RAPID PROTOTYPING UTILISING THE LASER CUTTING METHOD

BY

JOHN MCGREGOR OEHLEY

Dissertation submitted in fulfilment of the requirements for the:

MAGISTER TECHNOLOGIAE

Engineering: Mechanical

In the

Faculty of Engineering

at the

Technikon Free State

June 2000

Supervisor: D.J de Beer (M.Dip. Tech.)
Co-supervisor: Dr J.A. Strauss (Ph.D.)

DECLARATION

I, JOHN MCGREGOR OEHLEY hereby declare that this dissertation which has been submitted to Technikon Free State for the awarding of the degree MAGISTER TECHNOLOGAIE: ENGINEERING MECHANICAL, is my own independent work and has not previously been submitted by me or any other person for the award of a qualification.

....

J M Oehley Date

Student

ACKNOWLEDGEMENTS

A number of persons have given me invaluable assistance throughout the duration of this research project. In this regard I would like to thank the following persons in particular:

Dr J.A. Strauss and Mr D.J. de Beer for their very able supervision and guidance since the initial concept of this project was formulated.

Mr M.S. Camacho for his assistance and advice on all the computer software programs used.

The Technikon Free State and Science Park for their support and the use of equipment.

To my family and friends for their prayers and encouragement and for the guidance by my parents and the opportunities they afforded me.

Lastly, this dissertation would not have been possible without the grace of God.

UITTREKSEL

Die gewildheid van driedimensionele rekenaarontwerpe en die metodes om dit te ontwikkel, neem by die dag toe. Die snelprototiperingsprosesse stel ontwerpers en vervaardigers in staat om direk vanaf die rekenaarontwerp 'n model te vervaardig of te "groei" soos dit bekend staan.

Die prosesse Stereolitografie (SLA), selektiewe laser sintering (SLS) en gesmelte-neerslagmodellering (FDM), word die algemeenste in Suid-Afrika en in die wêreld gebruik. Die probleem is dat die prosesse baie beperk is in terme van grootte en baie tyd in beslag neem. Verder is die koste van produkte en die masjiene buitensporig hoog.

Hierdie studie bied 'n innoverende metode om prototipes te bou (ingenieursmodelle, sowel as argitektoniese modelle), naamlik dwarssnit-prototipering (CSP), wat al die bogenoemde probleme sal uitskakel. Die CSP proses neem 'n driedimensionele model en deel dit op in 'n aantal snitaansigte met behulp van gespesialiseerde rekenaarprogramme. Die aansigte word belyn en dan met 'n laserstraal uitgesny. Al die los snitte word aanmekaar gelamineer om 'n groter, vinniger en goedkoper model te verkry.

Hierdie verhandeling kan gebruik word as 'n handleiding vir die gebruikers van hierdie spesifieke proses, aangesien die uiteensetting van die lasersnymasjien en die totale CSP-proses in detail bespreek en uiteengesit word.

SYNOPSIS

Due to the popularity of 3-dimensional CAD designs, the methods of manufacturing from these designs are increasing all the time. Rapid prototyping designers and manufacturers are now able to grow prototypes from the drawing files they have created.

Stereolithography (SLA), selective laser sintering (SLS) and fused deposition modelling (FDM) processes are commonly known in South Africa and throughout the world. These methods, however, are restricted by the size of the model that can be produced and are very time-consuming. The SLA, SLS and Sanders prototypes and machines are generally too expensive for the designer or entrepreneur.

This study presents an innovative method of producing engineering and architectural prototypes, i.e. the Cross-Section Prototyping (CSP) method. This method eliminates the problems that occur with other processes. The CSP method slices a 3-D model into evenly spaced layers with the aid of dedicated software. All the layers are referenced and the profiles are cut with a laser beam. The layers are laminated together to form the prototype at a reduced cost and in a shorter timespan. This method also allows models of larger geometry to be produced.

The layout of the laser cutting machine and the CSP process are discussed in detail. This dissertation can serve as an instruction manual for users of the CSP method.

Contents

page

Chapter 1: Rapid prototyping utilising the laser cutting method 1

1.1. Introduction to Rapid Prototyping 1

1.2. Problem statement 7

1.3. Purpose and procedure of the study 9

Chapter 2: Software 10

2.1. Slicing software 10

2.1.1. 3D drawings 10

2.1.2. 2D drawings 23

2.2. Plotter software 24

2.2.1. EngraveLab 24

2.2.2. Nu-tel 26

Chapter 3: Experimental setup 28

3.1. The X-Y gantry system 28

3.2. The Z-axis slide for gantry 32

3.3. The CO_2 laser 35

3.4. The cooler 36

3.5. The controller 38

3.6. The support table 41

3.7. Air purifier 43

page

Chapter 4: Laser operation and applications 45

4.1. Introduction 45

4.2. Definitions and description of a laser 46

4.3. Commercial lasers 47

4.4. Laser safety 50

4.5. The Carbon Dioxide laser 53

4.6. Applications of the CO_2 laser 59

4.7. Summary 61

Chapter 5: Materials 62

5.1. Laser interaction on materials 62

5.2. Material processing parameters 68

5.2.1. UHI 69

5.2.2. Acrylic glass 71

5.2.3. Masonite 73

5.3. Material choice 74

5.4. Summary 76

Chapter 6: Lamination 78

6.1. Locating method 78

6.2. Encoding 80

6.3. Adhesives 83

page

Chapter 7: Results and Rapid Prototyping products 87

7.1. The Architectural Prototype 88

7.2. The Engineering Prototype 96

7.3. Laser-cut prototypes compared to other rapid prototyping methods 110

Chapter 8: Conclusions and recommendations 121

Appendix A: Calculations of the laser-cut prototypes 131

References 138

Abbreviations and acronyms used 141

LIST OF FIGURES

Chapter 1 **Page**

Fig. 1.1	Figure illustrates the Stereolithography method	2
Fig. 1.2	Figure illustrates the Selective Laser Sintering method	3
Fig. 1.3	Figure illustrates the Fused Deposition Modelling method	4
Fig. 1.4	Figure illustrates the Laminated Object Manufacturing method	6
Fig. 1.5	Figure illustrates the CSP method, sliced in only one direction	8

Chapter 2

Fig. 2.1	Cone with given dimensions	10
Fig. 2.2	Cone in .stl format	11
Fig. 2.3	Section drawing of cone	12
Fig. 2.4	Imported sections of the cone	12
Fig. 2.5	Sorted sections in plot layout form	13
Fig. 2.6	The sectioning of a cone	14
Fig. 2.7	Section tools in MicroStation	15
Fig. 2.8	Layers of materials to form a union with the cone	17
Fig. 2.9	The intersected union	18
Fig. 2.10	Sliced view of layers	18
Fig. 2.11	Plot layout of cone (inner circles deleted)	19
Fig. 2.12	Exporting as an .stl file	20
Fig. 2.13	Surface model (non-stitched)	21
Fig. 2.14	Surface model (stitched)	22

Fig. 2.15 Capped solid of a model 22

Fig. 2.16 Side views of a townhouse 23

Chapter 3

Fig. 3.1 Photo taken of the X-Y plotter with the support table 28

Fig. 3.2 Photo of X-Y table 29

Fig. 3.3 Dimension layout of X-Y table 31

Fig. 3.4 Z-axis slide 32

Fig. 3.5 Dimension layout of Z-axis 34

Fig. 3.6 Photo of the 40W CO_2 laser 35

Fig. 3.7 Photo of the cooler consisting out of a radiator and fan, reservoir and pump. 36

Fig. 3.8 Isel - Stepmotor – controller C116-4 38

Fig. 3.9 Isometric drawing of the support table 41

Fig. 3.10 Dimension drawing of support table (first angle) 42

Fig. 3.11 Photo of (Nederman) Electrostatic filter 43

Chapter 4

Fig. 4.2 Energy level structure in the CO_2 laser 56

Chapter 5

Fig. 5.1 Different beam profiles (TEM_{nm} modes) 63

Fig. 5.2	Dimensions on laser beam	66
Fig. 5.3	Graph on UHI	70
Fig. 5.4	Graph on Acrylic Glass	72
Fig. 5.5	Graph on Masonite	73

