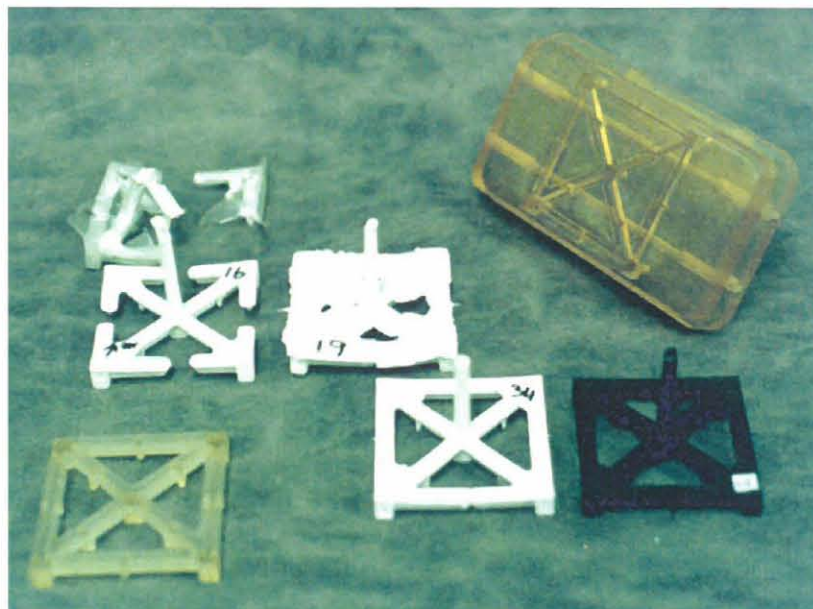


Figure 40: Various Moulded Parts with AIM Insert

Figure 40 records various injection moulding shots with the SLA tool insert in the top right hand corner and a SLA user part in the lower left hand corner for comparison.

vii. Documentation and Measurement of Parts

Significant setting changes were recorded to determine how these influence the part. Each part was cleaned and marked with the shot number on ejection. The features to be measured are the overall width of the part and the thickness of the rib sections. In order to maintain consistency, the orientation of the sprue-puller was used as a reference to ensure that the corresponding lengths and thicknesses of each part were measured.

For each dimension required, three measurements are taken in order to obtain an average.

The width measurements needed to be taken at the top surface of the part. This was to avoid the warping of some of the parts, as well as the draft included in the design of the part, from affecting results.

viii. Experimental Data

In total, 71 components were shot. At this point there was significant cavity damage. The detailed observations and parameter changes for the shots are in Table 16.

Table 16: Record of Shots.

Shot no.	Parameters varied	Parameter value	Observations
1	Cycle time (seconds) Release agent Shot size (mm) Back pressure (bar) Injection speed (mm/s) Post injection pressure (bar) Ejection speed (%)	300 dishwashing liquid 10 0 27 0 60%	Part stuck in fixed half (short shot) Difficult to apply – very viscous
2	Shot size Release agent	5 Q10	Shot short:- gradually filling cavity Part released better
3	Shot size	8	Short shot Ejected, did not drop free Fixed half temp: 30 37° C
4			Setting unchanged, better filling
5			Setting unchanged, same filling
6	Shot size	10	Short shot, large sink marks
7			Short shot, almost completely filled
8			Approx. 95% filled (same as 7)
9	Back pressure (bar)	5	Filled same as 8. First part of tool chipped off
10	Post injection pressure (bar)	20 @ 5 sec	Still not filled completely
11	Post injection pressure	20 @ 10 sec	Same as 10 release agent after each shot to ease release
12			Tool chipped – rib area Part did not eject – brittle broken by ejector
13	Shot size	12	No change- temp on fixed half 43°C
14			Part better filled- flash forming

			Part warm on ejection Warping – due to part design and ejector location
15			Part better filled. Forming cold weld lines at centres of outer beams – <i>Venting added in these areas</i>
16	Shot size Release agent Pigment added	10 WD-40 White	Still not filled properly Tool chipped- Flat area Part feels and looks better
17	Back pressure (bar)	10	Filled same as shot 15 Venting not sufficient Tool chipped Fixed half shows signs of swelling
18	Venting Ejection speed (%)	Increased 30	A lot of flash
19	Ejection speed	5	To reduce risk of inserts breaking more due to deforming on ejection Flash
20	Cycle time (sec) Ejection speed Back pressure	200 10 7.5	Less flash Part flatter – still cold weld lines Best filled part out of 20
21	Cycle time	30	Hardly any flash No breaking of part on ejection
22	Cycle time	20	Cycle too short, part still soft
23	Cycle time	60	Cycle too short, part very hot
24			Cycle same, part very hot
25			Cycle same, part very hot
26	Cycle time	120	No breaking, little warping
27			Sprue blocked cold slug – no fill
28			
29			
30			Little flash or warping
31	Back pressure	8	Part worse than previous
32			Better filled
33	Back pressure	9	Best part out of 33
34	Back pressure	10	Stable filling
35	Injection speed (mm/s)	29	
36			First full part. Quite a bit of flash and warping
37	Back pressure (bar)	8	Still full; less flash than shot 36. Slight breaking on ejection due to cold welding
38			Same results as shot 37
39	Injection speed (mm/s)	33	Same result as shot 38
40			Part not filled properly. Hydraulic system switched off, i.e. no back pressure.
41			Hydraulic system off again. Part filled. Still cold welding
42			Better
43			Same as shot 42
44			Same as shot 42 – First sign of consistency
45			Ditto. Cold welds still occurring. Tool chipped further.
46			Less filled
47			Back to normal fill
48	Cycle time (seconds)	90	Slightly better, but still cold welds
49	Injection speed (mm/s)	36	Less breaking
50	Cycle time (seconds)	60	Still breaking
51	Post injection pressure (bar)	10	Still breaking
52	Post injection pressure (bar) Back pressure (bar)	15 9	Less breaking
53			Better than shot 52
54			Same as shot 53
55			Same as shot 53
56			Screw needed to be plasticised –part not filled well
57			Same as shot 55

58	Back pressure (bar)	9.5	No noticeable change
59			Increased warping Insert chipping more
60	Back pressure	9	More chipping off cavity insert
61			Part breaking more on ejection Steam is forming when release agent is applied. The insert is getting very hot. (thermocouples no longer work) This is due to short waiting times between shots – approx. 10 seconds
62	Injection speed (mm/sec)	30	Injection speed reduced to try and prevent more breaking of the cavity insert. This has no effect; more chipping – Insert is now seriously damaged. Higher injection speeds will now be tested
63	Injection speed (mm/sec)	50	Less cold welding; i.e. less breaking on ejection
64	Injection speed (mm/sec)	55	Same as shot 63
65	Cycle time (seconds)	75	No real effect
66			Ditto
67	Back pressure (bar)	10	Almost no cold welds or breaking
68			Best part out of 68. No breaking on ejection. Part filled 100%. More tool chipping
69			No part breaking. More warping. This may be due to inserts getting hot – poor insert heat dissipation
70			Ditto
71	Cycle time (seconds)	300	Part breaks on ejection. This cycle time seems too long. Part shrinks onto the insert too much.

A problem that was observed is that shot size is specified in millimetres of screw travel and not in volume. It is therefore difficult to gauge the shot length to obtain required volume or mass. The only method is to start with a short shot and build up to the required shot length. This is not only time consuming but risky for fragile tooling.

The original dimensions of the part are summarised in Table 17.

Table 17: Original Part Dimensions

Dimension	Epoxy Insert	Original CAD Model
Overall width (mm)	74.47	75.00
Rib thickness	1.71	2.00

Dimensional data of the trial parts were only considered from shot 21 to 70 as the earlier shots were mainly used for machine set-up and were erratic. These dimensions are reflected in Table 18.

Table 18: Moulded Part Measurements

Shot No.	Rib Thickness (mm)				Overall width (mm)				
	Read 1	Read 2	Read 3	Ave.	Read 1	Read 2	Read 3	Ave.	
21	1.53	1.49	1.50	1.51	73.37	73.37	73.37	73.37	
23	1.56	1.56	1.57	1.56	73.36	73.36	73.36	73.36	
26	1.48	1.46	1.47	1.47	73.30	73.35	73.31	73.32	
30	1.50	1.49	1.48	1.49	73.38	73.39	73.39	73.39	
31	1.51	1.50	1.50	1.50	73.42	73.43	73.44	73.43	
32	1.49	1.48	1.47	1.48	73.39	73.41	73.41	73.40	
33	1.51	1.50	1.47	1.49	73.46	73.47	73.46	73.46	
34	1.55	1.51	1.47	1.51	73.34	73.23	73.37	73.31	
35	1.71	1.69	1.68	1.69	73.59	73.61	73.62	73.61	
37	1.67	1.67	1.67	1.67	73.65	73.66	73.64	73.65	
38	1.66	1.67	1.65	1.66	73.67	73.68	73.65	73.67	
39	1.70	1.67	1.68	1.68	73.51	73.52	73.50	73.51	
40	1.62	1.61	1.62	1.62	73.50	73.52	73.51	73.51	
41	1.63	1.64	1.65	1.64	73.65	73.65	73.64	73.65	
43	1.61	1.61	1.59	1.60	73.56	73.57	73.57	73.57	
44	1.68	1.62	1.62	1.64	73.55	73.55	73.56	73.55	
45	1.64	1.60	1.60	1.61	73.43	73.44	73.45	73.44	
46	1.58	1.57	1.59	1.58	73.46	73.56	73.59	73.54	
47	1.60	1.60	1.60	1.60	73.39	73.45	73.38	73.41	
48	1.63	1.60	1.61	1.61	73.66	73.65	73.62	73.64	
49	1.63	1.61	1.64	1.63	73.75	73.75	73.76	73.75	
50	1.63	1.66	1.61	1.63	73.64	73.65	73.66	73.65	
51	1.65	1.64	1.63	1.64	73.63	73.63	73.62	73.63	
52	1.64	1.68	1.64	1.65	73.66	73.66	73.65	73.66	
53	1.63	1.64	1.62	1.63	73.53	73.53	73.53	73.53	
54	1.64	1.63	1.62	1.63	73.56	73.55	73.55	73.55	
55	1.60	1.61	1.59	1.60	73.54	73.50	73.51	73.52	
56	1.64	1.63	1.63	1.63	73.52	73.56	73.54	73.54	
57	1.68	1.67	1.64	1.66	73.56	73.56	73.57	73.56	
58	1.65	1.69	1.69	1.68	73.51	73.50	73.51	73.51	
60	1.64	1.65	1.65	1.65	73.48	73.49	73.48	73.48	
61	1.61	1.65	1.64	1.63	73.45	73.42	73.45	73.44	
62	1.68	1.68	1.68	1.68	73.49	73.48	73.53	73.50	
63	1.63	1.64	1.65	1.64	73.49	73.52	73.53	73.51	
64	1.66	1.70	1.67	1.68	73.55	73.54	73.54	73.54	
65	1.68	1.64	1.67	1.66	73.69	73.68	73.67	73.68	
66	1.64	1.65	1.63	1.64	73.45	73.45	73.44	73.45	
67	1.62	1.63	1.64	1.63	73.53	73.52	73.53	73.53	
68	1.65	1.64	1.62	1.64	73.52	73.54	73.52	73.53	
69	1.64	1.65	1.62	1.64	73.43	73.43	73.45	73.44	
70	1.61	1.61	1.58	1.60	73.41	73.41	73.39	73.40	
Mean					1.61				73.52
Standard Deviation					0.06				0.10

ix. Data Processing

- Machine parameters

The optimum machine parameters were selected from the list of observations. Those conditions that lead to a full part, were selected.

- Part shrinkage

The manufacturer's specification for shrinkage factor of polypropylene is 1.6%. From the data collected the overall shrinkage can be calculated.

Overall shrinkage = $100 \times (\text{CAD} - \text{Part}) / \text{CAD}$ _____ **E.5.**

- For the rib thickness (the average measured part rib thickness was 1.61mm),

$$\text{Overall shrinkage} = 100 \times (2 - 1.61) / 2 = \mathbf{19.5\%}$$

$$\text{Shrinkage from CAD to insert} = 100 \times (2 - 1.71) / 2 = \mathbf{14.5\%}$$

- For the overall width (the average measured part width was 73.52mm)

$$\text{Overall shrinkage} = 100 \times (75 - 73.52) / 75 = \mathbf{1.97\%}$$

$$\text{Shrinkage from CAD to insert} = 100 \times (75 - 74.47) / 75 = \mathbf{0.71\%}$$

- Shot Size Calibration Curve

In order to calibrate the shot size, the volume of the sprue and runners were calculated. This volume must be added to the part volume to calculate total shot weight.

The volume of the "modified user part" was 14.912 cm³ (from the CAD model), and the sprue volume (to the reference point) was 0.8959 cm³. This gives a total volume of 15.8079 cm³. The shot size required to fill the part was 10mm. This defines the first point of the calibration curve.

x. Results

- Machine Parameters

From the observations in Table 16, the 'optimum' machine parameters were selected. These are reflected in Table 19 and should be a good starting point for future trials.

Table 19: Optimum Machine Parameters

Parameter	Value
Cooling time (s)	60
Shot size (mm)	From calibration curve
Back pressure (bar)	9
Injection speed (mm/s)	35
Post injection pressure (bar)	15

For the rest of the parameters, the initial conditions used for this experiment can be carried forward to future testing.

- Tool Wear

In order to obtain preliminary data with respect to the life of an epoxy insert, the measurements taken were plotted in Figures 41-44 as a function of shot number in order to distinguish any trends.

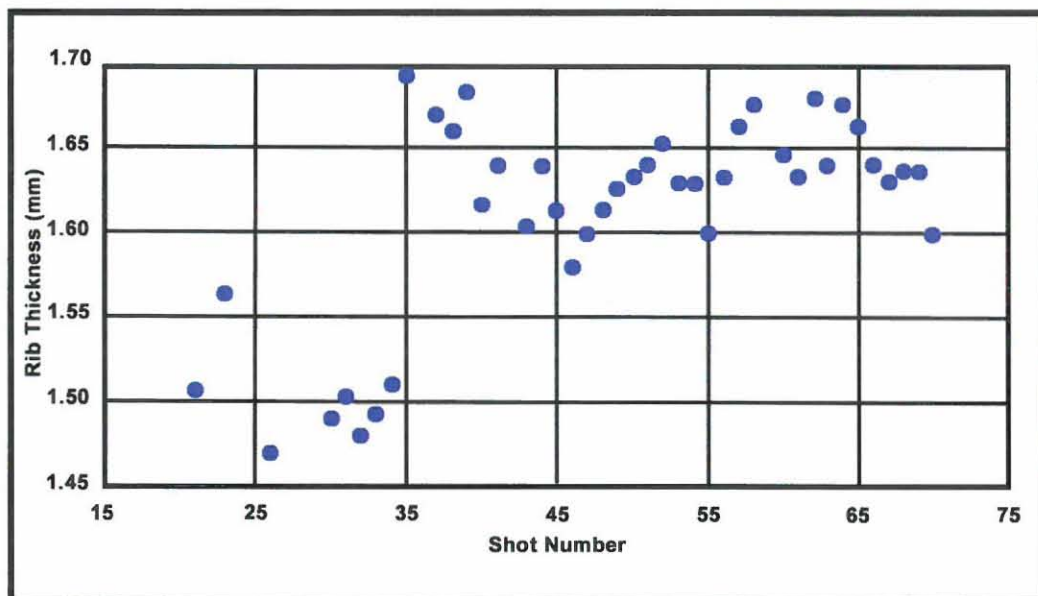


Figure 41: Rib Thickness Versus Shot Number

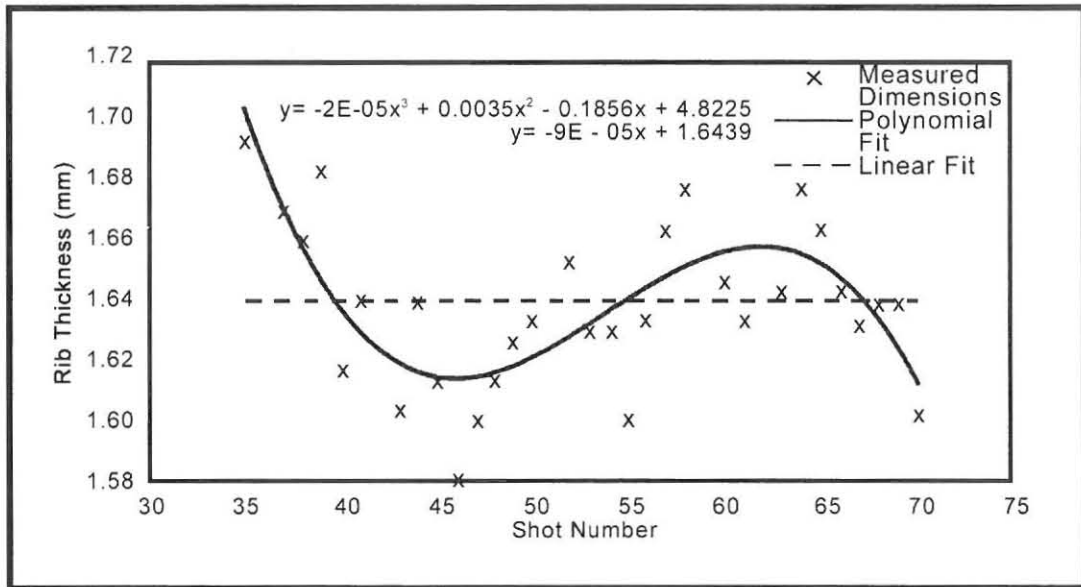


Figure 42: Curve Fits to Rib Thickness Measurements

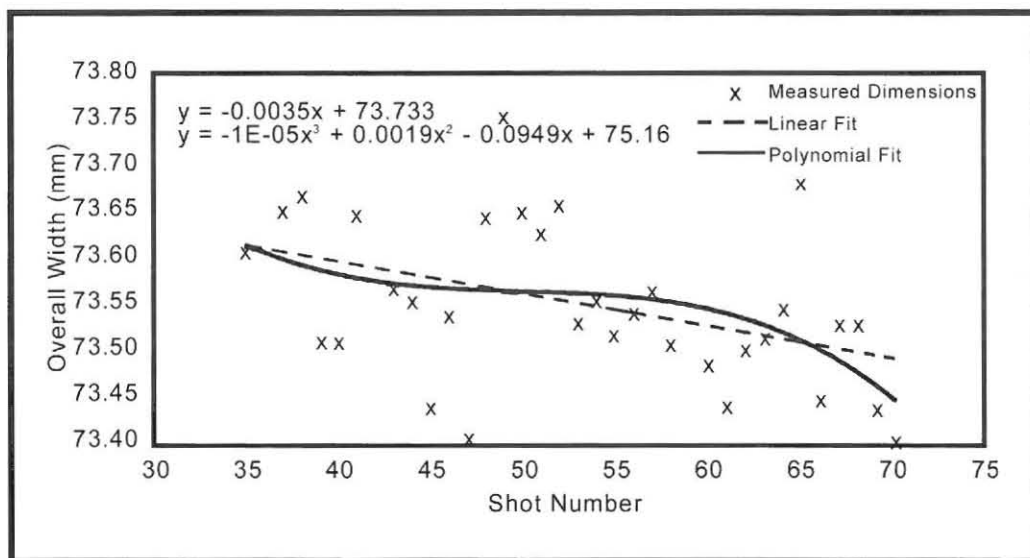


Figure 43: Overall Width Versus Shot Number

- Shot Size

Figure 44 illustrates cubic volume of a component versus the shot size in mm required for machine setting. It is assumed that the curve will be linear and that it will pass through the origin (this will probably be proved wrong once more data points become available).