Chapter 6

Fig. 6.1	Sliced model of a horse with reference pens	78
Fig. 6.2	3mm x 2mm ref. pens (Z-sliced)	79
Fig. 6.3	10mm and 5mm ref. pens (Z-sliced)	79
Fig. 6.4	3mm x 2mm ref. pens (X-sliced)	80
Fig. 6.5	3mm x 2mm ref. pens (Y-sliced)	80
Fig. 6.6	Plot layout with numbering	80
Fig. 6.7	Numbers engraved on the material	81
Fig. 6.8	Plot layout of the second cut	81
Fig. 6.9	Complete layout of the horse model with proper encoding	82

Chapter 7

Fig. 7.1	A townhouse with dimensions	88
Fig. 7.2	Plot layout of townhouse: 1mm thickness (X –Y sliced)	89
Fig. 7.3	Plot layout of townhouse: 2mm thickness (X –Y sliced)	90
Fig. 7.4	Plot layout of townhouse: 3mm thickness (X –Y sliced)	91
Fig. 7.5	Plot layout of townhouse: 1mm thickness (Z sliced)	92

Fig. 7.6	Plot layout of townhouse: 2mm thickness (Z sliced)	93
Fig. 7.7	Plot layout of townhouse: 3mm thickness (Z sliced)	94
Fig. 7.8	An engineering impeller	96
Fig. 7.9	Plot layout of impeller: 1mm thickness (X –Y sliced)	97
Fig. 7.10	Plot layout of impeller: 2mm thickness (X –Y sliced)	98
Fig. 7.11	Plot layout of impeller: 3mm thickness (X –Y sliced)	99
Fig. 7.12	Plot layout of impeller: 1mm thickness (Z sliced)	100
Fig. 7.13	Plot layout of impeller: 2mm thickness (Z sliced)	101
Fig. 7.14	Plot layout of impeller: 3mm thickness (Z sliced)	102
Fig. 7.15	Dimensional drawing of the horse	104
Fig. 7.16	Plot layout of the Horse sliced in the X direction	105
Fig. 7.17	Plot layout of the Horse sliced in the Y direction	106
Fig. 7.18	Plot layout of the Horse sliced in the Z direction	107
Fig. 7.19	Photo of the horse model sliced in the X direction	108
Fig. 7.20	Photo of the horse model sliced in the Y direction	109
Fig. 7.21	Photo of the horse model sliced in the Z direction	109
Fig. 7.22	Scale drawing (1:1) of the chess piece	114
Fig. 7.23	Prototype on laser cutter (scale 1:1) of the chess piece	114
Fig. 7.24	Scale drawing (1:1) of the fly-wheel cover	115
Fig. 7.25	Prototype on laser cutter (scale 1:1) of the fly-wheel cover	115
Fig. 7.26	Scale drawing (1:1) of the impeller	116
Fig. 7.27	Prototype on laser cutter (scale 1:1) of the impeller	116
Fig. 7.28	Scale drawing (1:1) of the house	117

Fig. 7.29	Prototype on laser cutter (scale 1:1) of the house	117
Fig. 7.30	Scale drawing (1:1) of the hostel	118
Fig. 7.31	Prototype on laser cutter (scale 1:1) of the hostel	118
Fig. 7.32	Scale drawing (1:1) of the beach house	119
Fig. 7.33	Prototype on laser cutter (scale 1:1) of the beach house	119

Chapter 8

Fig. 8.1	Model sliced in 3mm as well as 1,5mm pieces	125
Fig. 8.2	Fly-wheel cover manufactured, using concurrent engineering	128
Fig. 8.3	Diagrammatic layout of product development	129

LIST OF TABLES

Chapter 2		Page
Table 2.1	Cutting pen specifications	26
Chapter 3		
Table 3.1	X-Y gantry specifications	30
Table 3.2	X-Y gantry technical data	30
Table 3.3	Dimensions of the X-Y gantry	31
Table 3.4	Specifications of Z-axis slide for gantry	33
Table 3.5	Technical data of Z-axis slide for gantry	33
Table 3.6	Technical specifications on the 30W CO_2 laser	35, 36
Table 3.7	Cooling system testing data	37
Table 3.8	Technical specifications of the Air purifier	44
Chapter 4		
Table 4.1	Summary on laser specifications	49
Chapter 5		
Table 5.1	Laser capabilities	65
Table 5.2	Results on UHI (3mm)	69
Table 5.3	Results on UHI (2mm)	69
Table 5.4	Results on UHI (1,5mm)	70
Table 5.5	Results on A.C. glass (3mm)	71

Table 5.6	Results on A.C. glass (2mm)	71
Table 5.7	Results on A.C.glass (1,5mm)	72
Table 5.8	Results on Masonite (3mm)	73
Table 5.9	Results on first test (minimum distances)	74
Table 5.10	Results on second test (minimum distances)	75
Table 5.11	Results on third test (minimum distances)	75
Table 5.12	Final results on minimum distances	76

Chapter 7

Table 7.1	Results on townhouse X-Y-sliced (1mm thickness)	89
Table 7.2	Results on townhouse X-Y-sliced (2mm thickness)	90
Table 7.3	Results on townhouse X-Y-sliced (3mm thickness)	91
Table 7.4	Results on townhouse Z-sliced (1mm thickness)	92
Table 7.5	Results on townhouse Z-sliced (2mm thickness)	93
Table 7.6	Results on townhouse Z-sliced (3mm thickness)	94
Table 7.7	Summery on the townhouse	95
Table 7.8	Results on impeller X-Y-sliced (1mm thickness)	97
Table 7.9	Results on impeller X-Y-sliced (2mm thickness)	98
Table 7.10	Results on impeller X-Y-sliced (3mm thickness)	99
Table 7.11	Results on impeller Z-sliced (1mm thickness)	100
Table 7.12	Results on impeller Z-sliced (2mm thickness)	101
Table 7.13	Results on impeller Z-sliced (3mm thickness)	102
Table 7.14	Summary of the impeller	103

Table 7.15 Results of the horse cut in the X direction 105

Table 7.16 Results of the horse cut in the Y direction 106

Table 7.17 Results of the horse cut in the Z direction 107

Table 7.18 Summary on different slice directions 108

Table 7.19 Summary of chess piece 114

Table 7.20 Summary of Fly-wheel cover 115

Table 7.21 Summary of the impeller 116

Table 7.22 Summary of the house 117

Table 7.23 Summary of the hostel 118

Table 7.24 Summary of the beach house 119

Table 7.25 Summary of all the engineering prototypes 120

Table 7.26 Summary of all the architectural prototypes 120

Chapter 8

Table 8.1 Summary of all the engineering prototypes 126

Table 8.2 Summary of all the architectural prototypes 126

CHAPTER 1

Rapid prototyping utilising the laser cutting method

1.1. Introduction to Rapid Prototyping

During the last ten years the technical groundwork was done for a technology (actually a group of technologies), called Rapid Prototyping (RP). RP is the process by means of which a computer-aided-design (CAD) file is turned into a solid model by using one of several techniques, for example: sintering, layering, deposition, or sculpting, etc. [30].

Understanding the basic prototyping methods can help a company to make the best choice when selecting a prototyping technique. System choice depends on factors such as model accuracy, equipment cost, model material, type of model and modelling time. Prototyping costs are also becoming more and more important [31].

In general, rapid prototyping is an additive fabrication technique for the building of products by adding raw material layer by layer, using different techniques [12]. These techniques normally only differ in the way or method the model is built up, layer upon layer, and may also include a variation of different materials [20].

According to a technology audit done in 1999, 42 RP systems were available internationally [7]. In South Africa the only technologies are: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Sanders 3D printing, and Laminated Object Manufacturing (LOM) [7].