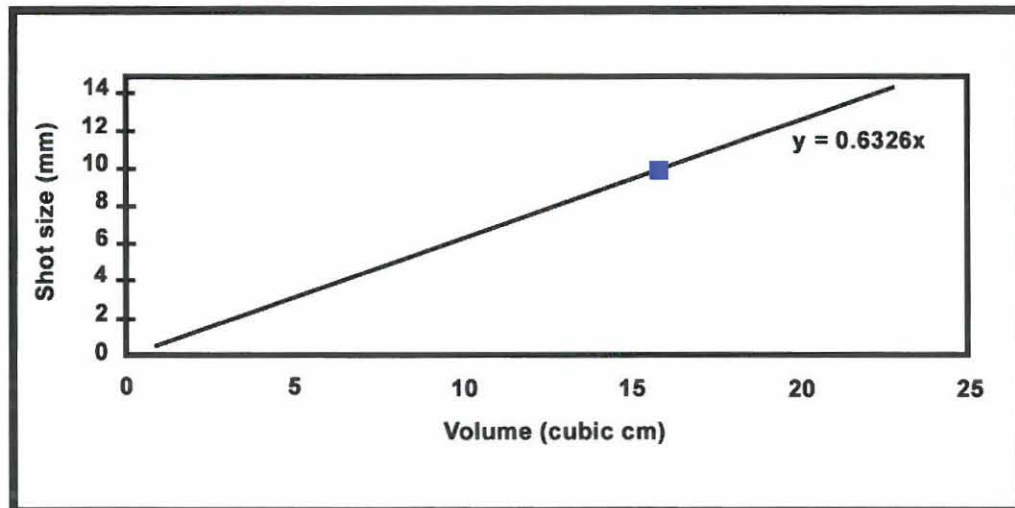


Figure 44: Shot Size Calibration Curve 1

xi. Observations

- Parameter Setting as Recorded in Table 16

According to findings during the literature study, a recommended cycle time of approximately 5 minutes would be necessary for Direct AIM™ and this value was used as an initial value for the testing. It was found that with this setting, parts were breaking substantially when they were ejected. In order to combat the breaking, the cooling time was reduced to 60 seconds from shot 23 as per Table 16. The shorter cooling time resulted in far less breaking taking place. This appeared to be the shortest time possible; a cooling time of 20 seconds for shot 22 recorded in Table 16, was too short. The plastic was still soft on ejection.

The longer the cooling time, the greater the shrinkage of the part. Much of the other research work investigated by the author involved the production of simple parts, especially flat round disks. For simple parts like that, increased cooling times mean that the part actually shrinks away from the side walls, and can thus be easily ejected. In the case of the modified user part, however, increased cooling times mean that the part shrinks 'onto' the inserts, especially in the rib sections. As a

result, the parts break on ejection. Preliminary testing therefore seems to indicate that cooling times of 5 minutes may be too long for certain more complex parts and that cooling time of 60 seconds is long enough to allow the part to cool sufficiently to be ejected. This may result in uncontrolled post shrinkage, as the part is not constrained while cooling outside of the mould.

From shot 44 in Table 16, the wait times between cycles were consistently short (in the order of 10-20 seconds). At shot 61, steam formed when the release agent was applied to the inserts. This indicates that the temperature of the inserts was starting to increase dramatically. The glass transition temperature of the resin used (SL5180) is between 65° C and 90° C. It is estimated that the temperature was reaching 55° C to 66° C by shot 61 (thermocouples were attached to the inserts in the cooling channels during the testing and indicated temperatures of 45° C). The epoxy resins are poor conductors of heat and temperatures at the insert surface would have been higher than the 45° C indicated by the thermocouples. This clearly indicated that cooling with water channels would not have been an effective method. Swelling was also visible on the surfaces of the fixed half insert. It thus appears necessary to cool between shots. For future testing, a delay of 60 seconds between cycles should be used as an initial value.

The release agents used for the test (Q10 and WD-40) are standard release agents for conventional injection moulding; these are oil based. It is possible that these are not ideal for ACES inserts as they tend to retain heat longer. "Spray and Cook", (a vegetable oil) was tested with noticeable improvement.

The injection speed does not appear to be responsible for the chipping of the inserts. The first piece chipped off at shot 9 with an injection speed of 27mm/s. The plastic injects directly onto the sprue puller, and not onto the inserts, so this should not damage the inserts directly. By increasing the injection speed to 33 mm/s at shot 39, less breaking occurred during ejection of the part. This can be attributed to the fact that less cold welding was taking place. The cold welding can be attributed to the part design and the multiple flow paths that take place during filling. For this design the injection point needs to be investigated with flow analysis.

It appeared to take a number of shots with the same settings in order for the part characteristics to stabilise; shot 6 was short even though the shot size of 10mm was used (the same shot size that produced full parts towards the end of the testing).

About 3 shots must be allowed for the changes in the parameter setting to fully take effect.

- **Design of Components for Direct AIM™**

The modified 'User part' used for this preliminary research proved to be quite complex. The thin, deep ribbed sections (2mm wide) and sharp corners ($\pm 20^\circ$) made the part difficult to eject. Only 1° of draft was included on the rib sections. The ejector pins were located on the four outer corners of the part. The detail at the middle points of the ribbed sections 'locked' in the inserts, and resulted in the part warping when ejected. This could have been improved by adding additional ejectors in these areas. The tool also chipped substantially on the sharp corners. It also seems that the steps formed by the SLA growing process on the vertical surfaces caused the part to eject with increased difficulty due to the increased friction on the surface.

Future designs should avoid sharp corners if possible; the sharpest corners should be greater than 90° . There should also be extensive draft placed on all sides of the part penetrating the inserts, 3° of draft should be sufficient. Time needs to be spent on the location of the ejector pins to prevent the part from warping when ejected and substantial time needs to be spent on finishing the inserts. The surfaces for all thin, ribbed sections need to be polished smooth to ease the ejection of the part.

- **Preliminary Tool Wear Characteristics**

Although 71 parts were produced in total, the first chip occurred at shot 9 as recorded in Table 16. By the end of the testing, the insert had chipped substantially in a number of places. Depending on the application of the part being moulded, the first chip appearing on the insert may render the insert obsolete. If this were the case for the part tested in this experiment, only 9 parts would have been produced or post machining would be required to correct the flaw. As can be seen by the observations, the first 'full' part was only produced at shot 34. Factors contributing to the chipping of the tool thus need to be eliminated. Contributing factors may include insufficient application of release agent, incorrect part design, and simple inexperience in tool setting with Epoxy inserts.

There was a noticeable difference in the mean value of the rib thickness between testing on day one and two. The mean for day one was approximately 1.5mm, and increased to about 1.64mm on day two. These changes can be attributed to the time

the system required to stabilise. In order to obtain any possible trends in the data, the first day's results were excluded from the trend analyses.

It was difficult to determine any significant trends in the dimensions of the part as a function of tool wear. Deterioration is more a function of chipping rather than abrasion. As this was the authors' first experience with epoxy tooling the initial shots were more erratic. In future a more gradual approach would be advisable as this could also contribute to the chipping of the tool.

- **Shrinkage Factors**

An overall shrinkage factor for the rib thickness of 19.5% was calculated; the average measured rib thickness was 1.61mm. This included 14.5% shrinkage from CAD model to insert. This is an excessive shrinkage factor, especially if one takes into account that polypropylene manufacturers specify 1,5% shrinkage for the material. There was 1° of draft included on the rib sections of the part and the original value was 2mm for the thickest part of the rib.

An overall shrinkage of 1.97% was calculated from the overall width of the part, with an average width of 73.52mm. The shrinkage from CAD to insert was 0.71%, leaving a shrinkage factor during moulding of 1.26%. This seems more reasonable and compares favourably with the manufacturer's specification.

The factors calculated were further influenced by the changing machine parameters. A larger sample size would be required to obtain more accurate data.

- **Shot Size Calibration**

In general it takes a number of shots to set-up the moulding process correctly. Parameters are adjusted until full parts are consistently produced at a specified level of quality. As per Table 16 it took approximately 40 shots to obtain satisfactory parts in this experiment. While this may be acceptable when using conventional steel tooling, it is problematic for Direct AIM™. If 100 parts are possible from ACES inserts, 40 shots to set-up the process represents 40% of the total parts that can be produced. Furthermore the experiment indicated that the tool damage is more likely to occur within the initial 40 shots. It is thus necessary to minimise the number of shots required to set-up the process.

On the injection moulding machine, shot size is indicated in mm of travel of the screw. It does not seem possible to obtain accurate information on what sort of volume of plastic this would represent (the screw nose does not fill the entire barrel; and the volume taken up by the screw in the barrel is difficult to obtain). The author feels that an empirical calibration curve should be developed in order to equate the shot size with the volume of the material delivered with a shot. It is expected that this will be a linear curve as per Figure 44. This would greatly improve the initial setting of the shot size and reduce the number of iterations required to stabilise this setting.

xii. Conclusions

Parameter setting:

- A cycle time of 5 minutes as suggested by 3D Systems USA appeared to be too long. The longer the cooling time, the greater the shrinkage, more complex parts shrink onto the insert and break more readily when ejected. A cycle time of 60 seconds was preferred for the preliminary tests conducted.
- A time delay between cycles needed to be introduced in order to prevent the inserts from becoming too hot. Steam was rising off the inserts during testing (when release agent was applied), and swelling was visible on the fixed half insert. It was estimated that surface temperatures were in excess of 55° C. Polymer melt temperature on entering the tool was 200°C. This clearly indicated that the glass transition temperature of the SLA resin (90° C) was exceeded. A delay of 60 seconds between shots should be sufficient with a sprue break setting on the moulding machine to reduce the heat transfer from the nozzle to the tool.
- The release agents used appear to be sufficient to eject the part, but possibly not ideal for use on epoxy inserts, as they were oil-based. Using an organic lubricant should be tested.
- A high level of expertise would be preferable to obtain consistent results. The operation of the ENGEL injection moulding machine was left to the author. The author completed the Basic Injection moulding setting course of the Plastics Federation of South Africa as part of the preparation for this project.

Conclusions relating to part design and its effect on the inserts were:

- Sharp corners and minimal draft on the part as well as finishing of the vertical surfaces of the cavity adversely effected the ejection of the part. This contributed to the chipping of the mould.
- This chipping was the main restriction in the number of parts that could be obtained. Gradual wear of the cavity was negligible and the swelling of the inserts did not seem to affect the dimensional criteria.
- Shrinkage factors were within the specified material shrinkage range.

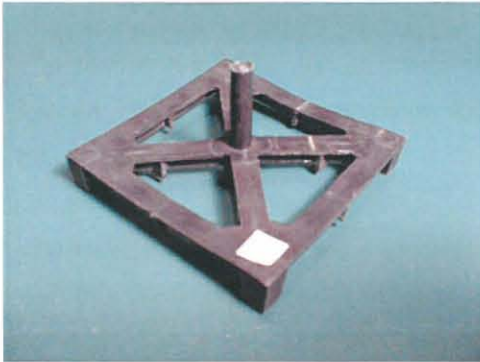


Figure 45: User Part Showing Warping and Cold Weld Lines

Figures 45 & 46 depict parts obtained as well as the SLA insert fitted to the injection mould tool.

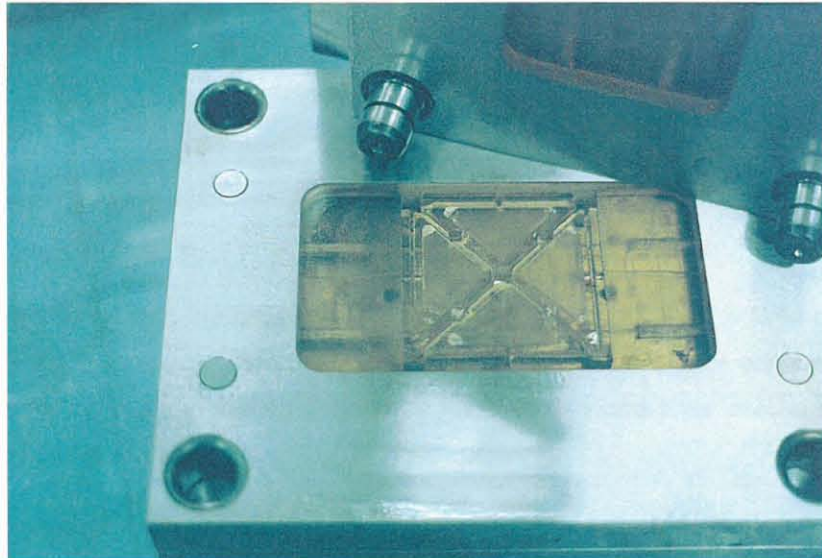


Figure 46: User Part Cavity Insert Showing Signs of Chipping

xiii. Mould Flow

The author obtained a trial version of 3D QuickFill. This is a Desktop Plastics Flow Analysis software package from C-MOLD. C-MOLD is one of the leading providers of polymer analysis software. This package provides the designer with a quick overview of the fill, cooling, hot spot and flow direction profiles of the part.

The 3D CAD model is exported as a .STL file with a course cord height setting (typically 2mm). The injection point is indicated and normal material and moulding parameters are selected.

The results are presented in colour coded still graphics or with the filling as animated frames. The software also provides useful design guidelines to optimise the design of the component.

The results obtained in the experimental moulding correlated with the results achieved with the QuickFill program. Some of the design and gating flaws in the tool could have been avoided by the use of this product prior to the tool manufacture.

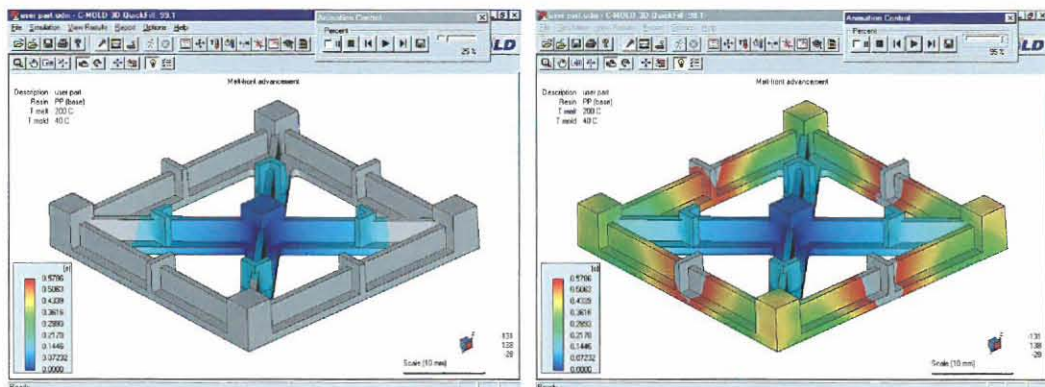


Figure 47: User Part Filled 25% to 95%

The melt flow within the cavity clearly indicates the last areas to be filled as can be seen in Figure 47. These are also the same areas where cold weld lines occurred. A cold weld line forms as the two joining flow faces have cooled and knits poorly, not forming an integral seam joint.

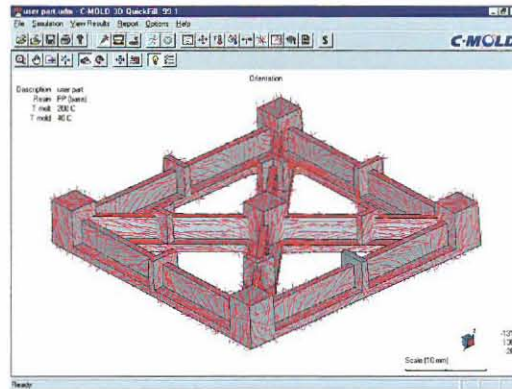


Figure 48: Material Flow Direction

One of the significant insights was the flow direction profile. Figure 48 clearly indicates high turbulence areas where the greatest damage was sustained in the tool. This leads the author to believe that the turbulence induces lateral force on the sidewalls of the cavity. This in turn causes shear between the layers of the SLA inserts and results in delamination and chipping.

A more even and gradual flow within the tool would therefore have less of a damaging effect and prolong the tool life.

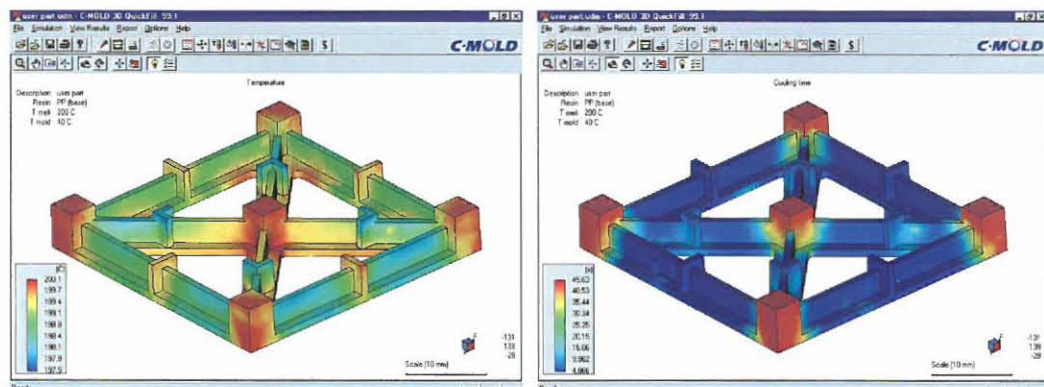


Figure 49: Material Temperature Versus Cooling Time

In Figure 49 the areas with larger volume of material retains heat and therefore takes longer to cool. Sink marks resulted in these areas as the ribs leading to corners solidify, preventing material flow during the back pressure cycle.

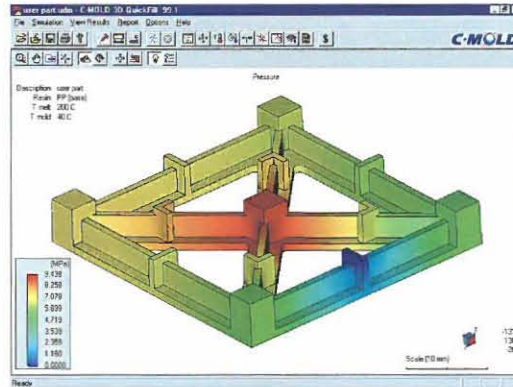


Figure 50: Injection Pressure Curve.