The above-mentioned technologies function as follows:

Stereolithography

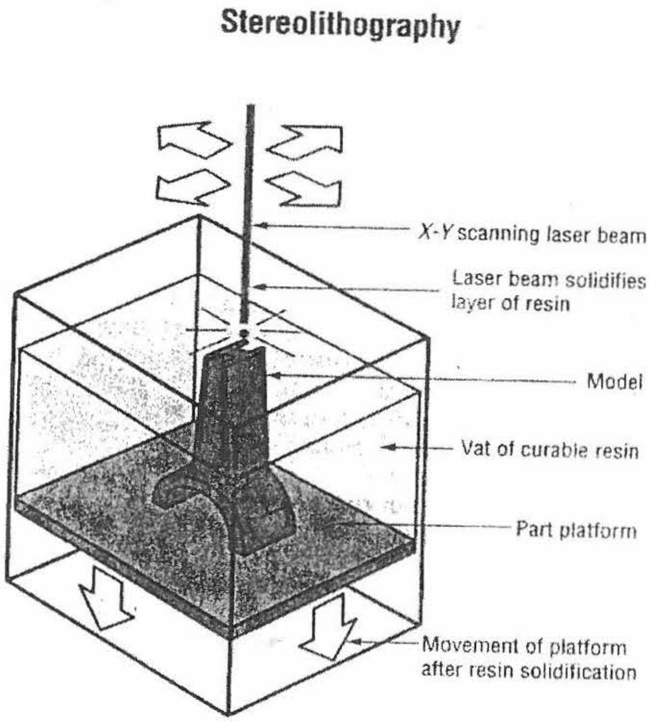


Fig.1.1. Figure illustrates the Stereolithography method

The Stereolithography (SLA) method is used to build models when a laser cures the prototyping material, which is a type of photopolymer, called a photosensitive resin [9]. The core of the process is a photosensitive liquid plastic, which solidifies when exposed to a certain wavelength of ultraviolet light. The system uses an ultraviolet laser to selectively cure the liquid to create the part. Cross sections, referred to as layers, are constructed one at a time on the surface of a vat of photosensitive resin. To construct the layer, the laser traces the perimeter of the layer and then cross hatches the areas that are to be solid. The cured layer is then lowered below the surface exactly one-layer thickness. Fresh liquid polymer flows in to cover the newly solidified layer. Once the surface of the vat is perfectly level, construction of the next layer is begun. Layer construction continues, layer by layer, until the entire part is built.

Selective Laser Sintering

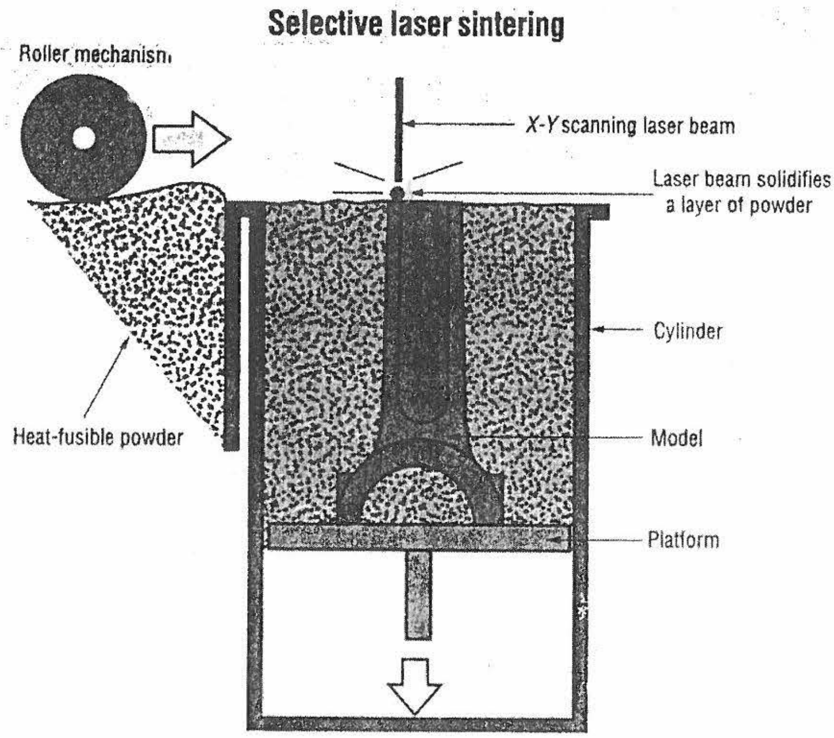


Fig.1.2. Figure illustrates the Selective Laser Sintering method

The second rapid prototyping method, selective laser sintering,is used to build prototypes with thermoplastic materials and or metals. SLS from DTM Corp., Austin, Texas, uses a Sinterstation machine and a wide variety of materials such as polycarbonate, nylon, and fine nylon, as well as wax and metals. The SLS process uses 3D CAD data in a STL format. In a build chamber, the SLS process deposits a thin layer of heat-fusible powder onto a part-building cylinder, which is the modelling table. A heat-generating $C0_2$ laser selectively draws an initial cross-section of the object on a layer of powder. The intensity of the laser beam is modulated to melt and sinter the powder only in areas defined by the object's design geometry [12].

Materials for SLS

The SLS process differs from other systems, because it builds models in a variety of materials to best fit an application. Polycarbonate is durable, heat-resistant, and compatible with the investment casting process. Another material that can withstand and perform in demanding environments is nylon. To create a metal model, the designer chooses a steel and copper matrix material bonded with a thermoplastic binder that mixes to produce a material with properties that exceed those of *7075* aluminum [23, 30].

Fused Deposition Modelling

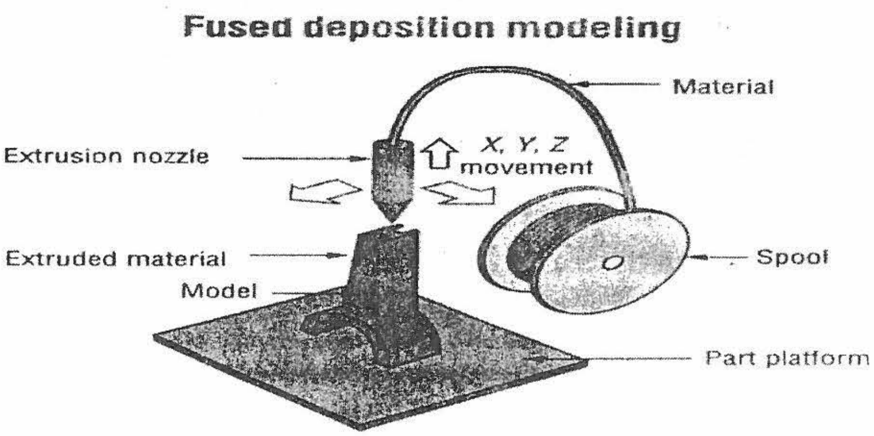


Fig.1.3. Figure illustrates the Fused Deposition Modelling method

A rapid prototyping technique using an extrusion method for thermoplastic material was developed by Stratasys Inc., Eden Prairie, Mirin. The modelling system has an extrusion nozzle that melts and extrudes plastic supplied in the form of a filament on a spool. The placement of the extrusion bead along the path is guided by a plotter-like mechanism. The system operates in the X-, Y- and Z-axes to draw the model one layer at a time. The material solidifies, laminating to the proceeding layer [23].

Sanders 3D Printing

The Sanders Modelmaker II system uses a patented inkjet technology, to build up models, layer upon layer, on a Z-axis build table. Build layers as fine as 0,013 mm enables the system to construct models, prototypes and patterns with exceptionally fine detail and smooth surface finishes, even on rounded contours. The table is precisely positioned (within 0,003 mm) after each build layer, and a flatbed milling subsystem mills off excess vertical height. In addition to creating a known surface reference for the next layer to build on, the milling technique enables any level of surface depth cutting within the 0,003 mm limit. Multiple print-heads, mounted over the table on a precision *X/Y* drive carriage, deposit tiny droplets (0,075 mm in diameter) in a drop-by-demand method, to deposit material digitally controlled to within 0,006 mm. One jet deposits droplets of green thermoplastic material in order to build the actual pattern. A second jet deposits droplets of red wax that supports all pattern overhangs and cavities during the build process. The materials, which are ejected from the heads as hot liquids, solidify to align a trace of 0,1 mm wide by 0,06 mm high, enabling the construction of freestanding walls as narrow as 0,1 mm. When the model is completed, it is immersed in a solvent bath that completely dissolves the wax support. Within minutes of the dissolving of the supports, the model is ready for visual inspection, painting, and investment casting or moulding in RTV (Room Temperature Vulcanising) [6].

Laminated Object Manufacturing

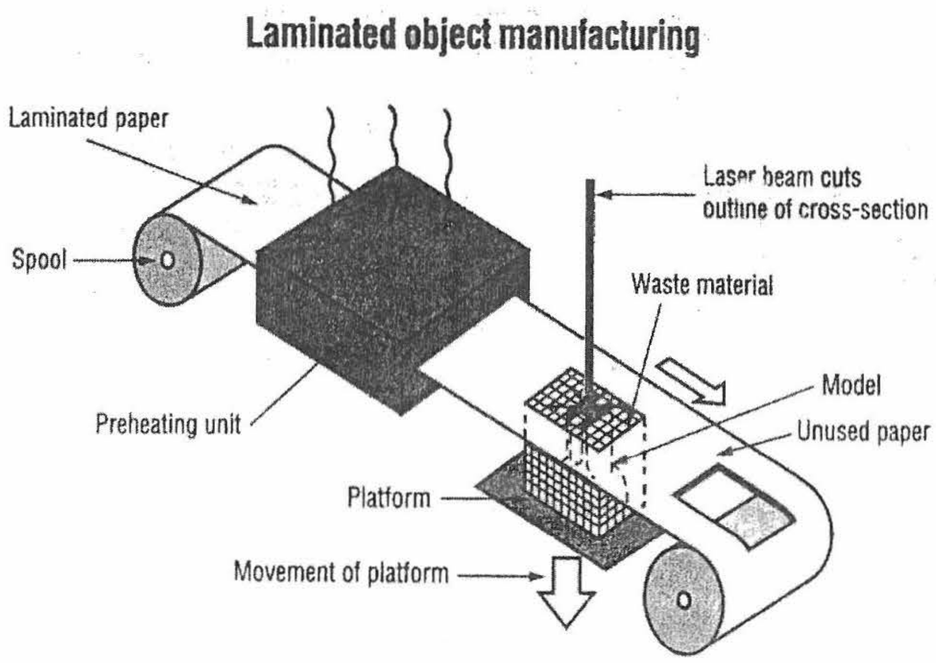


Fig.1.4. Figure illustrates the Laminated Object Manufacturing method

In Laminated Object Manufacturing, adhesive sheets of paper are used to form a prototype from a CAD model. The preheated paper travels to the build area and is fused to a previous layer. A laser cuts a pattern representing a cross-sectional layer of the model and dices the unused paper into waste material (see Fig.1.4.) [23]. Many film, foil and sheet materials can be used. A layer is first glued to stack then cut with the laser beam. Laser power is adjusted to cut through only one layer of the lamination. When metal foil is used, the finished part is furnace brazed together. It is also possible to use the laser itself to braze the cross sections together, or activate an adhesive that will selectively glue them together to achieve a well-formed prototype.

It is an accepted fact that, due to the very expensive prices of the RP technologies, not all of them will be available to the SA industry. This opens up an opportunity to look at new developments, which will address the need for **faster**, **bigger** and **cheaper** concept models or prototypes.

1.2. Problem statement

The RP techniques that are used are very expensive and restrictive with regard to size. A recently developed modelling process builds large physical prototypes from materials cut with a laser. Prototypes as large as cars can be constructed with the Cross-Section Prototyping (CSP) process devised by LaserCAMM, Menlo Park, California. It works with a wide range of materials and in some cases slashes modelling time by over 80%, compared to other prototype methods. The CSP process can produce large models using two different build styles [17].

One CSP style constructs models that resemble the interconnecting partitions of an egg crate. The system first partitions a CAD file into cross sections in two perpendicular directions. It leaves some space between the slices and adds interlocking slots where the slices intersect. It then uses a laser to cut the sections from plastic, wood, foam, or similar materials. The assembled parts create a large open-cell framework, which can be quickly filled with foam and sanded.

The second CSP build style constructs models that are completely solid. It slices the CAD file in only one direction. Cross sections are cut with a laser, stacked in alignment to laser-cut registration holes, and bonded together. Sanding the solid assembled shape removes steps and surface imperfections. Unlike those in other rapid-prototyping techniques, slices can vary from the thickness of paper to a 25mm section, depending on the level of detail required. The CSP process is said to overcome the size, speed, and material limitations associated with most rapid-prototyping systems. Applications for CSP include automotive styling models, aerospace wind tunnel models, and large tooling. Recently, a team built a half-scale model of a concept car for a trade show in one week at a cost to the client of less than $5,000. Conventional methods would have taken several weeks and would have cost over $30,000 [22].

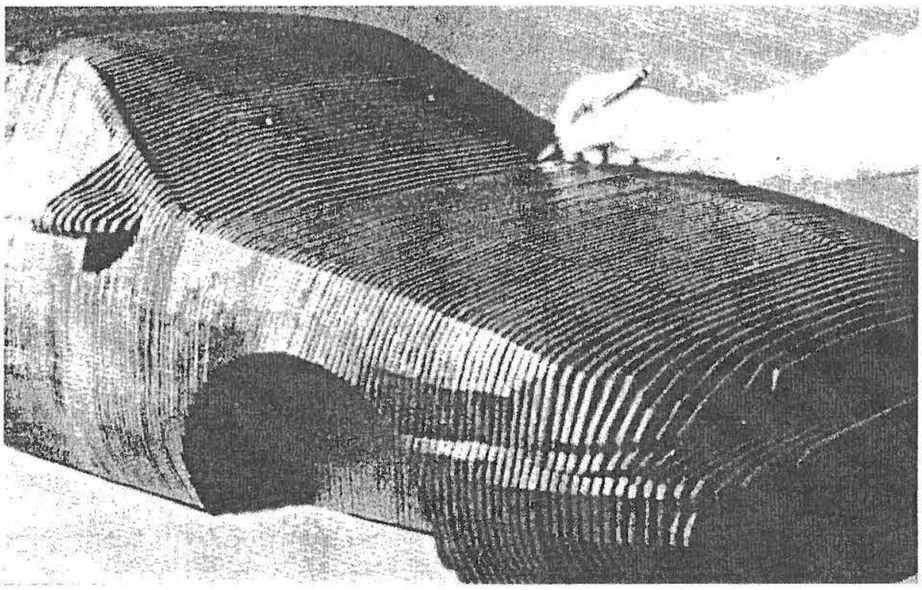


Fig.1.5. Figure illustrates the CSP method, sliced in only one direction

According to the above, faster and bigger prototypes can be built at a fraction of the price. But what are the limitations? It is the latest technique and very little information is available. The system is also very expensive, due to the use of high-power laser equipment. The same approach may be possible, using a low–powered CO_2 laser beam, which would result in a fairly inexpensive prototyping method, accessible to SMMEs or the entrepreneur [3].

1.3. Purpose and procedure of the study

The purpose of the study is to set up a system and a procedure manual to build faster, cheaper and bigger prototypes by means of CSP (cross-sectional prototyping). To achieve this, the limitations of a 30W $C0_2$ laser, an X-Y plotter and the most common software available need to be researched. This will include an analysis of material types and thickness, cutting speed and depths, as well as a suitable slicing method, to turn a 3D solid and surface model into machinable layers. From of these results, Rapid Prototyping models will be built and compared to the existing methods. A probable solution is envisaged through the use of the CSP process to solve the size, money and time problem.

Due to the fact that this is a new and own development, very little literature is available and testing will often have to rely on a trial and error approach.