The lowest pressure areas correspond with the flow images. Figure 50 would suggest that small runners radiating from the centre to the blue areas would have significantly improved part moulding.

xiv. Recommendations

- The parameter settings determined by this trial should form the basis of future trials. A delay should be introduced between mouldings to allow heat to dissipate from the split-line surfaces of the inserts. Additional trials should be conducted with other release agents.
- Part design should include greater draft angles and greater radii in the corners. All stair stepping should be removed from vertical faces by polishing of the insert cavities.
- As the growing process is only the start of the process, machine setting is critical to ensure highly accurate parts. It should be considered to add additional material to the split-line faces and machine these to size to ensure proper fit and accuracy.
- It is critical to obtain the optimum parameters i.e. shot size, ejector positions, injection point location etc. before commencing. These will reduce the amount of risk with AIM tooling and will limit the amount of set-up shots required.

4.2. Study 2 – Bottle Opener

i. Part Design – Bottle Opener

The bottle opener closure was designed to fit within the same insert format as the user part.

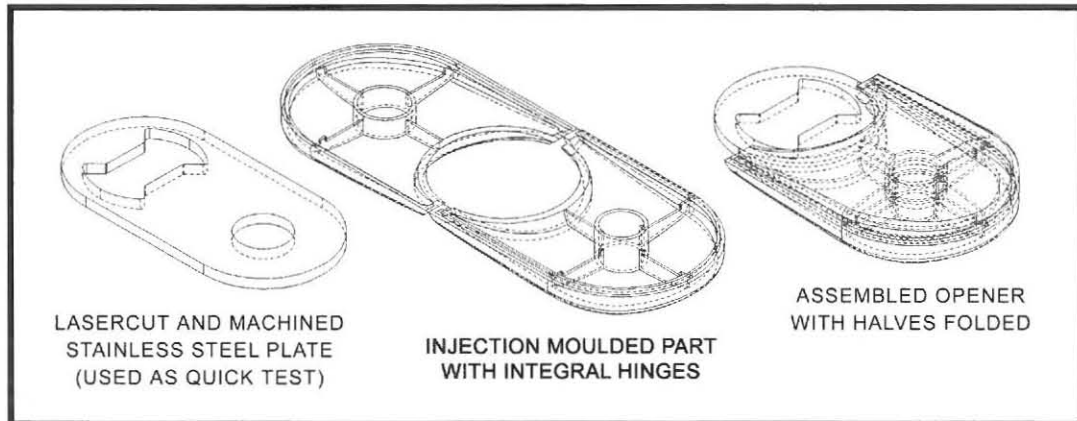


Figure 51: Bottle Opener Parts

- Overall length open: 130mm
- Length halves folded closed: 65mm
- Width: 50mm
- Thickness halves closed: 16.5mm

The closure design as per Figure 51 consisted of two halves, located symmetrically about the sprue. On removing the sprue the parts are joined with an integral hinge. The metal plate is contained between the two halves by the boss feature locking into each other. Thin rib features within the closure halves also restrain the plate.

This design was intended to evaluate the following features:

- Integral Hinge capability – Cannot be simulated.
- Alternative gating – As opposed to direct gating.
- Fit of components – Mating accuracies, Warping, Shrinkage, Cavity Sizes
- Thin rib and wall sections
- Formed surfaces – Ease of finishing and quality.

The general wall thickness of the part was set to 2mm. According to Brendell [5] the general tolerance for a 15mm diameter component should be 0.018mm. A design tolerance of 0.2mm was used to compensate for the laser cutting, SLA and injection

moulding processes. The rib thickness was 0.7mm, within the ratio to prevent sink marks on the outer surface of the part. The boss sections were kept to 1mm wall thickness to reduce flexibility for the clipping of the two halves. A zero tolerance was used on the boss features to ensure an interference fit.

A ring gap of 0.5mm around the component mating edge was used to visually reduce misalignment.

A general draft angle of 3° was used on vertical faces to improve the release from the cavity insert. This was based on the experience gained from the first trial.

An integral hinge is defined as a flexible connection between two movable parts made from thermoplastics. Various designs depend on toughness, ductility and flexural strength within a thin connecting section between the parts for operational performance. This is a common way to eliminate hinge parts or assembly features from mating parts. The basic guidelines provided by Hoechst [12] were used. Depending on moulding trials the hinge section is opened to facilitate material flow.

The metal plate would also act as an easy test gauge for size and fit evaluation. The plate was CAD modelled and exported as a .dxf file for laser cutting. The plate material is 304 Stainless steel. The unit cost per plate was R5.70 (excluding VAT). Post machining was required in the bottle gripping area. The plates were cut to an accuracy of 50 micron.

- Length: 80mm
- Width: 40mm
- Thickness: 3mm

ii. Insert Generation and Finishing

As per the first trial the components were CAD modelled with Intergraph EMS 3D CAD modelling software. The parts were scaled to compensate for injection moulding shrinkage – 1.7% for Polypropylene (PP). The runner and gating system was modelled as part of the component. The sprue in the centre of the insert opens into a circular well to reduce the initial material velocity. A fan gate all along its edge connects the well with both halves of the component to facilitate even flow and reduce the risk of cold weld lines. The well would also form a platform for the sprue-puller/ centre ejector. The ring clip features would form the other ejector positions.

The parts were subtracted from the basic insert form to create the cavity and core inserts. The two .stl files were produced with a cord height tolerance of 0.01 and forwarded for processing to the SLA system.

The inserts were processed as ACES parts with a layer thickness of 0.15mm. Both parts were orientated with the cavity and core facing upward i.e. with the splitline support free and positioned in the centre of the platform. Standard cure depth and sweeper velocities were used.

Processing time was 23 hours. As these were not the only parts grown, a part specific time is not available. The parts were removed from the platform and processed as standard.

A large amount of finishing was required as the splitline faces again, were not flat. The layer stepping reduced hole sizes by 0.3mm and was reamed to size. Outer edges of the insert were finished to fit the cavity plates of the standard die set.

The cavities were sanded and polished to a level six finish to remove all stair-stepping to obtain best possible finish on the outer surface. This would also facilitate better ejection. The thin rib slots were also polished to aid ejection.

Finishing time accounted for approximately 8 hours of labour.

iii. Tool Modification

As the ejector configuration differed from the first trial the following tool modifications were required:

- The Ejector plate and Support plate were modified to accommodate the 3 ejector pins.
- Three new ejectors were cut and ground to size.
- A new sprue bush was machined.

The modifications took 2 days to complete at a cost of R300. With the standard die set approach a saving of approximately R5000 was made.

iv. RTV – Tooling

Silicon rubber moulds were produced from the inserts before they were fitted to the tool. The reasons for doing this were:

- The process of growing the inserts with SLA is expensive.
- Limited tool life is expected.
- Casting of insert sets would be a cost effective alternative to reproduce multiple sets of inserts.
- Different filler materials could be used with the casting process to obtain better thermal and chip resistant qualities.

The process for generating silicon moulds were:

- The casting masters were cleaned with isopropanol and dried in an oven at 40°C for 30 minutes.
- The casting masters were fitted with cooling pipe extensions to locate them in the casting boxes
- Aluminium casting boxes (any non-absorbing and stiff material is suitable) were generated. These would also be used during the casting process to ensure dimensional stability. A clearance of approximately 10mm was allowed around the casting master. The box also extended 10 mm past the casting master. The box was secured to the foundation and sealed to prevent silicon from leaking during the curing process.
- The masters were positioned with the splitline facing upward to minimise the risk of air entrapment on critical surfaces.
- As the silicon releases well from the SLA Epoxy, no release agent was required.
- The Elastosil M4370 with a mixing ratio of 9:1 was used. This is a room temperature vulcanising silicone (RTV). This material has excellent temperature resistance. (Needed for casting exothermally reactive casting epoxies) and minimal dimensional distortion (<0.1%) required for accurate reproductions. The silicone has a high Shore A hardness (± 55). However, it has low tear resistance and low elongation at break (130%). Therefore care must be taken during de-moulding.
- The silicone has high gas permeability and was degassed in a vacuum chamber to reduce the air trapped in the liquid silicone after mixing.
- The liquid silicone was poured into the box, ensuring an even flow with as little air trapping as possible.
- The moulds were left for 8 hours to solidify.

- Once the masters and the box forms were removed, the silicone moulds had to be post-cured in an oven at 45°C for an additional 5 days to counter poor tear resistance. The silicone can be cured at 80°C for 4 hours to obtain the same results.

The total silicon material cost for the two insert halves was	: R 436.80
Casting boxes	: R 500.00
Labour	: 16 hours

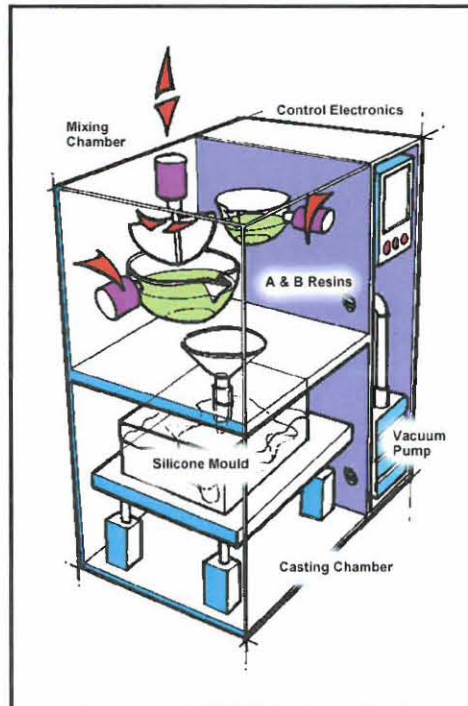


Figure 52: Typical Configuration of a Vacuum Casting System for RTV

Figure 52 is a typical layout of a modern commercial vacuum casting system used for resin casting.

v. Casting of Inserts

There are essentially two different types of metal-filled casting epoxy resins:

- Room temperature setting
- High temperature setting

Room temperature setting epoxies do not have high hardness values and can be easily modified with hand tools, making processing convenient.

High temperature setting epoxies are considerably more difficult to process. They require baking at temperatures after the epoxy has initially set. The temperatures are gradually increased to a maximum of between 160° and 200°C. These epoxies have high hardness and increased wear resistance, but are difficult to work with.

vi. Casting Materials



Figure 53: Sample Moulding in ALWA MOULD V.

ALWA MOULD V

Alwa Mould V is a cold setting casting resin that sets at room temperature. The material is easy to handle and process, and therefore can be machined using conventional techniques or worked with hand tools. The resin is mixed with aluminium powder as per Figure 53 to reduce shrinkage and improve thermal conductivity. At a room temperature of approximately 20°C the preparation sets within half an hour. At temperatures above 20°C the pot life is shorter.

- **Technical Data:**

Data refers to a mixture of 1 part Alwa-Mould V casting resin, 2 parts filler AL 065 V and 3% hardener.

Maximum service temperature:	up to 120°C
Reaction temperature:	up to 130°C
Linear concentration of a test part:	250 x 50 x 20mm at 20°C - 30°C approx. ± 1mm/m
Thermal conductivity:	0,90 kcal/hm °C
Density:	1,8kg/dm ³
Compressive strength at 20°C:	90 – 110 N/mm ² = 900 – 1100 kp/cm ²

Compressive strength at 130°C:	80 – 90 N/mm ² = 800 – 900 kp/cm ²
Dynamic viscosity:	approx. 7,000 mPa
Impact resistance:	J = ca. 44N cm ²
Stabilized:	approx. 12 months
Casting resin:	R154,60/1kg
Aluminium powder:	R118,60/2kg
Hardener:	R6,33/0.030kg
Cost per kg mixed:	R92,25/1kg

- Processing

Alwa Mould V was the first epoxy to be cast into the silicone moulds. The mixing ratio was set to 60% aluminium powder and 40% Mould V. The aluminium powder used was Alwa 065 aluminium filler with a grain diameter from 0.001 – 0.065mm.

The processing as follows:

- The processing temperature of the resin system should be over 20°C. To avoid setting faults, the master to be filled and the material should be the same temperature. Due to the dissipation of heat, masters with a good thermal conductivity, (metal, metal filled resins) are not appropriate. A slight shrinkage can occur.
- Blocks can be inserted to displace resin, not only to reduce material usage but also to help prevent volume concentrations. Polyurethane foam is recommended. With this technique large volumes can be cast weighing up to 1000 kg.
- Sharp edges should be avoided, as these are possible areas susceptible to breaking, and should be rounded or broken.
- The casting should be covered to prevent the heat from escaping.
- Copper tubes for cooling or heating can be cast in at a distance of 10mm – 30mm from the surface.

Table 20 can be used as a guide to trouble shoot the moulding process.

Table 20: Trouble Shooting Table for Alwa Mould V Processing.

Pot life is too long	Not enough hardener or temperature of resin filler mixture is too low. Check the hardener carefully. Mixture should be at 21°C.
Small cracks and white coating on the back of the mould	Filler has settled out. Mixture must be thoroughly stirred immediately before pouring or too early poured.
Mould has warped (thin moulds)	Heat disappeared too quickly. Cover the mould after casting or if de-moulded early, cover as soon as the mould is flat on the table and clamp down. Cover the mould box and pour mixture in through a funnel, de-mould only when cool. Do not place on a metal sheet when mould is warm.
Volcanoes or sink holes appear when mould sets	Hardener was not mixed in evenly. Mix hardener thoroughly down to bottom of container, scrape stick and sides and mix well.
Uneven cure of mould	Residues of mixture from bottom or sides of container, with higher or lower concentrations of hardener, were included in the mould. Use mixing containers with smooth inner surfaces.
Excessive distortion	Conductive and insulating materials were combined in pattern or mould box, causing uneven dissipation of heat during cure. Use materials of compatible thermal conductivity for pattern and mould box. Conductive materials should be heated to room temperature immediately before pouring and insulated to avoid dispersing heat more quickly than from other surfaces.
Thin edges and ribs break off	Strength is not adequate. Cast in perforated sheets and reinforcements.
Mould has excessive shrinkage	Mixture is not correct. Filler quantity too low. Mould was not allowed to expand during exotherm. Check scale accuracy. Follow mixing chart carefully. Release mould box ends can't be released, carefully de-mould at peak exotherm and immediately lay flat to avoid distortion. If a thin mould, cover at once and clamp down.
Cracks occur in mould	Cast in closed steel frame. If a steel frame is used, cast only in one that can be opened at least diagonally. Temperature of resin filler mixture was too low and filler settled out (pot life was too long). Mixture should be at least 21°C. In any case, stir thoroughly before pouring. Large steel or aluminium elements used as reinforcing. Use thin, perforated sheets as reinforcement.

Copper cooling tubes (9.5mm diameter) were mounted in the silicone moulds and the epoxy cast over them.

The moulds were left overnight in the silicone moulds. The moulded inserts were de-moulded and cleaned with steel wool and filed on the side faces to remove flash. They were post cured at 45°C for 5 days. The time can be reduced to 4 hours if cured at 80°C.

Two sets of inserts were produced in this way. The resin seems to have settled slightly in the mould insert with the aluminium powder being deposited more on the surface of the insert, whilst the epoxy resin settled to the back of the insert. This is an advantage as the mould surface has higher metal content and thus greater heat transfer can occur. Air bubbles were formed on the back of some of the castings. This is due to air bubbles in the mixture not being vacuumed out, and simultaneously proper closing of the silicone moulds did not occur. There were no air bubbles on the working surfaces, which is critical for mould integrity.

The back-faces of the castings were milled flat to remove excess material to facilitate fitting in the tool. The aluminium epoxy moulds had minimal shrinkage due to the high

filler to resin ratio. The curing action starts with an exothermic reaction, followed by cooling. Shrinkage only occurs in the latter stages of the cooling process.

Total material cost per set of inserts : R106.68
Labour : 16 hours

Dimensional Change

Dimensional change occurs at each step of the insert production process:

- The design is converted from 3D objects to a triangulated .stl file.
- The Stereolithography part is grown from the sliced .stl file.
- The SLA part is hand finished.
- Silicone moulds are produced from the SLA part.
- Aluminium filled epoxy is cast into the silicone moulds.
- The inserts expand and contract during the curing process.
- The Cast inserts are finished and fitted to the tool.

The deviation is a cumulative deviation from CAD to final casting. For the complete process the moulding shrinkage and process tolerance still has to be added. Table 21 indicates the deviation introduced by each process compared to the original design.

Table 21: Dimensional Deviation

Dimension	Design (mm)	SL (mm)	Mould V (mm)	SL deviation (%)	Mould V deviation (%)
Moving half					
Top width	82.00	81.92	81.52	0.10	0.59
Top length	150.00	149.82	148.95	0.12	0.70
Base width	92.00	91.79	91.62	0.23	0.41
Fixed half					
Top width	82.00	81.92	81.34	0.10	0.80
Top length	150.00	149.75	149.20	0.17	0.53
Base width	92.00	91.88	91.25	0.13	0.82

The Stereolithography moulds had low dimensional deviation from the original dimensions with the largest deviation being 0.23% shrinkage. The processes of silicone moulding and epoxy casting led to the greatest dimensional change. The greatest deviation was 0.82% shrinkage from the original. The greatest dimensional change from the SLA part to the aluminium filled epoxy casting was 0.87mm and the greatest percentage change was 0.71%

The large range of dimensional change (0.10% - 0.23%) would make it difficult to incorporate a rating factor into the SLA mould design. Improvement of the post processing facilities (by CNC machining) would result in better judgement of these factors.

ALWA MOULD H

Alwa Mould H is a high temperature rated, addition curing casting resin. The advantages of Mould H are its high deflection temperature and its heat resistance after processing. The disadvantage with the resin is that it requires significant baking of the casting before it can be removed from the mould. This leads to degradation of the master or mould form.

- Technical Data

Reactivity at room temp.:	with 3% catalyst – approx. 40min.
Curing before de-moulding:	3hr at 80°C, 2hr at 120°C (pattern inside)
Curing after de-moulding:	2hr at 160°C, 6hr at 200°C (pattern removed) (Allow to slowly cool at 40°C to avoid stress)
Density at 20°C:	approx. 1,7kg/dm ³
Viscosity of blended material:	approx. 25.000mPa
Modulus of elasticity:	approx. 6900N/mm ²
Flexural strength:	approx. 119N/mm ²
Impact strength:	approx. 17 kJ/m ²
Ball indentation hardness:	approx. 260N/mm ²
Glass transition temperature:	approx. 310°C
Linear shrinkage:	approx. 0,1mm – 0,5mm / m

- Processing

Alwa Mould H is a viscous grey resin that can be used in pure form or with aluminium and or other fillers. A pure mixture (i.e. 100%) Mould H with 3% catalyst was used to cast a set of inserts.

The master pattern, including the release surface construction and casting box should be dried for about 24hr at 50°C before coating with release agent. The master pattern negative should have the same or higher shrinkage coefficient as the casting from Alwa Mould – H.

Three layers of release lacquer should be sprayed over the still warm model with 15 minute time intervals.

To get a low viscosity the material needs to be heated to 40°C to make it more fluid and therefore easier to pour. The viscosity of the resin makes it very difficult to vacuum any air bubbles out of it.

This is followed by the curing routine listed in Table 22.

Table 22: Processing of Alwa Mould H

Process	Time actual	Time (h)	Temp. (°C)	Observation
Cast	16:00	0	23	
Curing	09:30	17:30	40	Set temp - 80°C
	10:00	18:00	74	
	11:50	19:50	70	Set temp – 120°C
	12:30	20:30	82	Bulging on mould top
	13:15	21:15	94	
	13:42	21:42	105	
	14:00	22:00	105	Set temp – 160°C
	14:40	22:40	115	
	15:30	23:30	135	Severe bulging – moving h
	16:10	24:10	140	Set temp – 200°C
	09:15	41:15	180	Set temp – 180°C
	10:00	42:00	145	
	10:46	42:46	120	Set temp – 50°C
	11:34	43:34	105	Door left ajar
	12:05	44:05	50	
	12:30	44:30	45	Remove moulds

After de-moulding, the inserts were examined. Significant warping of the inserts was observed with a maximum deflection between the faces of 4.80mm. The expansion of the copper tubes at the elevated temperatures had exceeded the expansion of the mould material. As the copper could not extend transversely, due to the shear forces from the partially set epoxy, the tubes had bent in the direction of least resistance. This was toward the back of the mould and caused the surface of the insert to de-mould from the silicone.

The surface of the moulds had small bumps, indicating that air bubbles were trapped under the surface as indicated in Figure 54. This was noticeable on the back of the mould as large air bubbles were trapped just below a thin surface skin of the mould.



Figure 54: Mould H Air Bubbles

This is attributed to the large amounts of air that could not be removed from the resin, even by vacuuming. The air entrapment is deleterious to the function of these moulds as injection mould inserts. A smooth consistent surface with uniform substructure is required to withstand the clamping and injection pressures of the injection process. These defects would result in localised pitting or cracking of the mould.

Alwa Mould H proved to be unsuitable for rapid tooling applications for the following reasons:

- Air entrapment causes surface defects and reduces structural integrity.
- Considerable processing is required within a controlled environment.
- Cooling tubes cannot be cast in as part of the process.
- **Material cost for Alwa Mould H inserts : R334.86 (+/- double that of Mould V)**

vii. Casting Finishing

Due to the high volume aluminium filler, the cast parts machine and work well. The cavities can be polished with steel wool to a good shine. The initial surface finish is only as good as the master pattern used as the silicone reproduces every detail.

Hand finishing is time consuming and it is the author's recommendation that conventional machining and possibly CNC machining be used to ensure dimensional accuracy and process speed.

viii. Tool Trials

Testing was performed at the CSIR MATTEK Polymer Division, on an 80-ton Engel injection-moulding machine (the same as previous trials). The inserts were run in the following order:

- Steel Cast Bottle opener
- Un-plated aluminium epoxy bottle opener
- Plated aluminium epoxy bottle opener
- Plated SLA bottle opener
- Un-plated SLA user part
- Plated SLA user part

The surface temperature of the moulds was measured using a Major Infrared Thermometer probe (Model MT 692). It has a temperature range of -10°C – 260°C with an accuracy of 0.1°C .

The surface quality was evaluated by touch and sight and rated accordingly. Acceptable parts were deemed parts that could be cleaned and used for prototype testing.

Failure of the inserts was deemed to have occurred if:

- One catastrophic failure occurred (i.e. tool cracked or critical parts chipped off)
- Two major failures occurred (i.e. two large parts chipped off)
- Parts produced could no longer be used for prototyping purposes (i.e. poor surface quality that could not be repaired)

Figures 55 & 56 illustrate the epoxy inserts in the injection mould tool during moulding operation with a resultant part.

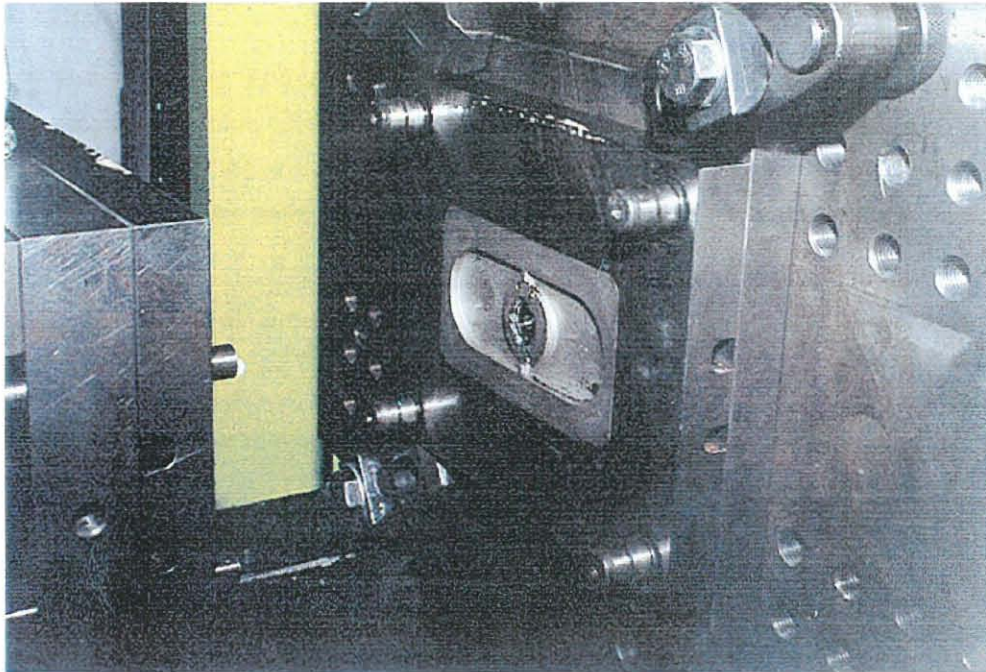


Figure 55: Fixed Half Insert Mounted in Injection Moulder

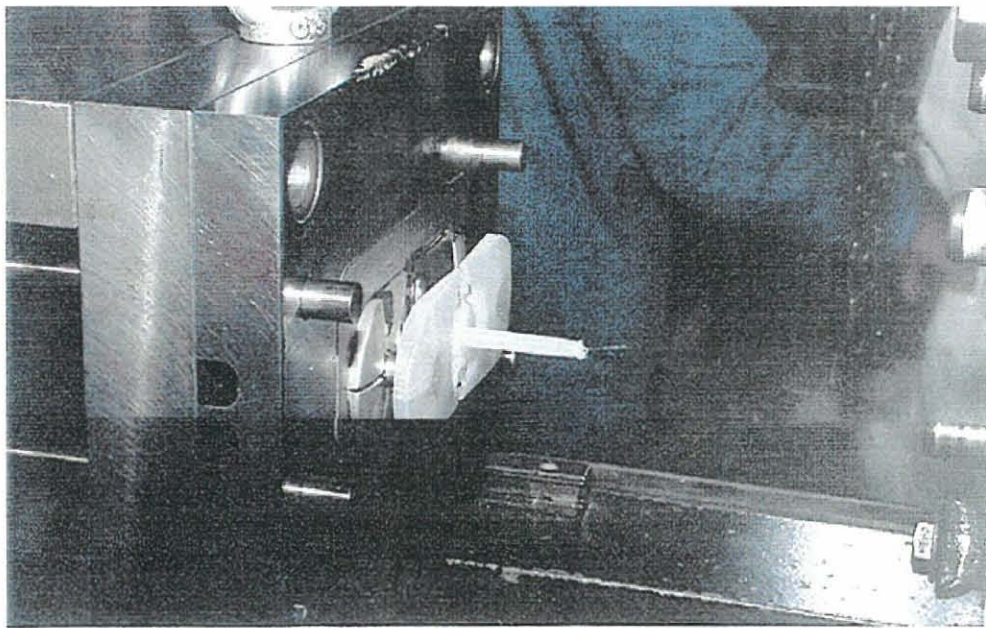


Figure 56: Moving Half with Epoxy Plated Insert Mounted in Injection Moulder

- **Cooling**

The aluminium epoxy mould inserts had copper tubing inserted into the moulds before the aluminium epoxy was cast. This ensures a good contact surface between the copper tubes and the mould insert material. The SLA mould inserts had cooling tubes grown in them, which has the same effect of machining channels into the material.

Running cooling water through the SLA parts was not chosen for two reasons:

- The hydrophilic nature of the inserts would allow unwanted water to penetrate the surface and soften the inserts, increasing the possibility of breakage.
- The low thermal conductivity of the inserts would make cooling water ineffective as the primary cooling medium.

Forced air convection removes heat from the mould parting faces effectively as it is in direct contact with the surface experiencing the most heating. If heat build-up occurs between mould cycles, the length of cooling can be adjusted accordingly and so forced air convection was chosen as the primary cooling medium in place of cooling water. Use of a compressed air current is convenient and available in most production facilities.

- **Un-Plated Aluminium Epoxy Bottle Opener Insert**

The tool was modified to include half round runners from the sprue to the side corners of the part. This allowed better flow into the part and prevented pressure build up on the front face of the part.

The tool was run using the same parameters as the cast steel tool except that longer cooling and injection times were used. 40 Parts were produced using polypropylene. There was slight damage to the tool in the form of a crack along the curved base (an area with a sharp corner causing stress concentration). There was also a small chip around the sprue area, but this did not affect any area of the part.

The material was changed to ABS to see whether the tool could withstand a harsher moulding material. There were problems with the ABS material. It leaked from the barrel causing a decrease in shot size over time. The ABS increased the stress exerted on the insert and cracks on the insert were rapidly enlarged. The ABS

material used caused the failure of the insert by removing an entire section between two ribs on the 58th shot. This was categorised as a catastrophic failure.

Tool life would have been greatly extended had ABS not been used. The insert had suffered no major damage while moulding with PP.

Typical temperatures recorded were:

Moving half Cavity: 45°C

Fixed half Cavity: 34°C

Sprue bush: 52°C

This clearly indicates the effective heat dissipation of the aluminium epoxy inserts and imbedded copper cooling tubes.

Table 23 is a sample of 40 good parts measured that weren't distorted, indicating minimal deviation.

Table 23: Dimensional Results of Un-plated Aluminium Epoxy Inserts Using PP.

Shot No.	Width (external)	Hole to hole (internal)	Wall thickness
4	49.84	93.00	2.02
10	49.81	92.96	2.10
11	49.84	92.90	2.13
12	49.89	92.91	2.12
13	49.79	92.84	2.11
14	49.89	92.89	2.13
16	49.88	92.92	2.14
20	49.82	92.85	2.20
21	49.93	92.82	2.23
22	49.91	92.89	2.22
23	49.91	92.87	2.27
24	49.88	92.90	2.21
26	49.90	92.96	2.22
30	49.87	92.86	2.27
32	49.91	92.90	2.29
35	49.95	92.86	2.31
36	49.89	92.86	2.28
37	49.93	92.84	2.29
38	49.98	92.85	2.29
39	49.95	92.82	2.28
Average	49.89	92.89	2.21
Std Deviation	0.05	0.05	0.08

- **Parameters**

The following two tables, Table 24 & 25 indicate the materials used for the tests as well as the machine settings for the injection moulder. The temperature variance is due to the material melt flow.

Table 24: Parameters for Un-Plated Aluminium Epoxy Insert Using PP.

Materials		Cooling	
Plastic	Polyfin Polypropylene 1100N	Type	Water at 25°C
Release Agent	Spray 'n Cook	Duration	45 sec
Injection		Post Injection	
Maximum injection pressure	200 bar	Post injection pressure	12 bar
Injection time	5 sec	Post injection time	5 sec
Injection speed	20 mm/sec	Back pressure	5 bar
Temperatures			
Nozzle temp.	210°C		
Heating zone 1	205°C		
Heating zone 2	200°C		
Heating zone 3	195°C		

Table 25: Parameters for Un-Plated Aluminium Epoxy Insert Using ABS.

Materials			
Plastic	Polyvac ABS 765	Cooling time	30 sec
All other parameters are the same as above except			
Injection		Post Injection	
Maximum injection pressure	180 bar	Post injection pressure	20 bar
Injection time	10 sec	Post injection time	10 sec
Injection speed	80 mm/sec	Back pressure	10 bar
Temperatures			
Nozzle temperatures	240°C		
Heating zone 1	225°C		
Heating zone 2	210°C		
Heating zone 3	190°C		

- **Surface Quality**

The aluminium epoxy inserts as per Figure 57 had a slightly rough surface and this was reflected on the parts produced. The surface finish was acceptable and could certainly be used for prototype testing. A slight ridge formed by the crack on the back of the part was noticeable. This feature could be trimmed off easily.

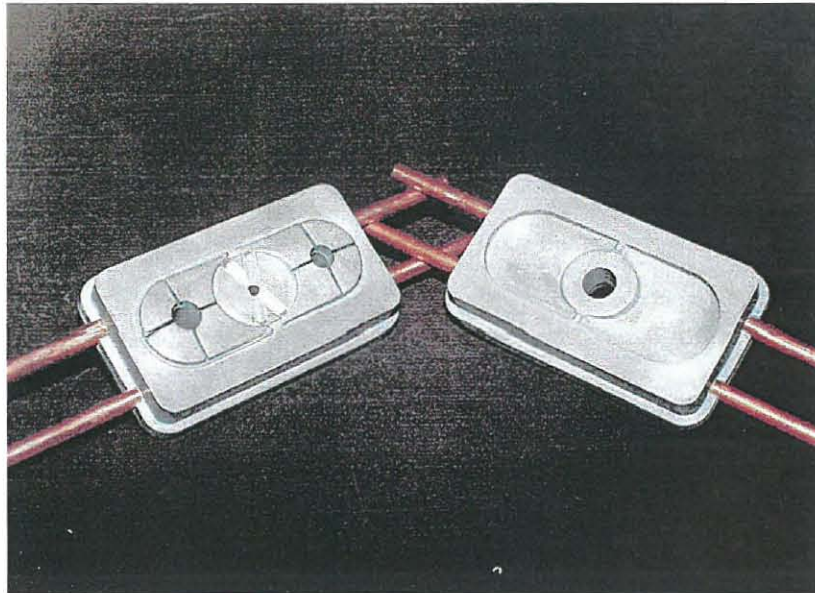


Figure 57: Un-Plated Aluminium Epoxy Inserts.

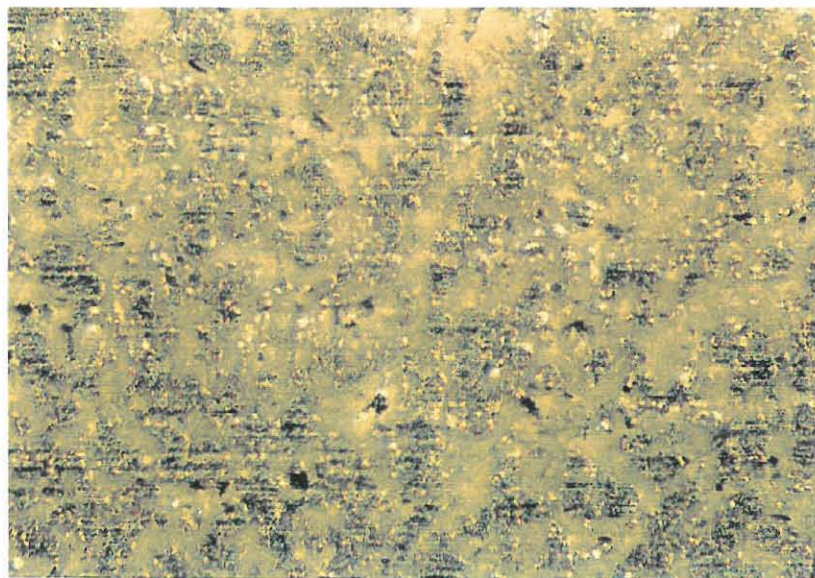


Figure 58: Surface Detail of an Un-Plated Aluminium Epoxy Insert

Figure 58 is a microscopic surface view of the inserts in Figure 57.

- **Plated Aluminium Epoxy Bottle Opener Inserts**

The tool was modified to include half round runners from the sprue to the side corners of the part. This allowed better flow into the part and prevented pressure build-up on the circular part face closest to the sprue.

The tool was run until 80 parts were produced in polypropylene. Testing was terminated due to time constraints. There was also degrading of the surface finish of the parts, and major damage to the tool. Initially the plating cracked causing ridges to be reproduced on the parts.

The strong bond between the plating and the aluminium epoxy caused plating chips to remove large chips of epoxy with them. This was noticeable around the ejector pins of the part. Poor alignment of the ejectors caused them to lift the plating and consequently chips of epoxy.

The plating produced an even distribution of temperature across the tool and heat was removed rapidly from the surface. The plating typically had temperatures 10°C less than the underlying epoxy. The epoxy did not heat beyond 50°C due to the water-cooling used.

Table 26 is a sample of 80 good parts measured that weren't distorted, indicating minimal deviation.

Table 26: Dimensional Results of Plated Aluminium Epoxy Inserts Using PP.

Shot No.	Width (external)	Hole to hole (internal)	Wall thickness
8	50.19	92.88	2.29
11	50.12	92.81	2.36
15	50.35	92.80	2.38
17	50.14	92.85	2.40
25	50.36	92.86	2.39
29	50.20	92.79	2.38
33	50.29	92.76	2.42
43	50.23	92.74	2.45
44	50.09	92.78	2.41
48	50.16	92.63	2.35
51	50.05	92.80	2.35
55	50.15	92.61	2.38
59	50.24	92.69	2.41
61	50.29	92.87	2.40
63	50.26	92.81	2.39
64	50.26	92.80	2.42
67	50.35	92.84	2.43
73	50.38	92.85	2.43
76	50.31	92.88	2.49
77	50.24	92.87	2.45
Average	50.23	92.80	2.40
Std Deviation	0.09	0.08	0.04

- **Parameters**

Table 27 indicates the material used for the test as well as the machine settings for the injection moulder.

Table 27: Parameters for Plated Aluminium Epoxy Insert Using PP.

Materials		Cooling	
Plastic	Polyfin Polypropylene 1100N	Type	Water at 25°C
Release agent	Spray 'n Cook	Duration	45 sec
Injection		Post injection	
Maximum injection pressure	200 bar	Post injection pressure	12 bar
Injection time	5 sec	Post injection time	10 sec
Injection speed	20 mm/sec	Back pressure	5 bar
Temperatures			
Nozzle temperature	205°C		
Heating zone 1	200°C		
Heating zone 2	195°C		
Heating zone 3	190°C		

- **Surface Quality**

Due to the thickness of the plating, any crack in the plating as per Figure 59 was reflected on the surface of the parts. This caused a rough finish although the surface could be improved by hand finishing. There were large plating chips on the fixed half of the tool, creating ridges of the outer face of the part. This was more serious than defects occurring on the inner surface of the part as these would not be visible after assembly.