CHAPTER 2

Software

2.1. Slicing software

The most difficult and unknown factor of the whole project was to find ways to slice a model by using the most commonly used CAD programs. Furthermore, ways had to be devised how to go about in the case of 2D drawings and 3D drawings. To make things even more interesting, there was the introduction of solid and surface modelling. In this chapter the slicing is divided into two main groups: 3D (solid and surface modelling) and 2D slicing.

2.1.1. 3D drawings

It is a well-known fact that businesses and designers are moving from the conventional drawing-board and 2D drawings to solid and surface modelling in CAD packages. Firstly we have to look at three possible ways of doing the slicing based on 3D drawings.

2.1.1.1. Solid modeling

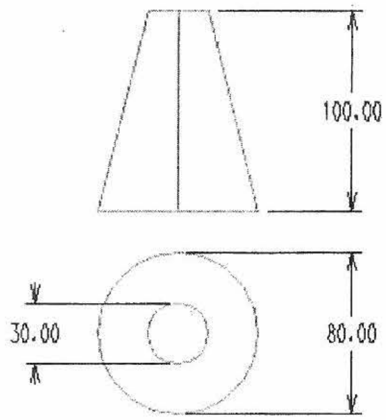


Fig. 2.1 Cone with given dimensions

To explain the principles of the different slicing methods for solid modelling, the example of a cone with given dimensions was used. (see Fig.2.1.)

The first way is by introducing a new package called Magics. Magics is mainly been used for the slicing of parts for SLA and SLS machines. The package does the slicing and rewrites the data to be available in understandable codes for the above-mentioned machines. Unfortunately only one of the tools of this powerful program is used. Together with our CAD program we discovered a very easy and quick way of slicing. A step-by-step procedure will make it easy to follow, and a short summary will follow at the end of the chapter

The Magics procedure

This procedure requires a model in *.stl* format, which means that the model has to be exported in *.stl* format from the CAD program. In this format, the model is viewed as a solid union and not as a combination of co-ordinates.

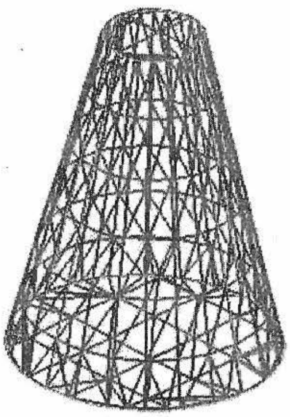


Fig. 2.2 Cone in .stl format

We use the tools in Magics to create sliced sections of the models, called sectioning. First of all one must decide in which way the slicing is to be done. In this case, it was in the Z-direction. The Z-direction is selected and the program is used to make a section drawing of the model in such a way that the operator can see exactly how the specific section looks, e.g. Fig 2.3.

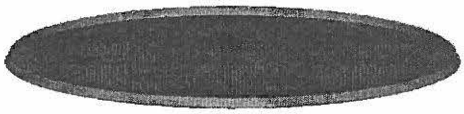


Fig. 2.3 Section drawing of cone

What happen here is that a reference point (in our model the lower left corner) is determined. A height value is given, which determines the step size to be used. The step size is equal to the material thickness. The section is made at the reference point and the section drawing is exported as an *.igs* file. This format is readable on the CAD program and the cutting can proceed from there. Every time the thickness of the material is added to the previous height and the next section is exported.

When one returns to the CAD program, all the sections are imported, and the cone will look like the drawing below.

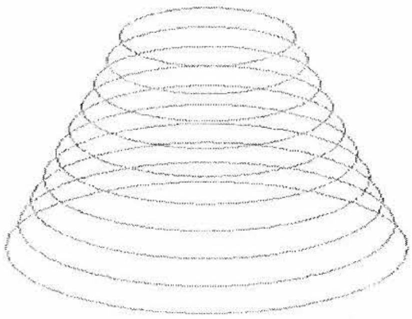


Fig. 2.4 Imported sections of the cone

For the final step, the sections are moved so that they do not intersect one another in the top view. Then the plot layout can be finalised.

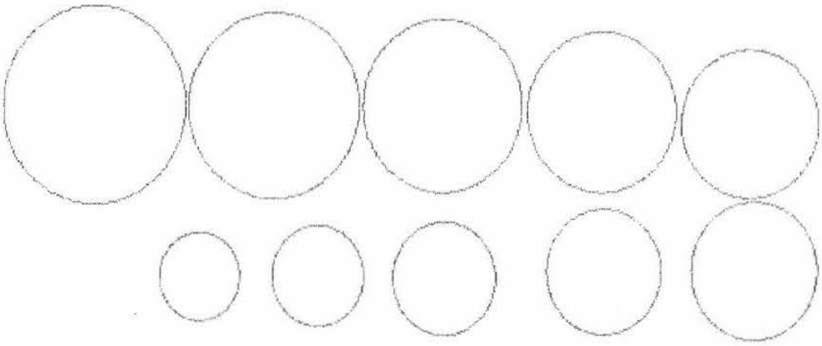


Fig. 2.5 Sorted sections in plot layout form

Advantages and disadvantages of the Magics slicing method

Advantages

1. The main advantage is that Magics has the potential to slice or section a model that is in *.stl* format.

2. Another advantage is the "hide front tool" in Magics, that gives you only the picture of the section without the remaining detail of the model.

Disadvantages

1. The only disadvantage is the introduction of a second software program that not only increases the time of the operation, but also the price thereof.

The MicroStation Sectioning method

Firstly, this method also requires a solid model and again a reference point has to be chosen, to do the sectioning from bottom to top in steps equal to the material width. To create a 2D-section, the section tools are utilised to generate a sectioned geometry of a plane that passes through a model at a calculated height. Most CAD packages include the same sectioning steps to be followed. An example from the MicroStation package is shown below.

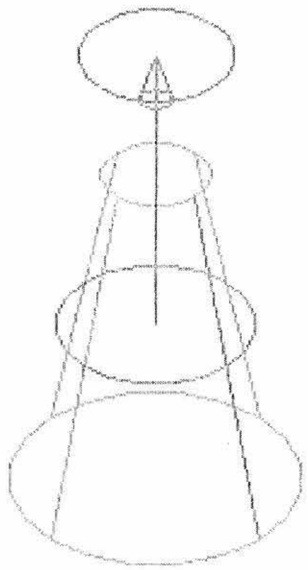


Fig. 2.6 The sectioning of a cone

1. Creating a section in MicroStation [2].

1.1. From the Utilities menu, choose Generate Section.

The Section Generation setting box opens.

1.2. Select the design file in which the section elements are to be placed by using the File menu in the Section Generation setting box. The elements are placed in the active design file by default.

1.3. Set the other settings to the desired values in the settings box. By default, the elements in the section geometry have the same level and symbology as the elements on which they are based.

1.4. Select one of the Section tools from the Tools menu in the Setting box. The tools differ only in how you define the plane on which the section is created.

Depending on the tool selected, a define plane is chosen by reference to an element, a fence, three data points, projection of an element or line string, or a plane that is perpendicular or parallel to the screen.

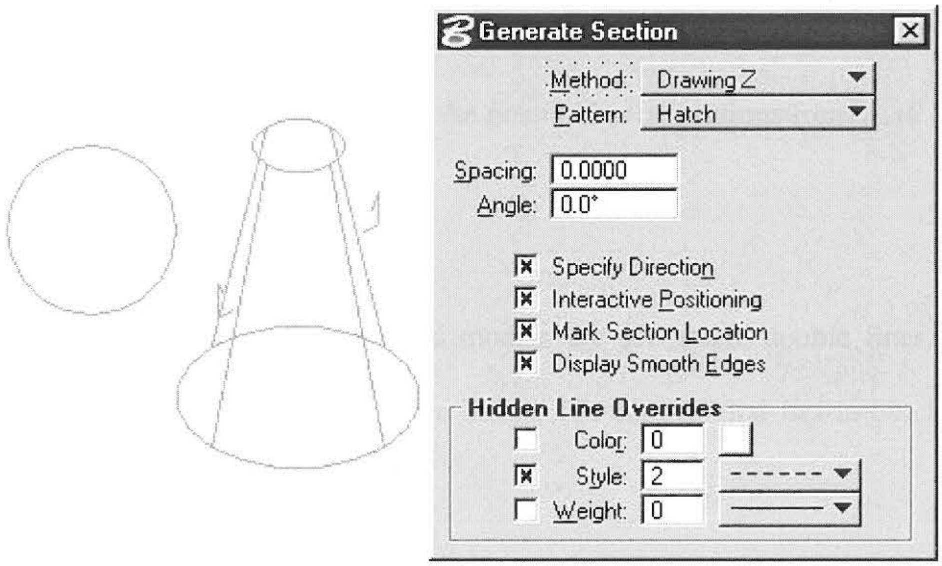


Fig. 2.7 Section tools in MicroStation

1.5. Accept the definition of the plane.

The section is generated.

1.6. Accept the section [2].

By repeating the whole process for the next section 10mm (material thickness) above the previous point, the sections are created. It is important to check that there are not two or more lines on top of each other resulting in a double cut on the laser table. For the final step, only move the sections so that they are not intersecting one another in the top view, and thus create the plot file.

Advantages and disadvantages of the Sectioning method

Advantages

1. The main advantage is that only one program is needed to cut or section a model. This not only saves time, but also machine costs.
2. MicroStation, as well as Magics, has the potential to do sections from a *.stl* file.

Disadvantages

1. Sometimes, when more complicated models are sectioned, double lines occur. This results in a double cut from the laser. The section first has to be checked before cutting.

The Boolean method

When talking about the Boolean method, it implies that one tries to produce a manual way to do the slicing. The idea is to construct an intersection between the model and a block consisting of layers of the same height as the material to be cut. This process is commonly seen as the first process of slicing. Unfortunately it is difficult and time-consuming. By constructing an intersection between the two, a model is created that is cut into parts with the height equivalent to the layers of material used. Each part can thus be moved away from each other and the top view can be plotted.

1. Creating a Boolean

1.1. Construct intersection.

This method is used to unite two or more solids. This means that a block is created which represents the layers of material and which is united with the cone.

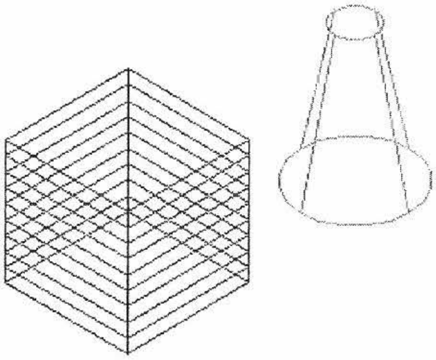


Fig. 2.8 Layers of materials to form a union with the cone

1.2. Setting: Keep the Original (First).

Only the cone will remain with the intersections of the second block. This means the model is joined with the blocks made up of layers.

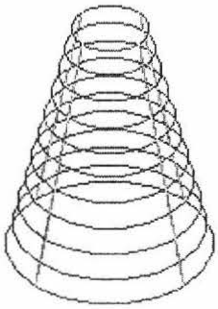


Fig. 2.9 The intersected union

By using an intersection, the cone is sliced up and the pieces are moved so as not to intersect.

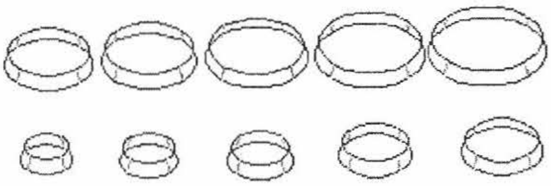


Fig. 2.10 Sliced view of layers

1.3. Delete the inner circle.

This means that each component will show an inner and an outer circle when looking from the top. The inner circle will be the same as the outer circle of the next layer. By deleting the inner circle of every layer and plotting the outer circle, the model is produced.

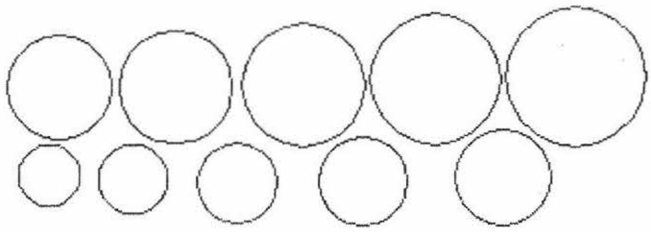


Fig. 2.11 Plot layout of cone (inner circles deleted)

Advantages and disadvantages of the Boolean method

Advantages

1. The only advantage is that only one program is needed to cut or section a model.

Disadvantages

1. Not for the use of *.stl* files.
2. It is a very time-consuming process and there is always a possibility of error.

2.1.1.2. Surface modeling

When a model consists of surfaces, one has two choices. The one is to export it into a *.stl* file format and to do the slicing by the MicroStation Sectioning and Magics methods. The second more difficult one is to convert a surface model into a solid model.

Export in *.stl* format

The method is by far the quickest and very few problems have occurred. The first and only step will be to export the model in a *.stl* format. Just click on the export *.stl* format tool and accept the changes. Now a model in *.stl* format is created and the slicing can be done by means of the MicroStation Sectioning or Magics method.

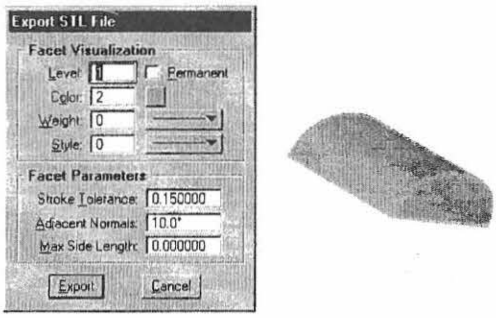


Fig. 2.12 Exporting as a .stl file

Advantages and disadvantages of the Export in *.stl* format method

Advantages

1.The advantage is that one can use two of the three slicing methods to do the slicing.

Disadvantages

1. The Boolean slicing method cannot be used.

Surface-to-solid modeling

Stitch Surfaces

This process only works with very simple models. When the model becomes too complicated, some errors occur. But it is still a possibility and can be used.

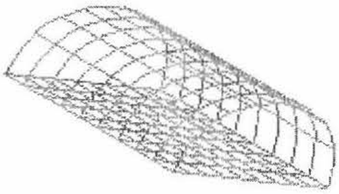


Fig. 2.13 Surface model (non-stitched)

CAD packages such as MicroStation have tools that convert surfaces to solids, but for this process the model has to be in the correct format. The surfaces have to be stitched to each other. This means that the function, Modeller Stitch Surfaces, is used to stitch sheets together along their common edges to form a new surface. If the identified surfaces enclose a valid volume, stitching all of them together produces a solid with a positive volume. The normal surface direction of the second identified surface is checked against the direction of the first surface. If it is not in a similar direction, the normal direction of the second surface is automatically changed to match that of the first surface. An internal default tolerance is used to determine whether the two edges are close enough to be stitched. If the gap is bigger than this default tolerance, the surfaces are not stitched together.

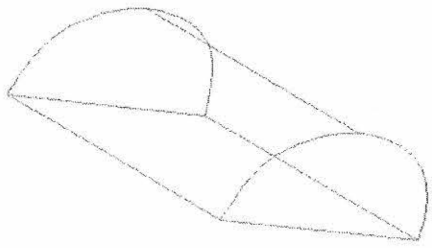


Fig. 2.14 Surface model (stitched)

Construct Capped Solid

Used to create a solid by adding caps to existing sheets. For example, after stitching a set of surfaces, the resulting sheet may have openings at both ends. This tool is used to directly change it to a true solid by adding planar caps. If non-planar caps are desired, more stitching operations should be applied rather than adding caps. This tool determines the right normal directions for the caps it adds to the existing sheet. The caps added to the existing sheet become integral parts of the original sheet. They are linked by means of topological information with the original sheets.