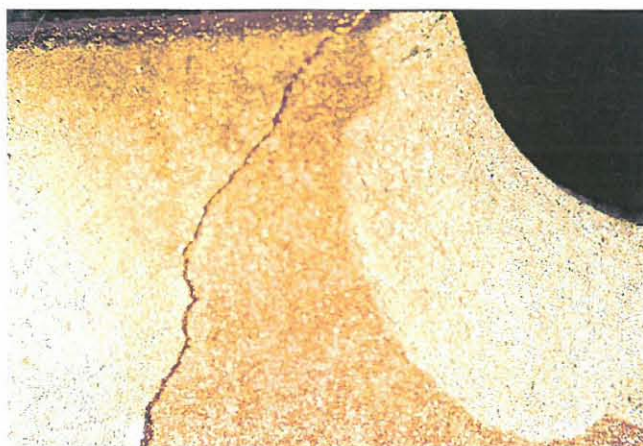


Figure 59: Plating and Epoxy Chip from Aluminium Epoxy Insert

Figure 60 is a microscopic view of the plated Aluminium Epoxy inserts' surface finish



Figure 60: Surface Detail of Plated Aluminium Epoxy Insert

- **Plated SLA Bottle Opener Inserts**

The tool was modified to include half round runners from the sprue to the side corners of the part. This allowed better flow into the part and prevented excess pressure on the part faces closest to the sprue.

The tool was run until 100 parts were produced in polypropylene. There was no surface damage to the SLA epoxy of the inserts. Cracks had started to form within the insert. The plating had poor adhesion and flaked off after being loosened from the surface.

Plating cracks occurred early in the experiment as visible in Figure 59. This was due to the thermal expansion of the nickel coating relative to the epoxy substrate. Concentric layers of cracking were noticed on the insert. This clearly indicates the radial effect of thermal transfer toward the edges of the insert where heat dissipation occurs. The plating began chipping from the gating areas and spread to the rest of the part. The flow of plastic over the areas aided the removal of plating from the surface. Temperatures of up to 68°C were measured on the inserts. The plating had no significant effect in heat dissipation.

Table 28 is a random sample of good parts produced with plated Stereolithography inserts that were measured that weren't distorted.

Table 28: Dimensional Results of Plated Stereolithography Inserts Using PP.

Shot No.	Width (external)	Hole to hole (internal)	Wall thickness
1	49.35	92.88	1.76
2	49.17	92.77	1.71
19	49.33	92.92	1.84
20	49.39	92.84	1.69
24	49.25	92.87	1.66
26	49.07	92.97	1.49
29	49.24	92.87	1.70
41	49.39	92.93	1.70
42	49.26	92.94	1.67
43	49.21	92.88	1.72
44	49.23	92.96	1.63
45	49.25	92.95	1.66
57	49.22	92.89	1.70
61	49.17	93.01	1.59
66	49.22	92.95	1.61
70	49.21	92.86	1.71
81	49.27	93.15	1.67
82	49.23	92.87	1.66
84	49.27	93.49	1.69
91	49.33	92.86	1.64
Average	49.25	92.94	1.68
Std Deviation	0.08	0.15	0.07

- **Parameters**

Table 29 indicates the material used for the test as well as the machine settings for the injection moulder for the test with plated Stereolithography inserts.

Table 29: Parameters for Plated SLA Inserts Using PP.

Materials		Cooling	
Plastic	Polyfin Polypropylene 1100N	Type	None in clamped position. Air at 25°C on opening mould
Release agent	Spray 'n Cook	Duration	120 sec
Injection		Post injection	
Maximum injection pressure	200 bar	Post injection pressure	20 bar
Injection time	5 sec	Post injection time	20 sec
Injection speed	60 mm/sec	Back pressure	10 bar
Temperatures			
Nozzle temperature	220°C		
Heating zone 1	215°C		
Heating zone 2	208°C		
Heating zone 3	190°C		

- **Surface Quality**

The lines along which plating had chipped away as per Figure 61, showed up on the parts produced. The lines were not noticeable individually due to the thin plating thickness but an overall roughness caused by these lines was noticeable. The surface quality of the parts was reasonable although there would need to be surface finishing on each one. The parts were the roughest of all the parts produced. Plating did not prevent chipping as seen in Figure 62.



Figure 61: Plating Cracks on SLA Inserts



Figure 62: Chipping Around Sprue Bush



Figure 63: SLA Bottle Opener Inserts Before Plating.

Figure 63 depicts the two inserts before plating. The inserts were hand finished to remove all stair stepping prior to plating. Engineering Blue was used to check mating surfaces, this did however stain the resin parts. Care should be taken not to damage or round sharp cavity edges on splitline surfaces.

- **Un-Plated SLA User Part Inserts**

The user part provided a number of problems particularly with ejection of the part. As ejection took place on the corners of the part, it tended to warp the part. In certain cases, sticking occurred and the part fractured (Cold weld lines formed at the rib detail of the outer bars).



Figure 64: Chipping Around Gate Area

The sharp edges of the mould chipped off rapidly as per Figure 64. Sharp changes in flow direction around the corners were the primary reason for chipping. The vertical faces of the corners had not been smoothed due to inaccessibility of their position. Cracks were visible throughout the mould within its internal structure. These cracks would propagate and eventually cause a catastrophic failure.

An impact-modified polypropylene was used for the user part. The higher impact resistance would aid ejection and prevent bending of the part.

Table 30 is a sample of 46 parts produced with un-plated Stereolithography inserts indicating observations per shot.

Table 30: Stereolithography Un-Plated User Part Test Record.

Material: SASOL Polymers Polypropylene 2340PC

SHOT NUMBER	OBSERVATIONS
1	Short shot, weld lines in middle of part
2	
3	Part cracked and distorted on ejection
4	Part cracked and distorted on ejection
5	Better filling, part cracked and distorted on ejection
6	2 cracks on part, post injection time = 30 seconds
7	Part cracks at weld lines
8	Part cracks at weld lines
9	Short shot, cracked at weld lines
10	Part cracks at weld lines
11	Short shot, cracked at weld lines
12	Part cracks at weld lines
13	Part cracks at weld lines, post injection pressure = 25 bar, for 40 sec, cooling time = 90 sec
14	Part cracks, insert chip near weld line
15	Part cracks, insert chip near weld line
16	Part cracks, insert chip near weld line
17	Short shot
18	1 small crack, polymer burn marks near weld line
19	3 part breaks at weld lines
20	Small flash
21	Polymer burn marks at weld lines, insert chipped at sprue
22	Small crack, insert chipped from sprue
23	Small crack, edges rough from insert chipping, injection pressure = 130 bar, cooling cycle 120 sec
24	Part cracked and warping
25	Part cracked and warping, mould temp: fixed half = 49°C; moving half = 52°C
26	Short shot, part cracked
27	Four cracks
28	3 cracks, insert chips from base, mould temp: fixed half = 51°C; moving half = 50°C
29	1 crack, insert chipped in cold weld area
30	
31	Short shot, part cracked
32	1 small part crack, insert chipped in middle
33	2 small cracks, warping, mould temp: fixed half = 51°C; moving half = 60°C
34	Part has small crack, sprue sheared off
35	Part cracked
36	Part cracked, warping
37	Flash
38	Flash
39	Flash
40	Flash, short shot
41	2 cracks, short shot
42	2 cracks, rib snapped
43	Flash
44	Very big insert chip from diagonal corner (10x4mm), MAJOR FAILURE
45	Chip filled out
46	2 big insert chips off from diagonal corner & sprue

Table 31 is a sample of good parts produced and measured from un-plated Stereolithography inserts.

Table 31: Dimensional Results of Stereolithography Un-Plated User Part Trials

Shot No.	Support width	Support length	Vertical height	Diagonal corner to corner
1	7.43	7.33	7.13	54.91
4	7.30	7.24	7.04	54.76
9	7.26	7.22	6.89	54.71
17	7.25	7.25	6.83	54.68
21	7.22	7.19	6.86	54.82
22	7.23	7.19	6.91	54.76
23	7.22	7.33	6.88	54.76
24	7.26	7.26	6.88	54.86
26	7.19	7.16	6.80	54.75
29	7.22	7.16	6.82	54.87
30	7.20	7.14	6.79	54.76
32	7.23	7.23	6.86	54.80
34	7.21	7.17	6.87	54.84
38	7.18	7.20	6.88	54.79
40	7.17	7.13	6.84	54.71
41	7.22	7.17	6.88	54.70
42	7.23	7.18	6.82	54.76
43	7.21	7.17	6.87	54.84
44	7.21	7.17	6.82	54.66
46	7.21	7.15	6.89	54.57
Average	7.23	7.20	6.88	54.77
Std Deviation	0.06	0.06	0.08	0.08

- Parameters**

Table 32 indicates the material used for the test as well as the machine settings for the injection moulder for the test with un-plated Stereolithography inserts.

Table 32: Parameters of Un-Plated SLA User Part Inserts Using PP

Materials		Cooling	
Plastic	Polyfin Polypropylene 2340PC	Type	None in closed position. Air at 25°C on mould opening
Release agent	Spray 'n Cook	Duration	120 sec
Injection		Post injection	
Maximum injection pressure	100 bar	Post injection pressure	20 bar
Injection time	5 sec	Post injection time	20 sec
Injection speed	60 mm/sec	Back pressure	10 bar
Temperatures			
Nozzle temperature	220°C		
Heating zone 1	215°C		
Heating zone 2	208°C		
Heating zone 3	190°C		

- **Surface Quality**

Chipping of the mould resulted in the part being oversized. These oversized areas could be removed by hand. The top surfaces were smooth except on corners where oversizing occurred. Sharp ridges were apparent on some of the corners. SLA chips were embedded in some of the parts, making them un-suitable for prototyping purposes. The vertical faces showed the SLA layers, as they had not been smoothed due to poor accessibility. Overall the surface finish was poor. Figure 65 shows a set of un-plated SLA inserts before trials, in Figure 66 the chipping is evident on the same inserts post trials.

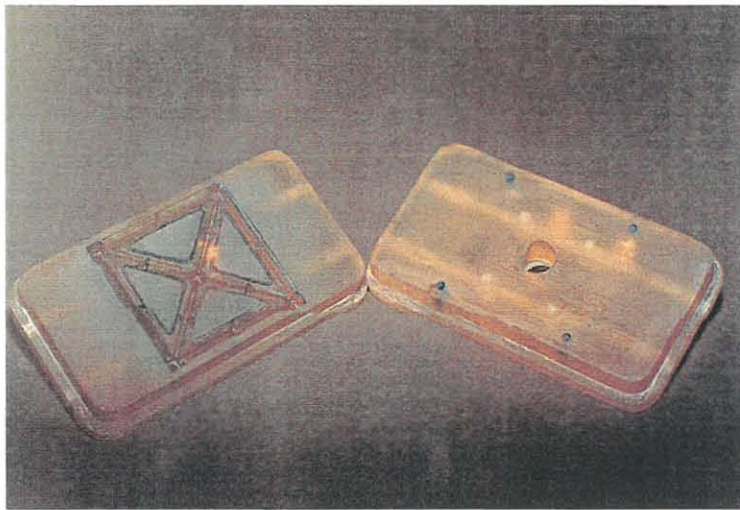


Figure 65: SLA User Part Inserts (not plated)



Figure 66: Chipping from Cavity - User Part Insert (corner next to gate)

- **Plated SLA User Part Insert**

There were problems ejecting the user part from the moving half insert. The parts were sticking as the detail at the centre on the outside ribs and caused cold welds in this area (points furthest from the sprue). This is caused by material flowing around obstacles. The cooler front faces of the flowing plastic cannot fuse together and forms a weak seam line. These areas are prone to snapping.

The plating in these regions caused large corner build-up, such that an overhang was formed. Parts could not be ejected easily due to this overhang and broke when the part was ejected. Testing was terminated after 12 parts were produced and every one broke at the cold weld. Sticking got progressively worse as the test continued.

The plating had exceptionally poor adhesion to the SLA inserts, especially on the fixed half. After 4 cycles all the plating on the fixed half side in the cavity area had been removed. The plating on the ejection side also wore rapidly, indicating a fault in the plating of the inserts.

Table 33 shows the observations of the trial with plated SLA inserts.

Table 33: Stereolithography Plated User Part Test Record.

Material: SASOL Polymers Polypropylene 2340PC

SHOT NUMBER	OBSERVATIONS
1	Part sticking in cavity, part tore, cooling cycle 120 sec
2	Plating chips form fixed half, cavity insert chips from sharp corners, few plating chips from ejector side
3	Plating chips, part cracks
4	Plating chips (most of fixed half gone), cavity insert corner chips, part cracked
5	Plating chips, part cracked
6	Cavity insert corner chips, plating chips, part stuck in cavity
7	Plating chips, part cracked
8	Part cracked, plating chips
9	Plating chips, part cracked
10	Plating chips, part cracks, short shot
11	Plating chips, part cracks, short shot
12	Plating chips, part cracks, cavity insert chips in middle corner
	TERMINATE TRIAL, ALL PARTS CRACKED, PARTS STICKING IN CAVITY.

The material used and machine settings for the trail with plated SLA inserts are tabled in Table 34.

- Parameters

Table 34: Parameters for Plated SLA User Part Inserts Using PP.

Materials		Cooling	
Plastic	Polyfin Polypropylene 2340PC	Type	None in closed position. Air at 25°C on mould opening
Release agent	Spray 'n Cook	Duration	90 sec
Injection		Post injection	
Maximum injection pressure	100 bar	Post injection pressure	20 bar
Injection time	5 sec	Post injection time	20 sec
Injection speed	70 mm/sec	Back pressure	10 bar
Temperatures			
Nozzle temperature	220°C		
Heating zone 1	215°C		
Heating zone 2	208°C		
Heating zone 3	190°C		

- Surface Quality

As none of the parts were complete, roughness was not examined. The roughness was similar to the un-plated insert parts.

4.3. Study 3 – QuickCast Bottle opener.

i. QuickCast Bottle Opener Tool

QuickCast would evaluate the process of manufacturing steel inserts via the investment casting process.

ii. Tool Design Changes

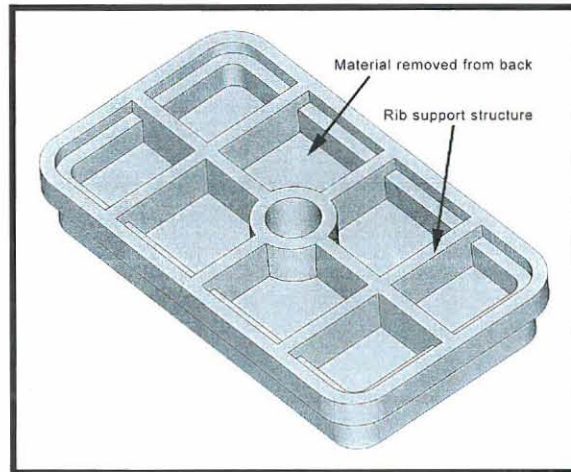


Figure 67: Cored Insert for Investment Casting Process.

To facilitate the investment casting process, design changes were required to the original CAD model. Figure 67 shows the rear of the inserts was hollowed out to form an even wall thickness of 10mm. Around the ejector holes bosses were created. A central rib connecting the ejector pinholes was added to provide support for the shutoff faces. Additional ribs were added perpendicular to the central rib. The CAD model was scaled to compensate for the shrinkage factor for the investment casting process as well as the injection moulding process. The only other feature that was removed was the text inside the one part half. The CAD model was converted into .stl files and exported to the SLA system.

iii. QuickCast Patterns and Finishing

The .stl files were orientated with the split-line faces, facing upwards and supports forming in the hollowed back of the inserts. The QuickCast honeycomb internal structure was created and vent and drain holes were added to remove liquid resin after the parts were grown.

The growing was considerably faster than the conventional ACES format due to the reduced draw time of QuickCast. The grown parts were also superior without the meniscus effect on the split-line faces. The parts were drained of excess resin and whipped down with Isopropanol until all excess resin was removed from the outer surface.

Care was taken to remove all resin from the rib slots and small detail areas on the outer surface. The SLA parts were placed in the centrifuge and spun for 8 hours in various orientations to remove additional liquid resin from the internal structure.

The parts were post cured in the PCA for 10 hours. Stair stepping was not removed. Care was taken to seal all vents and drain holes and the parts were pressure tested.

The parts were packed and shipped to the CSIR MATTEK foundry.

iv. Investment Casting of Tool Inserts

The two inserts were assembled onto a wax tree in preparation for the casting process. Water-based slurry was used to hand coat the tree. The shell was not wrapped or reinforced. It was built up to a thickness of $\pm 10\text{mm}$, and was flash fired to remove the QuickCast patterns and the wax tree.

The Parts were cast with low melt alloy steel (EN19). This steel could be heat treated and hardened after casting.

v. Casting Results

The casting process produced inaccurate tool inserts. The part shrinkage was not equal for both halves. Both insert halves warped. Porosity was visible around the ejector pinholes. The ceramic forming the thin rib features was destroyed during the pouring process. This formed inclusions in the metal. The parts had to be machined to become functional inserts.

vi. Insert Finishing

Due to time and cost constraints the inserts were machined to produce functional parts. In some cases this required the removing of excess material to clean up undercuts caused by the casting process. The following machining was required:

Cavity Insert

- Clock up on sprue bush hole and ream to 18.00mm diameter.
- Machine outer edges of insert, referenced from sprue bush hole. (faces mating with die plate)
- Machine shutoff face with new depth reference.
- (cavity was not machined – this would have require CNC machining)
- The rear was machined flat and lost material was compensated by using standard shim plate.
- Slots were added to accommodate copper cooling tubes.
- One of the cavity halves was hand polished.

Core Insert

- Clock up on sprue-puller hole and ream to 6mm diameter.
- Machine outer edges of insert, referenced from the sprue-puller hole.
- Centres of ejector pinholes – align with ejector plate and ream. (Due to shrinkage the holes we offset).
- Machine shut off surface. – Flatness
- Machine sprue bush shut off – with new reference.
- Machine step detail as per original design. – For part fit.
- Slots were added to accommodate copper cooling tubes.

The cost of the basic machining was R 2 000,00. To completely re-machine the inserts and recover all intended detail the cost would have been R 7 500,00.

The CNC machining of new aluminium inserts would have cost R 6 000,00 per set. Taking into account the cost of growing QuickCast Masters, investment casting of parts and raw material cost, not to mention time and cost to recover the casting, the CNC route would be the more cost effective method for this design.

The machined inserts were fitted with copper cooling tubes and the hollow rears were back filled with Alwa Mould V to provide good thermal conductivity.

vii. Tool Trials

The durability of the cast steel insert has not been tested. The inserts were used to set the parameters for the SLA and aluminium epoxy inserts. 30 shots of HDPE and 30 shots of ABS were produced. There was no damage to the insert and no significant heating of the insert surface occurred.

- **Parameters**

Tables 35 & 36 note the materials and process settings for the trials with the cast steel inserts

Table 35: Parameters for Cast Steel Inserts Using HDPE.

Materials		Cooling	
Plastic	Hostelin HDPE GA7260	Type	Water at 25°C
Release agent	Silchem Silicone spray	Duration	20 sec
Injection		Post injection	
Maximum injection pressure	18 bar	Post injection pressure	10 bar
Injection time	4 sec	Post injection time	3 sec
Injection speed	8% of max.	Back pressure	5 bar
Temperatures			
Nozzle temperature	211°C		
Heating zone 1	200°C		
Heating zone 2	196°C		
Heating zone 3	191°C		

Table 36: Parameters for Cast Steel Inserts Using ABS

Materials			
Plastic	Polyvac ABS 765		
All other parameters are the same as above			
Maximum injection pressure	37 bar		

viii. Surface Quality

The parts reproduced the surface detail precisely. There was no damage to the tool and thus no damage or change to the surface finish of the parts. The polished side of the cavity had an excellent surface finish whereas the unpolished side reflected the stair stepping as well as the casting finish of the tool.

ix. Dimensional Tests

Three measurements were taken on the bottle openers produced by all tools as per Table 37 & 38. Four dimensions were taken on the user parts produced. All measurements were taken with a Mitutoyo digital vernier, (Model: CD – 6" BS) accurate to 0.01mm.

Table 37: Dimensional Results of Cast Steel Bottle Opener Part Trials With HDPE.

Shot No.	Width (external)	Hole to hole (internal)	Wall thickness
1	49.40	92.69	3.35
2	49.96	92.72	3.35
3	49.76	92.50	3.40
4	49.80	92.74	3.28
5	49.77	92.72	3.28
6	49.72	92.66	3.26
7	49.81	92.87	3.25
8	49.69	92.87	3.28
9	49.82	92.72	3.27
10	49.92	92.87	3.28
11	49.89	92.92	3.29
12	49.84	92.97	3.27
13	49.79	92.82	3.25
14	49.75	92.65	3.25
15	49.82	92.91	3.28
16	49.86	92.82	3.25
17	49.84	92.83	3.26
18	49.80	92.91	3.25
19	49.59	92.90	3.30
20	49.64	92.87	3.29
21	49.92	92.71	3.26
22	49.48	92.90	3.26
23	49.84	92.63	3.25
24	49.84	92.52	3.27
25	49.86	92.91	3.27
26	49.68	92.70	3.28
27	49.85	92.88	3.26
28	49.84	92.84	3.28
29	49.13	92.66	3.30
30	49.93	92.83	3.24
Average	48.26	92.78	3.28
Std Deviation	0.82	0.12	0.03

Table 38: Dimensional Results of Cast Steel Bottle Opener Part Trials With ABS.

Shot No.	Width (external)	Hole to hole (internal)	Wall thickness
1	50.76	93.92	3.38
2	50.84	94.11	3.36
3	50.82	94.02	3.41
5	50.80		3.33
6	50.74	94.06	3.37
7			3.40
8	50.80	94.00	3.37
9	50.81		3.34
10			3.36
11	50.81		3.34
12	50.79		3.45
13			3.34
14	50.81	94.03	3.36
15			3.34
16	50.84	94.07	3.37
17	50.87		3.33
18	50.88	94.10	3.43
19	50.79	94.01	3.36
20			3.33
21	50.85	94.12	3.40
22	50.79		3.34
23	50.86		3.33
24	50.74		3.34
26	50.85	94.05	3.41
27	50.71		3.33
28	50.85		3.34
30	50.70	94.04	3.40
Average	50.81	94.04	3.36
Std Deviation	0.05	0.06	0.03

Figure 68 is a comparative plot of the various tool trials, measuring the width of the part whereas Figure 69 compares the hole to hole dimension. Tolerances applied were to be within 0.3mm of the original dimension.

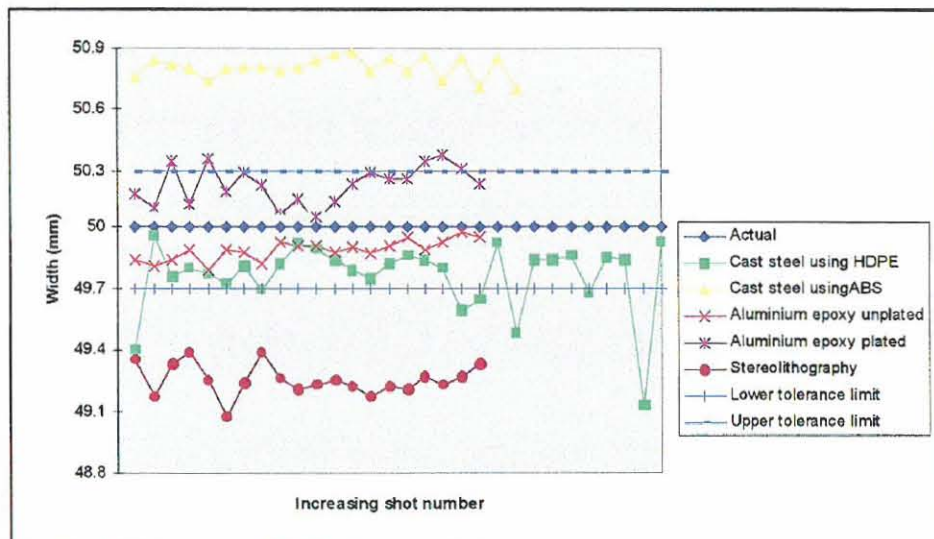


Figure 68: Bottle Opener Width

As can be seen in Figure 68 only the un-plated aluminium epoxy, plated aluminium epoxy and some of the cast steel PP parts fell within tolerance limits. The SLA parts were undersized by 0.7mm. The cast steel insert had large variation as can be seen from some of its data points. The difference between the dimensions of the ABS parts and the HDPE parts are attributed to expansion of ABS on cooling.

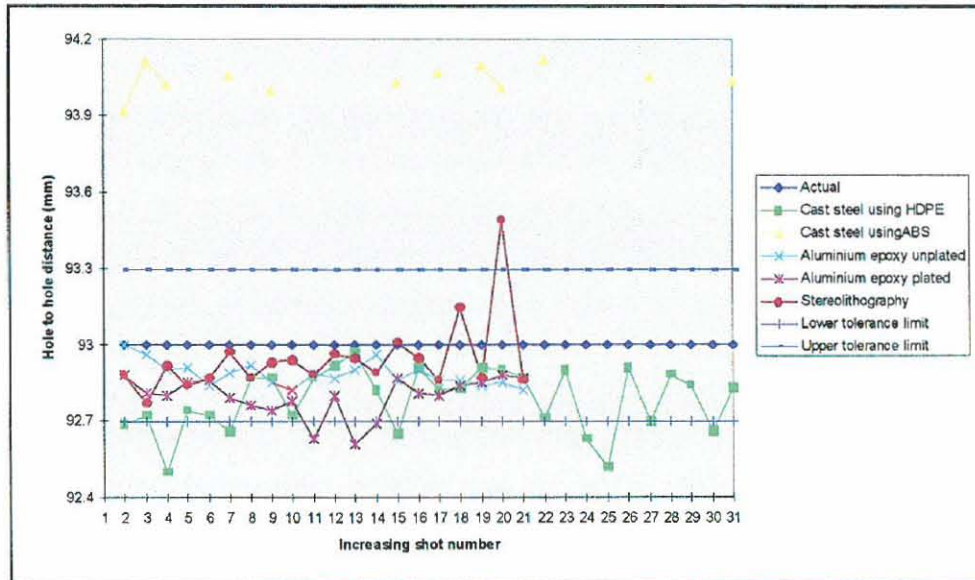


Figure 69: Hole to Hole Dimension for Bottle Opener

Most of the inserts produced parts within the tolerance limits. Again the cast steel insert had the most variation and differences in dimensions between ABS and HDPE parts. The tolerances of the SLA parts became worse as the mould degraded. Figure 70 shows a polished cavity finish and the normal step finish produced by the growing process.

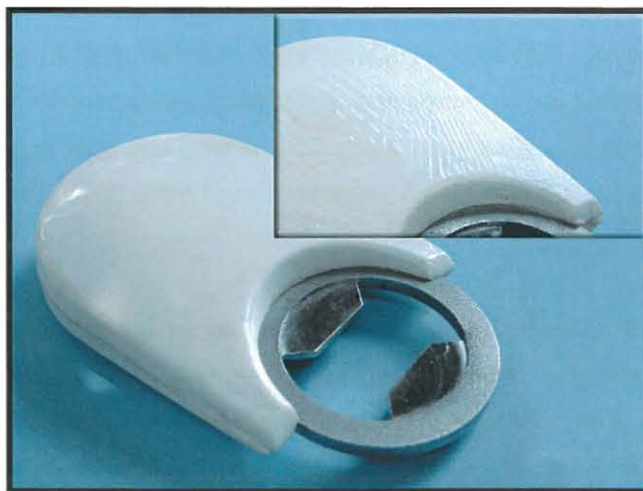


Figure 70: Assembled Opener Showing Polished and Natural Sides

x. Observations

- **Stereolithography Inserts**

The SLA parts that were grown had a large meniscus that needed to be removed to enable injection moulding. Growing the inserts in a different orientation could reduce this feature. A different orientation could prevent interaction of flow profiles. Putting the part at 45° to the sweeper blade could result in less flow profile interaction as the blade engages the part more gradually and not edge on. The leading edge build-up is accentuated when the blade strikes a large interface between open resin and the part. By reducing the interface length, less of an effect would be evident. Growing parts on an incline could also reduce the meniscus effect, but stair stepping would be present, requiring extensive hand finishing. This could also compromise compressive strength of the inserts.

Leading edge build-up can be overcome through several techniques:

- Use three sweeps, two fast sweeps followed by one slow sweep.
- Build a breakwater around the part, thus disturbing the laminar flow before the parts leading edge.
- Reducing resin viscosity.

Three sweeps could reduce leading edge build-up but would increase growing time. A breakwater would require more expensive resin to be used. Reducing resin viscosity is only achieved by changing resin temperature or compounding with other materials, both of which are not good for the controlled process of Stereolithography.

Hand finishing of SLA inserts is time consuming and less accurate than precision machining. The importance of draft angle and corner radius was highlighted with the User part. Larger radii and greater draft angle could have reduced the sticking of the parts in the mould. Rib width need to facilitate finishing of the vertical walls as well as visual inspection.

Fitting the inserts to the injection mould tool is unproductive time and should be minimised. More accuracy could be achieved by machining the interface faces of the insert as well as the ejector pin and sprue bush holes. A small CNC milling machine could have been used to run a standard two-dimensional pocket program to clean outside dimensions. The QuickCast inserts clearly indicated that ejector holes

are better left as a machining process as shrinkage and post processes affect the dimensional accuracy of positioning and shape.

Stress areas in the insert, such as sharp corners should be avoided. These are the first to be damaged in the moulding process. Heat treatment of the SLA parts should be investigated as a possibility to obtain a normalised part. The heat must however be kept below the glass transition temperature for the specific resin.

- **Silicone Moulds**

Transparent silicones as per Figure 71 would aid the mould pouring as air bubble entrapment could be seen and could be avoided. No air entrapment was found on the moulds, but the possibility exists.

Preferably mixing and casting should be done under vacuum to reduce the risk of air in the casting medium.

Curing the castings at higher temperatures would result in faster production times. Higher temperatures could affect the expansion of the SLA mould master and possibly cause an oversized cavity in the final mould. The use of a casting box does relieve the effect of expansion greatly. The moulds produced did not suffer from distortion as previous trials without a casting box.

The silicone moulds did not tear until the Alwa Mould H insert was cast. Sections of the mould were torn by sharp corners of the insert after baking at high temperatures. The mould suffered from slight distortion caused by exposure to temperatures of 160°C for several hours. The moulds should be able to produce at least 5 Alwa Mould V inserts based on the wear shown by this type of material.



Figure 71: Sample Transparent Silicone Mould

- **Aluminium Epoxy Inserts**

Alwa Mould V was well suited for this method of bridge tooling. The ease of processing allowed air bubbles to be removed from the mixture easily. There were no defects in the inserts caused by air entrapment. The material was easily machined and able to be modified by hand. Stabilisation of the epoxy needs to occur by baking the demoulded inserts at temperatures up to 130°C for several hours. This can be achieved in a rapid tooling environment by leaving inserts in an oven overnight. The maximum temperature that the inserts can be baked at without causing stress cracks from the copper tubes or warpage of the moulds needs to be determined. The higher the temperature, the shorter the stabilisation period for the epoxy and consequently a shorter rapid tooling cycle time.

Metal fillers other than aluminium can be used with this material. Copper would allow greater heat transfer rates than aluminium resulting in shorter cycle times. The grain size could aid in thermal transfer. A larger grain would transfer heat faster than smaller grains, as fewer particles are required to transmit heat over a fixed distance. Small grain sizes would be needed as a material binder, which is one of the primary functions of metal filler. This aspect should be investigated further to provide a better bridge tooling option.

The life of an Alwa Mould V tool could be in excess of a 100 parts. Further tests need to be undertaken to establish accurate estimates of tool life. The type of polymer used has a major effect on the life of the inserts. Abrasive materials such as ABS or Polycarbonate should be avoided. If possible, easy flowing materials like polypropylene or high-density polyethylene should be used.

Alwa Mould H, and any high temperature curing epoxy, is not suitable for this method of bridge tooling. The inclusion of copper cooling tubes caused severe warping of the moulds. This stress would lead to stress cracking within the inserts and cause failure in the moulding process. Once the material is baked, it is brittle and difficult to process. The material forms a hard, ceramic type finish. The back surface also showed signs of several small cracks due to the expansion and shrinkage of the backing process.

Difficulty in processing the material, particularly due to a high viscosity, was the primary reason for air entrapment. As stated earlier, air entrapment could lead to failure during the moulding process. Not only does it compromise strength and propagate crack failure but reduces thermal transfer of heat.

- **Plating**

Nickel plating onto SLA inserts increased tool life. The plating was damaged by thermal expansion of the plating relative to the underlying SLA resin. The plating transmitted heat away from the plastic part faster than pure SLA resin. Plating onto SLA inserts is an economical way of increasing tool life. Adhesion of the plating onto the substrate was poor.

Silicone oils left on the inserts after the silicone moulding are the main cause of plating adhesion failure. Methods of cleaning the oil off using solvents also prevent easy plating. A possible technique to overcome this is to plate the inserts first and then use them as the master for silicone moulding. There is a strong possibility that the plating would tear off during the moulding but this should be investigated further. Tests to determine whether it is the plating process or oils on the surface causing these problems should be performed.

Plating onto the aluminium epoxy inserts was not as successful as for the SLA inserts. A precoat was required to cover all exposed epoxy before electroless nickel could be deposited. The precoat was very thick and had good adherence with the aluminium epoxy substrate. Electroless nickel was deposited onto the copper precoat. The combined thickness of these two coatings exceeded 100 μ m. This thick layer caused problems during the injection moulding as it cracked due to thermal expansion. The thick ridges it produced on plastic parts were highly noticeable and detracted from surface quality. The layer did remove heat rapidly from the surface and transmitted it evenly to the substrate. None of the parts had evidence of hot spots on them. The plating improved the surface roughness when compared to the original aluminium epoxy insert. This factor was however lost as the plating cracked, creating a poorer surface finish than the original aluminium epoxy insert, which did not degrade as rapidly.

The time required to plate the inserts can be reduced with experience. Once the process is defined, plating should take no more than a day.

It is recommended that alternative sources of plating be sought to determine skill and process capabilities.

- **Surface Quality**

The parts produced had various aspects, which affected their surface quality. The surface roughness of the original mould was the primary determinant of surface roughness in the parts. The plated aluminium epoxy insert produced the best surface finish and was similar to the polished steel tool. The plated SLA inserts were second best. The electrolytically deposited nickel was too thin to enhance the underlying surface roughness. Thin ridges on the plating caused slight surface defects on the first few parts produced before the plating was torn off. The SLA inserts had a good surface finish except that there were underlying traces of stair stepping although this was not reproduced on the parts. The aluminium epoxy had a matt finish due to the fine granular aluminium filler and epoxy. The surface roughness was acceptable for plastic part production.

A second factor affecting the part surface quality was the chipping of material from the inserts during production. This was noticeable in the plated aluminium epoxy insert due to the thickness of the plating and the fact that the plating tore away chips of aluminium epoxy. The general feel of the parts was slightly rough due to the softness of the various substrates.

The best consistent surface finish was obtained with the un-plated aluminium epoxy inserts.

- **Dimensional Accuracy**

Plated and un-plated aluminium filled epoxy inserts were the only sets that fell within the tolerance limits for the measurements taken. There was little variation in the aluminium epoxy inserts. This is partly due to the low changes that the insert underwent. No chips were removed from the insert. The dimensions of the other inserts changed due to chips, as well as the removal of plating.

The cast steel inserts had great variation in dimensions produced on its parts. The ABS parts were vastly oversized whilst the HDPE parts fell mostly within the tolerance limits. One must take into account that the tool was machined to provide a functional tool rather than an accurate one. Machining stock material will have to be included to make this a viable alternative. This would be difficult, as shrinkage is difficult to predict for the non-similar geometry of a cavity and core. These tools would also require longer runs to stabilise, similar to those of a production tool.

The SLA inserts produced consistently undersized parts. A scaling factor could be used to account for this in future designs. The scaling factor would be dependant on the polymer used for moulding.

- **Temperature Distribution**

Internal temperature distributions were not determined experimentally. Rather surface temperatures were measured periodically. Most of the aluminium epoxy inserts had their temperature stabilised at 50°C. The SLA inserts had temperatures up to 68°C. Cooling was necessary to lower this temperature to prevent tool damage. Plastic parts were ejected at approximately 70°C, having lost 130 – 140°C from their initial injection temperature.

Air cooling of the inserts aided in keeping temperatures within acceptable limits. There was noticeable heat build-up in the SLA epoxy inserts and these inserts had to have air cooling for longer periods. The rapid removal of heat by air convection allowed lower cycle times on the SLA inserts than if no cooling was used at all. Air-cooling was a quick effective means of cooling moulds and should be used in future.

Water cooling for aluminium epoxy inserts was effective at removing heat. The inserts did not exceed 55°C.

- **Costs**

The cost to produce bridge-tooling inserts follows the 80 – 20 Pareto principle. 80% of the cost can be associated with one process, Stereolithography. A typical cost breakdown would be:

○ Stereolithography inserts	R 8 000
○ Electrolytic plating of SLA inserts	R 520
○ Silicon Moulds	R 440
○ 5 sets of aluminium epoxy inserts	R 540
Total	R 9 500

If it is estimated that 500 parts would be produced (100 parts per aluminium epoxy set), the unit cost is set at R19 per part. These costs are an initial estimate. Mark up, labour

and facility costs have been excluded. Accurate estimates of tool life would increase the accuracy of these figures.

The marginal cost of an aluminium epoxy insert is very low in comparison to its potential output (approximately R100 for 100 parts). These inserts provide the best economical solution to providing a large number of functional prototypes. The SLA moulds should, if possible, not be used for production. 5 sets of aluminium epoxy inserts could be produced for the cost of one set of inserts. The SLA masters always stay in tact to reproduce silicone rubber tooling for longer tooling runs.

This method of rapid bridge tooling is used for parts requiring intricate machining or electric discharging. Simple designs such as the bottle opener could be produced faster using conventional machining. The Japanese approach to rapid tooling applications is to use high speed machining to produce tools rapidly. The advantage of this technique is that the rapid tool is the final production tool. The cost involved is higher than for conventional machining but can pay off when time is a critical factor. The method of bridge tooling used for these projects has its best application in the verification of product design as functional parts.