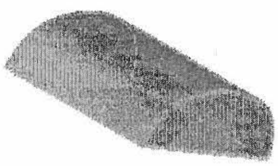


Fig. 2.15 Capped solid of a model

2.1.2. 2D-Drawings

In two-dimensional drawings one is limited with regard to the type of model that can be built. No slicing is possible. The only way out is to draw the drawing in 3D or to plot out all the side views and stick them together. This method only works if the model has flat walls. In this way, model houses can easily be built by means of 2D drawings. For example, if one has a drawing of a townhouse, it is easy just to plot out the front, back, left, right and top view. No slicing or 3D drawing is necessary.

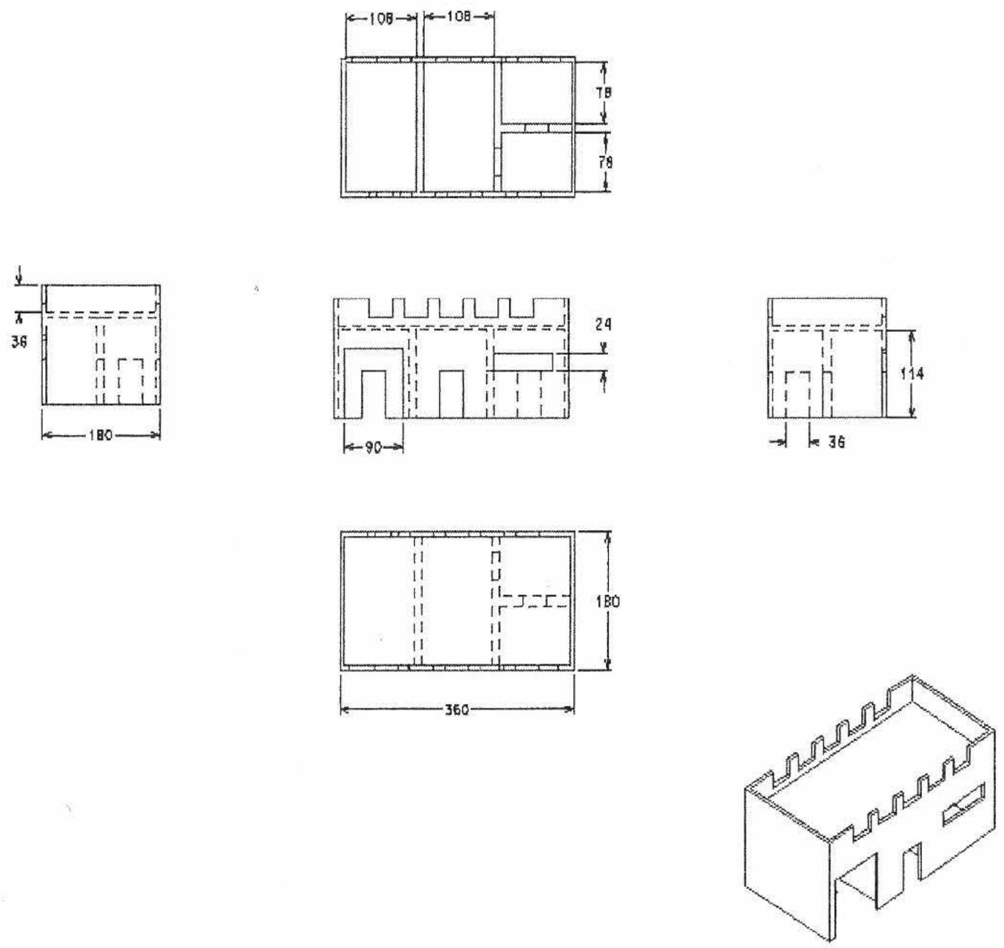


Fig. 2.16 Side views of a townhouse

2.2. Plotter Software

The file format in the cutting process is just as important as the slicing of the models. The program receiving the information is EngraveLab. EngraveLab is a program normally used by engravers. (More about this software later.) The program translates the file and stores it as a *.cdl* file. The data is then plotted out to a file in *.plt* format. The next program, Nu-tel that is directly linked to the plotter, translates the *.plt* file into usable data for the plotter.

2.2.1. EngraveLab

As mentioned, EngraveLab is the first program, receiving all the sliced sections of the model. The program needs the files in *.cdl* formats. The other way is to import a file into EngraveLab. The import command is used to open files in formats other than *.cdl* file format. Files formats that can be imported are the following:

>. AI	> .BMP	> .CDL	> .CMF
>. DC2	> .DCX	> .DIB	> .DWG
>. DXF	> .EPS	> .GC1	> .GIF
>. IMG	> .JPG	> .PCX	> .PCD
>. PLT	> .PRN	> .TGA	> .THZ
>. TIF	> .VE	> Wissen .PLT	> WMF
>. WPG			

It is important to realise that even if one can import a section into EngraveLab, the plotter program (Nu-tel) can only translate HPGL file formats. This means that one can import any section into EngraveLab, but not all of them are going to work. The only acceptable format when saving a sectioned file in the CAD program, is as a *.plt* file. This is done when plotted to a file on the correct HPGL driver.

After receiving the information, all the sections can be edited in EngraveLab. The most commonly used tools are scaling and start sequence tools.

Start Sequence

This option allows the operator to manually specify the order in which a given number of objects will either be drawn on screen, cut, plotted, routed or engraved. The objects will then be cut starting from the first selected object to the last. It is important to start cutting from the inside out. If a series of objects are re-ordered, but not all of the objects in a file, the re-ordered objects will be placed (and therefore drawn, plotted, cut, etc.) beginning at the same place in the order as the first object that was selected [11].

Size

The Size option allows the operator to re-size the selected object to any dimensions without affecting the size of other objects on the screen. Select Size from the Layout menu to access the dialog box. From within the dialog, one can change the size of the selected objects by editing the X- and Y- values, which represent the size of the object. Clicking on the checkmark will force the selected object(s) to the specified dimensions, while clicking on the X-button will close the Size dialog box and return to the main view screen.

The final layout is then plotted to a file in the next program. The file is generated when the plot function is used. The drawing is selected and sent as a *.plt* file from Engravelab.

2.2.2. Nu-tel

This is the last program in the software sequence. The Nu-tel program is directly linked to the plotter and controls the final outcome. There are a few steps that have to be taken:

1. Translate the HPGL plots file sent from EngraveLab. Step one wil be to translate the *.plt* file into understandable data for the plotter.

1. Specify pen information.

Table 2.1 Pen specification table

Number of passes	1
Depth increment	0
XY cutting speed	10
Z cutting speed	10
Reverse engrave	0
Home between pens	0

Number of passes: To achieve the smoothest finishing we only cut once.

Depth increment: Will be zero because of only one rotation.

XY cutting speed:	Choose the speed that's the best for the used material.
Z cutting speed:	Work at 10mm/sec
Reverse engrave:	No
Home between pens:	No, only one pen used.
F10	When finished, a time estimate will be given at the end.

3. Jog/test utility

This will be the final step. The desired file is opened and run through. It is important to set the "spacer thickness", that is the height at which the plotter will start cutting. The "spacer thickness" is influenced by the focus distance of the laser beam and can be set by adjusting the Z-axis arm of the gantry.

CHAPTER 3

Experimental setup

Fig. 3.1 Photo taken of the X-Y plotter with the support table

3.1.The X-Y Gantry System

The plotter is the center stage of this project. This means that the features of the plotter have a big influence on whether this project is going to be a success. The plotter had to have a big enough worktable to cut the desired sizes. It also had to have such a body that the laser beam could follow the movements easily and that the laser light could remain perpendicular to the surface of the table.