- **General**

Several new resins have been developed by Ciba-Geigy to extend the capabilities of Stereolithography. One of these resins has high thermal resistance and can be used for thermal testing or injection moulding. The advantage of a bridge tool in this resin, would be resistance to damage at high temperatures and thus possibly longer tool life. These resins may however not be available for the SLA500 machines but only the newer models.

An experienced injection mould tool setter is required to reduce the impact of moulding on the tool. In some cases bridge tools can be damaged without being able to produce a single shot.

xi. Recommendation

Growing inserts in various orientations should be investigated to find the optimal orientation. The possibility of using other resins for injection mould tools should be investigated. Mould inserts should be designed to include corner radii and adequate draft angles.

A small CNC milling machine should be available in the SLA facility. This would increase the productivity and increase the accuracy of finishing processes.

Metal fillers such as copper should be substituted for aluminium filler in the epoxy inserts to see if the heat transfer properties are improved.

Copper plating should be investigated as an alternative to nickel plating as it has better heat transfer properties. Other plating companies should be approached to perform similar work.

It is recommended that aluminium filled epoxy tools be used as a bridge tooling option. Plating onto SLA inserts improves the properties of the inserts and should be performed.

xii. Conclusions

Although various plating techniques were performed, and surface and thermal conductivity were improved, the plating also caused more severe damage once the insert started to degrade.

The un-plated aluminium epoxy inserts performed well at the best cost of manufacture as well as providing excellent dimensional accuracy.

The risk of using the SLA master as the tool insert is too great and should be avoided where possible.

This tooling method is best used in conjunction with normal tool making methods. Skilled and knowledgeable designers, tool makers and moulders are required to optimise the process for this type of process.

These methods of tooling still remain experimental and the delivery risks involved in any of these processes need to be taken into account when applying them commercially.

4.4. Study 4 - QuickCast Blow Mould Bottle Tool

The aim of this project was to evaluate the appropriateness of QuickCast tooling for blow mould tooling. The normal process of developing a new blow mould package for the client was 2 years. Our aim was to reduce this development process to two months.

The initial design phase and consumer trials lasted 2 weeks. During the two-week process CAD models were produced. These models were converted into SLA Prototypes for client and consumer evaluation.

The final design was converted into a tool design with QuickCast as the method of production. Cooling channels were incorporated into the rear of the cavity plates as well as an O-ring groove. Additional material was left on the split-line faces to facilitate final machining. The corner location pin and bush holes were incorporated into the casting patterns.

The two halves were grown on the SLA500 with good results. The QuickCast, honeycomb patterns were removed from the support structure. The outer surfaces were cleaned and wiped dry of all liquid resin. The liquid resin inside the patterns was drained before they were further spun in a centrifuge. The patterns were then post cured in the UV oven before being packed in sealed, moisture free containers. The patterns were then delivered to the foundry for casting. Figure 72 shows the pattern with wax runner system attached, ready for shelling process.

The casting results were disappointing. Porosity and pitting was evident in the tool and required extensive sealing to prevent cooling water leaking from the final tool. Shrinkage variations required that the shut off faces on both halves had to be machined to ensure alignment. This required additional hand finishing to blend the machining into the remainder of the cavity. Warping was evident in the castings and required heat treatment to normalise the casting before a press could be used to straighten the castings.

It was evident that a number of factors in the casting process can put this process at risk.

These are:

- Damage to the patterns during the process of building gates and risers.
- Damage and moisture penetration during the dipping process.
- Cracking of the casting shell due to the dissimilar materials of the pattern and the gating structure.
- As shrinkage is difficult to predict, cavities and cores will differ in shrink value.

- As these patterns tend to be expensive, only one set was produced, leaving no chance to repeat a poor casting.
- Any moisture or wet resin within the pattern could cause the shell to crack.
- Packing of the shell with insulation material is the only method to slow down cooling in areas to combat warping and porosity.

The tool was finished and fitted to the same mounting frame as the machined tool.

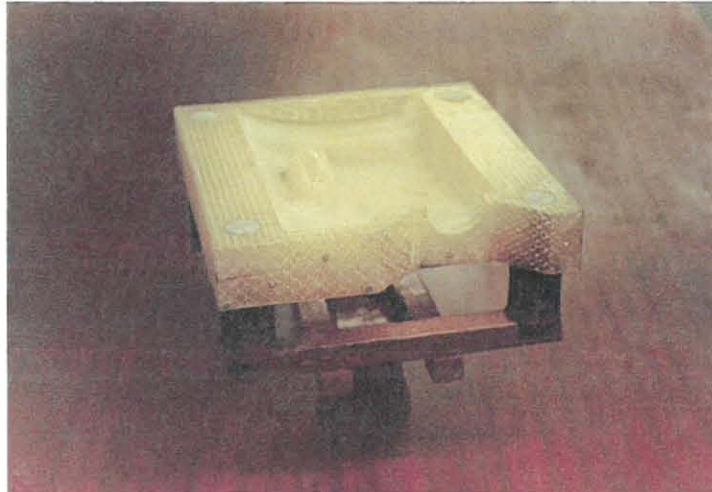


Figure 72: QuickCast Patterns for Blow Mould



Figure 73: Shelled QuickCast Patterns for Investment Casting

Figure 73 shows tool halves after shelling process, i.e. before investment casting. No parts were successfully produced with this tool.

4.5. Case Study 5 - High Speed Machining Blow Mould Bottle Tool.

The previous design was not successful, the design was converted by the author into a machine-able tool design. Provisional preparation was done in anticipation of the tool manufacture. The CNC tool paths were generated for both halves mounted simultaneously on the same milling machine.

The cavity plates were machined on the high speed-milling machine in the CSIR's tooling facility. With the preparation work done during the design phase, the final machining and assembly of the tool took 1 week. Minor modifications were required to interface with the blow-moulding machine and to improve part moulding.

The 3rd party part design was not ideal for blow moulding and resulted in numerous trials to blow acceptable parts.

The speed of response and delivery is a direct result of good project management and excellent communication. Interface between all computer based systems were trialed beforehand to ensure sound file transfer.

A third method was trialed where the patterns were machined and the cavity plates were produced by epoxy casting. The master patterns had to be destroyed to remove them from the castings. This tool was not trialed.

4.6. Study 6 - Conventional Machining – Bottle Cap

The same client as above required a bottle cap to finalise the consumer trials. The initial requirement was for 500 bottle caps. As functional sealing was required, a high level of accuracy and tight tolerances had to be kept. Alternative methods using conventional machining and SLA was tested to determine comparative delivery timescales.

As the cap consisted mainly of cylindrical shapes this design was a typical turning application. In these tools the ejection of the screw thread is the biggest obstacle.

The author converted the part in a tool design where the thread detail was incorporated in a section that was ejected with the part. The part was removed manually from the tool form while a second part was placed in the tool for the next cycle. This design was compatible with the trial die set and only cavity plates were replaced.

Water-cooling was provided for both halves of the tool.

To facilitate the removal of the cap from the tool part, an SLA part was produced, fitting the outer shape exactly. In this manner 500 bottle caps were produced in the first day of moulding.

Subsequently an additional 1000 bottle caps as per Figure 74 were produced from the same tool.

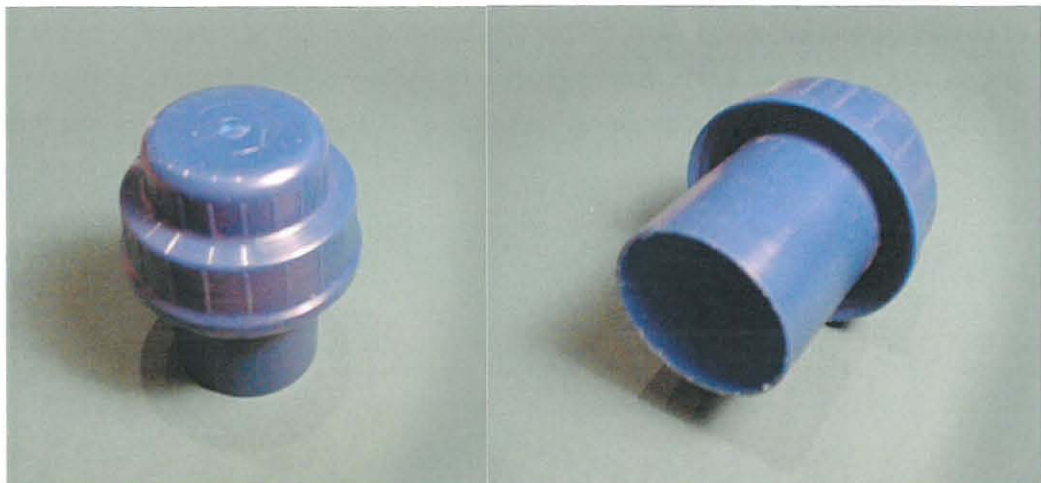


Figure 74: Bottle Cap Component

4.7. Study 7 - Conventional Machining – Crate Adapter.

The client initially approached the CSIR to produce a SLA part for a crate adapter. A crate required several. To functionally trial the improvement, an alternative was required. The client required the adapters in the same material as the crate and a large number to perform stacking trials. To minimise process risk the same route as the previous study was used – with the aim to determine lead times and required parts.

This was also essentially a cylindrical part and suitable to be turned. A small amount of sparking would be required.

The cap tool was used with a new set of inserts. The same ejectors were used, but instead of manual removal, a stripper plate was incorporated to run the tool fully automatic. Water-cooling was provided to both halves of the tool.

The only problem encountered in the manufacture of the tool was with the spark erosion. A rib was sparked in the wrong location. Press fitting and welding a machined insert into the area and re-sparking the rib rectified this. As this was part of the internal detail, a small visual flaw would not affect the appearance of the part. The ribs are visible in Figure 75.

The complete tool conversion was done within a three-week period and parts were provided within a four-week period from receiving the order from the client.

The speed of delivery of the two conventional tooling projects can be directly related to the availability of a mould base and the tooling experience of the author. The total cost of design and tool manufacture was R 19 500. This related in to a part price of R 13.24 for the 1 500 parts produced.

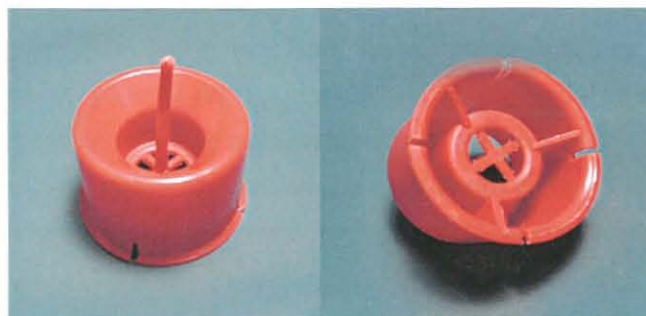


Figure 75: Crate Adapter

5. Discussion of Results

5.1. Observations

i. Temperatures, Cycle Times and its Effect on the Process

Page 134: (xi. Observations – Parameter Setting)

The longer the cooling time, the greater the shrinkage of the part. Much of the other research work investigated by the author involved the production of simple parts, especially flat round disks. For simple parts like these, increased cooling times mean that the part actually shrinks away from the side walls, and can thus be easily ejected. In the case of the modified user part, however, increased cooling times mean that the part shrinks 'onto' the inserts, especially in the rib sections. As a result, the moulded parts break on ejection. This effect also appears to be the most predominant cause of insert damage. Preliminary testing therefore seems to indicate that cooling times of 5 minutes may be too long for certain more complex parts and that cooling time of 60 seconds is long enough to allow the part to cool sufficiently to be ejected. This may result in uncontrolled post shrinkage, as the part is not constrained while cooling outside of the mould.

Page 185: (x. Observations – Temperature Distribution)

Surface temperatures were measured periodically. Most of the aluminium epoxy inserts had their temperature stabilised at 50°C. The SLA inserts had temperatures up to 68°C. Cooling was therefore necessary to lower this temperature to prevent tool damage. Plastic parts were ejected at approximately 70°C, having lost 130 – 140°C from their initial injection temperature.

ii. Design Considerations to Prolong Tool Life

Page 137: (xi. Observations – Preliminary Tool Wear Characteristics)

Deterioration is more a function of chipping rather than abrasion. Stair stepping on near vertical surfaces need to be removed to minimize grip of moulded parts on the cavity walls. This may be difficult in thin rib features and small detail areas. This combined with shrinkage of parts onto cavity features result in chipping during ejection of the moulded parts.

Page 181: (x. Observations – Stereolithography Inserts)

Stress areas in the insert, such as sharp corners should be avoided. These are the first to be damaged in the moulding process. Heat treatment of the SLA parts should be investigated as a possibility to obtain a normalised part. The heat must however be kept below the glass transition temperature for the specific resin.

iii. Best Results

Page 183: (x. Observations – Plating)

Nickel plating onto SLA inserts increased tool life. The plating was damaged by thermal expansion of the plating relative to the underlying SLA resin. The plating transmitted heat away from the plastic part faster than pure SLA resin. Plating onto SLA inserts is an economical way of increasing tool life. Adhesion of the plating onto the substrate was poor.

Page 184: (x. Observations – Surface Quality)

The best consistent surface finish was obtained with the un-plated aluminium epoxy inserts. As these inserts can be replicated relatively easily this would appear to be the most viable method for larger number of mouldings.

iv. Cost Effectiveness of Rapid Tooling

Page 175: (vi. Insert Finishing)

The CNC machining of aluminium inserts versus the cost of growing QuickCast Masters, investment casting of parts, raw material cost, process time and post finishing of the casting, the CNC machining in aluminium route would be the more cost effective method for machine-able designs.

Page 186: (x. Observations – Costs)

Rapid bridge tooling is proposed for parts requiring intricate machining or electric discharging. Simple designs such as the bottle opener could be produced faster using conventional CNC machining. The use of high speed machining to produce tools is becoming common practice. The advantage of this technique is that the rapid tool is the final production tool. The capital equipment cost involved is higher than for conventional machining but can pay off when time is a critical factor. The method of bridge tooling used for these projects has its best application in the verification of product design as functional parts.

vi. Skills Requirement

Page 187: (xii. Conclusions)

All the tool trials clearly proved this tooling method is best used in conjunction with normal tool making methods. Skilled and knowledgeable designers, tool makers and moulders are required to optimise the process for this type of process. This process does not and will never replace skilled tradesmen as they play a critical role in obtaining optimal results with fragile tooling.

vii. Disadvantages of Rapid Tooling

Page 192: (Case Study 7 – Conventional Machining – Crate Adapter)

The problem encountered in the manufacture of the crate adapter tool was with the spark erosion. A rib was sparked in the wrong location. Press fitting and welding a machined insert into the area and re-sparking the rib rectified this. As this was part of the internal detail, a small visual flaw would not affect the appearance of the part.

Rapid Tooling using SLA or Epoxy inserts can not be repaired effectively. Any errors in design, finishing or production would result in discarding the insert and starting afresh. This may result in a more costly exercise versus machining in softer metals.

viii. Alternative Application of Rapid Tooling

Page 193: (Case Study 8 – Stereolithography Mould – Wax Injection Moulding for Investment Casting)

Growing of wax moulds for investment casting over QuickCast is that numerous waxes can be produced accommodating the failures of the investment casting process. Only one SLA growing period is required and numerous castings can be produced, reducing the margin of failure.

5.2 Comparison With Other Methods

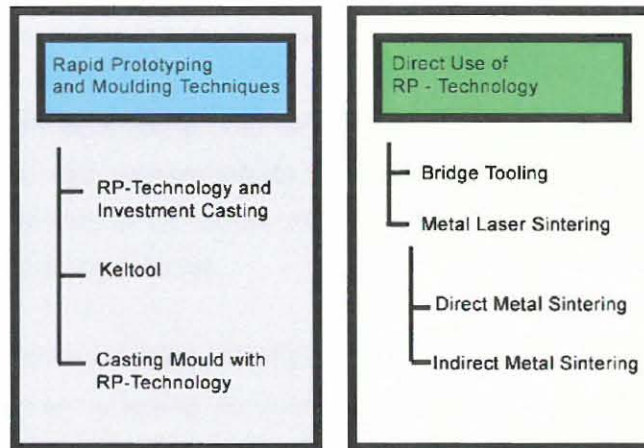


Figure 76: Rapid Tooling Processes.

Figure 76 illustrates two main categories of Rapid Tooling. The first, combining Rapid Prototyping technologies with secondary indirect processes to obtain tooling. These secondary processes introduce a range of processing inaccuracies and risks. The second category strives to generate tooling directly from the RP process. Currently this area is being focused on predominantly by RP manufacturers and will in future lead to Direct Manufacture.

As indicated in the case studies, RP tooling does not only mean tools generated with the use of rapid prototyping equipment.

Secondary tooling would include processes such as silicone rubber moulding, epoxy tooling, ceramic and spray metal tooling and KelTool. Secondary tooling requires a master pattern from which the tool is created. The master pattern must be accurate, possess the appropriate surface finish, and be durable enough to withstand constant handling and abuse during the tooling process.

Direct tooling, on the other hand, includes processes such as CNC machining, Direct AIM process and DTM / EOS RapidTool technologies. With direct tooling the master model is bypassed and the tool is produced directly using a rapid prototyping process.

The most common Secondary tooling process is RTV tooling. Silicone rubber moulds are produced with ease and has low impact on the master. Quantities of 5 – 100 parts can readily be produced with the right equipment. The only problem is, the urethane and

epoxy materials will not have the same mechanical and thermal characteristics as the final moulded part and the cost of these casting materials are high when compared to thermoplastics. The surface finish of the pattern is highly dependent on the skill of the model maker. Typical lead-time from receipt of master pattern to first part is 2 – 3 days.

It only requires an incremental step to transform this process into epoxy tooling for injection moulding. With multiple inserts for the injection moulding process 25 to 1 000 parts can be produced in the actual material of the final part. This depends on the complexity and moulding material.

Conventional Injection moulding techniques can be used. Ejectors and cooling systems are readily used in epoxy tooling. As indicated by the trials, these tools are susceptible to damage during the moulding process and the skill of the tool setter is important to ensure tool life. Depending on the availability of a tool frame, first parts can be produced within a 1 – 3 week period.

As for Direct tooling, CNC machining is the most widely used and understood process. The cutting of aluminium tools, especially on a high speed machining centre can provide excellent results in just as short a time as secondary tooling methods. This does however come at a price and is dependent on the complexity of the part.

The risks involved in moulding with the AIM process can be countered by using the secondary tooling method of RTV tooling and filled epoxy cast inserts.

At present every new technology is marketed as “the big solution” regardless of its benefits and shortcomings.

6. CONCLUSION

6.1. Time, Cost, Quality and Risk Versus Quantity of Parts

There are five key factors in determining the appropriate rapid tooling option.

These are:

- **Lead time**
- **Functionality**
- **Quantity**
- **Cost**
- **Part Tolerance**

If the selection process starts with defining the prototyping objectives and prioritising the trade-offs of each process in advance, the selection process will be relatively simple and the choices will be fairly obvious. Table 39 plots these various options to ease selection.

Quite often one or more options will have strong possibilities. Depending on the specific priorities of the five criteria one process will be the lead process.

For functionality it is best to divide the RT options into two categories based on the functionality of the final part:

- **Appearance – dependant parts**
- **Material – dependant parts**

Table 39: Key Factor Table

KEY FACTOR TABLE			
LEAD TIME	1- 5 DAYS	5 – 10 DAYS	10 – 60 DAYS
FUNCTIONALITY	<i>APPEARANCE DEPENDANT</i>		<i>MATERIAL DEPENDANT</i>
QUANTITY	1 – 10	10 - 50	50 - +
COST	FABRICATION MACHINING	RTV MOULDING (PARTS) AIM TOOLING (TOOL INSERTS)	EPOXY TOOLING (RTV PROCESS) KelTool PROCESS
TOLERANCE	SLA, FDM, SLS,		HIGH SPEED MACHINED TOOL

Appearance – dependant parts are for controlled environments. They have the look and feel of a production part but have limited physical functionality. These parts are used for engineering design reviews, feasibility studies, marketing analysis, photography and other non-abusive applications. They are for all intents and purposes, nice looking parts. Typical parts would include first-generation prototypes like SLA, SLS and LOM models as well as multiple urethane parts cast from silicone rubber moulds.

Material – dependent parts are more robust and can withstand a wider variety of uses, such as field-testing and Safety approval submittals. In most cases these parts are made from the production thermoplastic specified. The part can be machined from solid stock, or injection moulded. The advantage of injection moulded parts is that the intended tensile strength and flexural modulus of a production part is simulated. The disadvantage of the material dependant parts are, they cost more and take longer to produce than appearance dependant parts.

Each project has its individual criteria. Simple mistakes could jeopardise the success of a project. The only way to avoid these is to logically base all decisions on facts and established information. Make sure the information is from an unbiased source as each vendor uses each remote success as the new leading industry standard. It is important to identify a champion with the responsibility to keep abreast of the new technologies and developments. This will allow him to make decisions on a wide basis of information. This

person should preferably also have in-depth knowledge of the whole development process, as his input would be required throughout the project.

The successful projects were the ones where the goals were clearly defined in advance and contingencies were established to support the initial goals.

7. References

1. 3D Systems, *The Edge Vol. V, No. 3*, 3D Systems, California, USA, 1998.
2. Author unknown, *Advanced Injection Mould Tool Setting*, PFSA
3. Author unknown, *Basic Injection Mould Machine Setting*, PFSA
4. Author unknown, *Cutting Costs in Short Run Plastics Injection Moulding*, Morgan Industries
5. Brendell, A., *Taguchi Methods: Applications in World Industry*, IFS Publications, 1989.
6. Budinski, Kenneth G, *Engineering Materials: Properties & Selection*, Prentice Hall, 1996.
7. de Beer, D.J. , *Rapid Product Development – Technology or Process? Product Development Management in a Concurrent Approach*. *Journal of New Generation Sciences*, No. 1, 2003.
8. du Preez, WB, PhD., CSIR, TCT Brochure, 1998.
9. Furness, R.W., *The Practise of Plating on Plastics*, Clare o'Molesey Ltd, 1968.
10. Gastow, H., *Injection Moulds, 102 Proven Designs*, Hanser Publishers, 1983.
11. Hilton, P, *Making the Leap to Rapid Tool Making*, Mechanical Engineering, July 1995.
12. Hoechst, *Hoechst Plastics: Injection Moulding of Thermoplastics*.
13. Jacobs, Paul F, *Fundamentals of Stereolithography*, 1992.
14. Jacobs, P., *Recent Advances In Rapid Prototyping from Stereolithography*, 3D Systems.
15. Jacobs, Paul F, PhD, *Stereolithography and other RP&M Technologies*, 1996.
16. Marutani, Y. and Nakai, T., *Laser Research* 17, 1989.
17. Moubary, John, *Reliability-centred Maintenance*, RCM2, 1998
18. Pham, D.T., Gault, R.S. *Solid Ideas*, Manufacturing Engineer, October 1996.
19. Rhamati, S., *Stereolithography for Injection Mould Tooling*, Rapid Prototyping Journal, 1997.

APPENDIX A

INJECTION MOULDING FAULT FINDING CHART



INJECTION MOLDING CHART

FAULT DESCRIPTION	CLAMPING SYSTEM		INJECTION UNIT		MOULD		RAW MATERIALS		
	Causes	Checks	Causes	Checks	Causes	Checks	Faults	Checks	
<p>FLASH Excess material on parting lines/ pins/ slides <i>Material penetrating mould parting lines/ pins/ slides</i></p>	<p>Mould adjustment incorrect</p> <p>High pressure hydraulic system faulty</p> <p>Machine clamp capacity too small</p>	<p>Mould height</p> <p>Thermal expansion</p> <p>Mould safety/ dirty</p> <p>Hydraulic oil/ sticky, dirty control valves</p> <p>Projected area of cavity and injection pressure</p>	<p>High injection and / or follow up pressure</p> <p>Hold on pressure not operative</p> <p>Injection rate too high</p> <p>Melt temperature too high</p>	<p>B</p> <p>Injection pressure gauge</p> <p>A</p> <p>Pressure changeover reduce</p> <p>Measure melt temperature burn marks in component</p>	<p>Guide pins misaligned</p> <p>Projected area of cavity too large for machine</p> <p>Worn/ warped/ damaged mould</p> <p>Mould temperature setting too high</p>	<p>E</p> <p>Measure Calculation</p> <p>Measure and repair</p> <p>Measure/ material suppliers recommendations</p>	<p>Material viscosity (thin)</p>	<p>A</p> <p>Measure regrind additions</p> <p>Temperature Grade of material</p> <p>MFI of material</p> <p>Regrind</p>	
<p>BURN MARKS AT GATE AREA OF MOULDING Silver or yellow streaks radiating from the gate area: Brown and/ or black streaks <i>Burnt material entering mould during injection</i></p>			<p>Too high injection rate/s</p> <p>Nozzle temps too high</p> <p>Nozzle not seating on sprue bush</p>	<p>A</p> <p>Reduce Measure</p> <p>Carriage pressure and radius of sprue bush/ nozzle</p>	<p>Gates too small</p> <p>Gate land length too long</p> <p>Sharp projections in gate area</p> <p>Sprue bush leaking</p>	<p>Recommended sizes</p> <p>Recommended sizes</p> <p>Visual</p> <p>Visual</p>	<p>Rigid PVC only:</p> <p>Insufficient internal lubricants in formulation</p>	<p>Formulation</p>	
<p>BURN MARKS ON SURFACE OF MOULDING Yellow/ silver/ brown patches on moulding (not at gate or parting lines) <i>Burnt material entering mould during injection</i></p>			<p>Barrel-temps too high</p> <p>Nozzle suck back</p> <p>Material hang up in nozzle</p>	<p>A</p> <p>Measure</p> <p>Purge and observe</p> <p>Shot size hold on time too high</p>	<p>Rough surface in the mould</p> <p>Leak at sprue bush</p> <p>Venting efficiency</p>	<p>Check and repair</p> <p>Clean</p> <p>Clean</p>	<p>Material viscosity (thick)</p> <p>Moisture in material</p> <p>Regrind levels too high</p> <p>R PVC:- insufficient heat stabiliser</p> <p>:- too little internal lubricants in formulation</p>	<p>MFI</p> <p>Check VICAT</p> <p>softening</p> <p>Reformulate</p>	
<p>BURN MARKS AT PARTING LINES Yellow/ silver/ brown lines at furthest point from gate <i>Material decomposing as shot fills cavity</i></p>	<p>Clamping force too high causing mould distortion</p>	<p>Check mould location and alignment</p>	<p>Injection rate too high</p>	<p>B</p> <p>Check filling sequence of mould</p>	<p>Vents too small or blocked</p> <p>Rough surface in mould</p> <p>Mould distorting (poor construction)</p>	<p>Clean</p> <p>Polish</p> <p>Check</p>	<p>Moisture (volatiles) in material</p>	<p>Reset of surface finish</p>	



<p>SHORT SHOTS Incomplete moulding <i>Insufficient material in mould</i></p>			<p>Incorrect settings Material temps too low too high Machine hydraulic pressure Check valve on screw damaged Hopper blocked Screw back pressure too high</p>		<p>Check pressures during shot Erratic shots and shot mass Cooling system Cycle not completed (old machine only)</p>	<p>temp too low Gates too small or incorrectly located Runner system inadequate Vents blocked Burn mark on moulding Wall thickness to flow path ratio incorrect</p>	<p>E B</p>	<p>Measure Check material flow and distort Check filling sequence of moulding</p>	<p>Material viscosity Fillers and reinforcements R PVC lubricant balance</p>		<p>Grade and MFI regrind level</p>
<p>DELAMINATION Thin pieces of material peeling off surface of the moulding usually at and near the gate <i>Laminar cold and hot flow in mould</i></p>			<p>Material temp Hold on pressure too high</p>	<p>AC</p>	<p>Nozzle temp too high Shot mass</p>	<p>Mould too cold Gates too small Excessive mould release agents</p>	<p>E</p>	<p>Measure Do not use or use dry release agent</p>	<p>Regrind incompatible Contamination Excessive lubricants</p>		<p>Check MFI/ grade of regrind Check masterbatch or formulation</p>
<p>FLOW LINES AND PATTERNS Pattern of flow visible as superficial colour differences on surface, thin rough lines emanating from the gate area <i>Type of melt fracture during shot</i></p>			<p>Injection rate too slow or fast Injection pressure too low or high</p>	<p>B</p>	<p>Check filling sequence at various rates</p>	<p>Incorrect location/ design of gates/ product</p>			<p>Regrind level too high Regrind quality Additives 'plating out' Material viscosity</p>	<p>A</p>	<p>Measure Degradation Grade/ MFI/ temperature</p>
<p>SURFACE FINISH OF MOULDING Rough dull finish/ matt finish <i>Type of melt fracture during shot</i></p>			<p>Material temps too low Material not homogeneous Injection rate too slow</p>	<p>A B</p>	<p>Measure Increase back pressure Check filling sequence at various rates</p>	<p>Mould temperature too low Mould protection and release sprays Mould surface finish Design Cold slug well efficiency</p>	<p>E</p>	<p>Measure and increase Clean/ use release grades of material Observe Scratch marks on moulding Check</p>	<p>Moisture in material Material viscosity Material additives (glass)</p>		<p>Check MFI/ grade Formulation</p>

<p>SINK MARKS Areas where material has shrunk away from the original outer shape of mould</p> <p><i>Material shrinkage after injection</i></p>			<p>Hold on pressure to low Injection rate too low Material temperature too high</p> <p>Injection time too short Insufficient cushion</p>	<p>A B</p>	<p>Observe Measure Check mass of part Observe pressure change-over travel of screw</p>	<p>Material too hot Mould design incorrect Ribs Section thickness/ Wall thickness</p>	<p>E</p>	<p>Measure Measure Ribs of wall thickness</p> <p>Flow from thick to thin</p>	<p>Material crystalline Incorrect material viscosity (temps) quality of regrind NOTE: crystalline materials have higher shrinkage rates</p>	<p>A</p>	<p>Shrinkage rates Measure</p> <p>Degradation</p>
<p>WARPAGE Distortion of component directly after moulding or after storage</p> <p><i>Differential of material (check how operator packs the product)</i></p>	<p>Mould opening too fast</p> <p>Ejector too fast</p>	<p>Reduce and observe</p> <p>Reduce and observe</p>	<p>Hold on pressure too high Injection rate too high</p> <p>Material temperature too high Cooling time too short</p>	<p>C A F</p>	<p>Check part mass/ internal stress (polarised light) Reduce and observe Smooth mould filling Measure Measure component temp/ material Heat distortion temp</p>	<p>Cooling/ heating circuits on mould</p> <p>Cooling circuits incorrectly connected Incorrect position of gate Incorrect cooling channel/ mould design</p>	<p>E E</p>	<p>Water channels/ temp flow to both halves (compressed air) Temperature difference between mould halves Orientation of shrinkage Measure for hot spots on mould/ built in shrinkage</p>	<p>Viscosity Inconsistent material Differential crystallisation of material</p>		<p>MFI/ grade regrind levels Regrind/ grades Additives</p>
<p>BUBBLES Air entrapment within component</p> <p><i>Air inclusion during plastification/ mould filling</i></p>	<p>Clamping pressure too high/ no venting</p>	<p>Reduce and observe</p>	<p>Injection rate too fast Back pressure to low</p> <p>Screw speed too fast</p>		<p>Reduce and observe Increase/ observe/ bubbles in sprue As low as possible</p>	<p>No venting, blocked/ design Thick to thin sections (gate position) Inserts, pins affecting flow</p>		<p>Clean and observe</p> <p>Visual</p>	<p>Viscosity Wet material NOTE amorphous material prone to wide melting point</p>	<p>A</p>	<p>Measure Measure/ surface finish</p>
<p>GATE SPLAY Silver splash like marks around gate</p> <p><i>Laminar flow of hot/ cold in mould/ wet material</i></p>			<p>Injection rate too high</p>		<p>Reduce and observe</p>	<p>Gate land length too long/ Gate too small/ Incorrect position</p>		<p>Suppliers recommendations</p>	<p>Material viscosity too thick (temp) Material additives (glass) Moisture content too high</p>	<p>A</p>	<p>Measure temperature Formulation Check</p>

<p>WELD LINES Weak or visible lines usually across the direction of material flow at the furthest point from the gate or behind projection in cavity <i>Cold fronts of material not mixing in properly</i></p>			<p>Injection rate too low Material temps too low</p>	<p>A</p>	<p>Mould filling sequence Measure</p>	<p>Mould temps too low Venting inadequate Incorrect position of gates Inserts/ pins affecting flow</p>	<p>E</p>	<p>Measure Tendency to burn Mould filling sequence Visual</p>	<p>Viscosity Fillers/ additives Flow path/ wall thickness ratio</p>		<p>Grade and MFI Formulation Material suppliers data</p>
<p>CONTAMINATION Foreign matter in component Various</p>	<p>Oil and grease from clamping system in mould</p>	<p>Seals/ excessive grease on platen, bushes and tie bars</p>	<p>Residual material in barrel Environmental contamination Nozzle not seating correctly/ Drawing in material from nozzle tip</p>		<p>Purge Hopper lid in place Material build up/ Suck back</p>	<p>Mould protection/ release agents and lubricants Water and oil leaks Residual material from previous mouldings</p>		<p>Compatibility mould surface/ Slides Visual – seals and connectors Visual</p>	<p>Prior to processing</p>	<p>A</p>	<p>Visual Melt temperature Grade/ release agent</p>
<p>COMPONENT STICKING Component sticking in mould not being ejected Various</p>	<p>Ejector system not functioning Mould opening too fast</p>	<p>Visual Slow down and observe</p>	<p>Hold on pressure too high Cooling time too little</p>	<p>C</p>	<p>Component mass Ejector pins penetrate component</p>	<p>Temp difference between mould halves Rough unpolished mould areas Gates too large (submarine) Inadequate venting behind ejector pins Mould protection and lubricant residues Incorrect mould design</p>	<p>E</p>	<p>Product stuck on fixed half/ shrinkage Scratch marks/ damage No gate component separation Vacuum/ suction Draw angles, shrinkage, undercuts etc.</p>	<p>Additives 'plating out' Material decomposing Non lubricated material</p>	<p>A</p>	<p>Visual Melt temperature Grade/ release agent</p>

<p>SPRUE STICKING On mould opening sprue breaks from runner or product and remains in sprue bush</p> <p style="text-align: center;">Various</p>			<p>Hold on pressure to high</p> <p>Hold on pressure after gate has frozen off</p>	B	<p>Pressure change over</p>	<p>Does not match radius of sprue bush No cold slug well/ sprue puller/ incorrect design Nozzle orifice greater than orifice in sprue bush</p>		<p>Visual</p> <p>Measure</p> <p>Measure</p>	<p>Material brittle Wrong material (shrinkage)</p>	A	<p>Measure temperature</p>
<p>COMPONENT BRITTLE AND LOW IMPACT STRENGTH Component weak <i>Material decomposition</i></p>			<p>Back pressure too high</p> <p>Material temp too high</p>	A	<p>Reduce and observe/ material temperature</p> <p>Measure</p>				<p>Regrind quality/ addition levels to high High moisture content Wrong material</p>		<p>Degradation/ % added Measure Grade/ MFI</p>
<p>COMPONENT DIMENSIONS Dimensions of component erratic and out of spec. <i>Differential shrinkage/ various</i></p>	<p>Clamp pressure too high, mould distortion</p>	<p>Reduce and measure</p>	<p>Check ring inoperative</p> <p>Hold on pressure too high Instability of processing conditions</p>	C	<p>Erratic filling, component mass Component mass Oil temperature values, controls, control voltages, thermocouples</p>	<p>Instability of cooling water temp Poor cooling channel design Unequal mould temperature</p>	E	<p>Measure/ operation of tower/ chiller Hot spots Measure for hot spots/ flow to both halves</p>	<p>Post moulding shrinkage Post moulding water absorption Additives/ fillers</p>		<p>Grade of material Grade of material</p>



A. MEASURE TEMPERATURE WITH A PYROMETER	B. TO DETERMINE PRESSURE-CHANGEOVER POSITION FROM FIRST TO HOLD ON STAGES (LIMIT SWITCH/ CAM)	C. TO DETERMINE HOLD ON PRESSURE	D. TO DETERMINE HOLD ON PRESSURE TIME	E. TO DETERMINE MOULD TEMPERATURE	F. TO DETERMINE COOLING TIME OF PRODUCT IN MOULD
<ul style="list-style-type: none"> • Material: Purge out of barrel onto cardboard, insert needle probe to centre, allow to stabilise. Then compare reading with material suppliers recommendations ▪ For mould, component and barrel: use flat probe 	<ul style="list-style-type: none"> • Set shot weight limit switches • Set hold on pressure to zero • Set hold on limit switch very close to shot weight limit switch • Mould (it will be a short shot) • Move hold on limit switch further from shot weight limit switch • Mould (will be less short) • Repeat until cavity has been nearly filled. This is the position for the changeover to hold on pressure 	<ul style="list-style-type: none"> • Set pressure very low, with long hold on time • Mould and measure/ weigh component. Note pressure gauge reading. • Increase pressure slightly and repeat 1 & 2 • Set the hold on pressure when dimensional tolerances and weight are correct • Apply procedure D. to set hold on time 	<ul style="list-style-type: none"> • Reduce time to a minimum • Mould and weigh component without sprues and runners • Increase time by 1 second (it's best to allow a few shots for the machine to stabilise) • Weigh component and record • Repeat until component has does not increase. At this stage the gate has frozen off and optimum hold on time has been achieved 	<ul style="list-style-type: none"> • From material suppliers data, determine the heat distortion temperature • Do not set mould temperature higher than the HDT • Determine actual mould temperature with Pyrometer 	<ul style="list-style-type: none"> • Use pyrometer to measure temperature of ejected product • Increase cooling time in small increments until the temperature of the product is below the HDT for that material