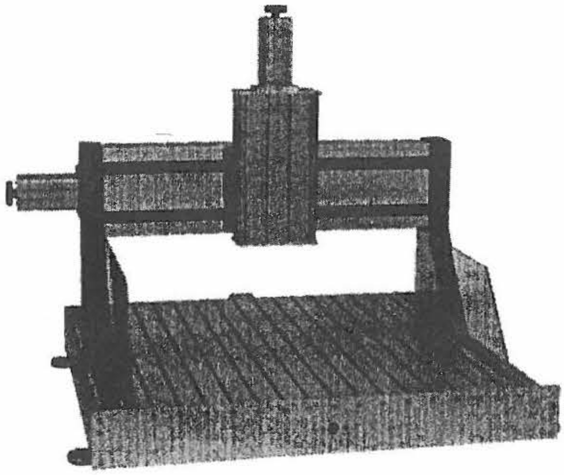


Fig. 3.2 Photo of X-Y table

3.1.1. Features of the X-Y table:

The X-Y table has the following features:

- A moving gantry that provides large stationary work surface.
- All axes are provided with home reference switch and far end limit switch with 0.01mm repeatability.
- The Y-axis is provided with aluminum dust cover and Teflon lip seals to ensure protection against contaminants.
- X-axis bearings and drive screw that are mounted beneath the work surface to protect them from dust and debris.
- Two patented double linear rails and four patented double bearing blocks on each axis.
- A 125 oz-in stepper motor.
- A standard anti-backlash ball screw and nut, 16mm in diameter with 5mm pitch.
- Heavy cast aluminum side plates that support the Y-axis and provide increased stiffness for cutting and positioning applications.

- The standard clearance under the gantry is 200mm.
- A work surface that is constructed of flat milled 30mm x 250mm aluminum table plates [27].

3.1.2. Specifications

Table 3.1. X-Y gantry specifications

Characteristic	Specification
Repeatability	0,01mm
Accuracy	0,1 mm / 300 mm
Max. Z Axis Load	22,7 kg
Motor Drives	Stepper
No Load Speed	127 mm/sec
Thrust Force at Low Speed	91 kg
Resolution	0,0125 mm

3.1.3. Technical data

Table 3.2. X-Y gantry technical data

Model	Table Size		Travel	
	mm	(in)	mm	(in)
054	1100 x 750	(53.1 x 29.5)	1000 x 540	(39,3 x 21,1)

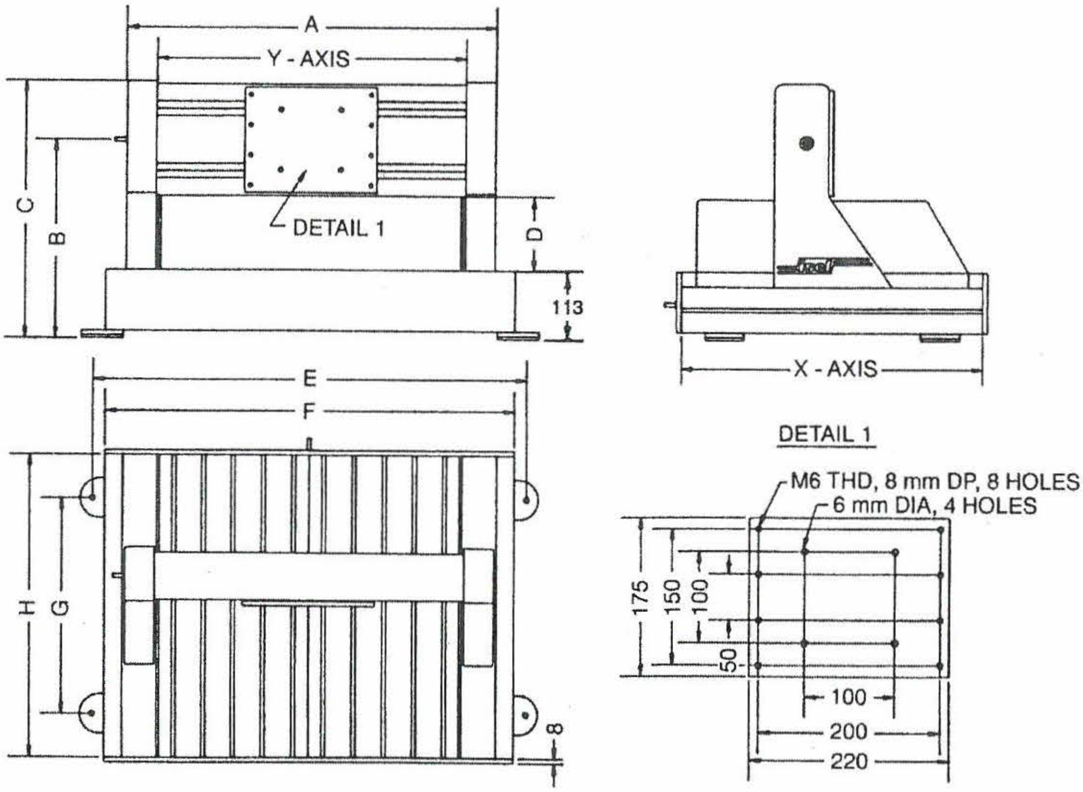


Fig. 3.3 Dimension layout of X-Y table

Table 3.3. Dimensions of the X-Y gantry

Model	Travel mm		A	B	C	D	E	F	G	H
	X	Y	mm	mm	mm	mm	mm	mm	mm	mm
054	1000	540	870	393	490	190	1119	1074	1185	1350

3.2. The Z –Axis slide for gantry

The Z-axis slide of the gantry plays a big role in the continuity of a plot layout and in the focussing of the beam. The slide only moves in the vertical direction, which makes it possible to place an on-off switch for the laser power at a certain height that will ensure cutting only when necessary. To focus the beam, the slide can be moved up or down to achieve the optimum focussing height, which is essential because different material thicknesses are used.

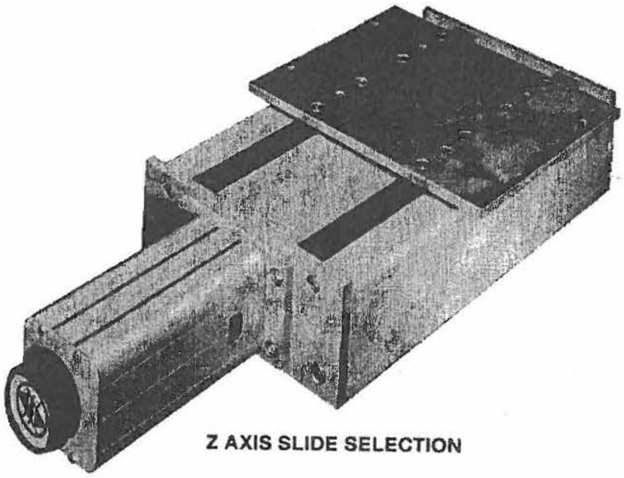


Fig. 3.4 Z-axis slide

3.2.1. Z-axis slide

The Z-axis slide features the following:

- Four T-slots on 50mm centres to mount tooling.
- A home reference switch and far end limit switch with 0,01mm repeatability.
- An aluminum dust cover and Teflon lip seals to provide protection against contaminants.
- A 125 oz-in stepper motor.

- Two patented double linear rails and four patented double bearing blocks.
- A standard anti-backlash ball screw and nut, 16mm diameter with 5mm pitch.
- Slide-to-slide mounting surfaces of flat milled aluminum 220 x 175 x 8 mm with 4 holes counterbored for M6 cap screws.
- A self-locking magnetic brake to maintain carriage position when power to the motor is turned off or interrupted. 200mA, 24V DC is required to disengage brake [27].

3.2.2. Specifications

Table 3.4. Specifications of Z-axis slide for gantry

Characteristic	Specification
Repeatability	0,01mm
Accuracy	0.1 mm / 300 mm
Max. Z Axis Load	22,5 kg
Motor Drives	Stepper
No Load Speed	127 mm/sec
Thrust Force at Low Speed	91 kg
Resolution	0,0125 mm

3.1.3. Technical data

Table 3.5. Technical data of Z-axis slide for gantry

Model	Motor	Travel		Weight		Length	
		Mm	(in)	Kg	(lb)	Mm	(in)
HL31SBM512040005	Stepper	175	(6,8)	11,3	(25)	400	(15,7)

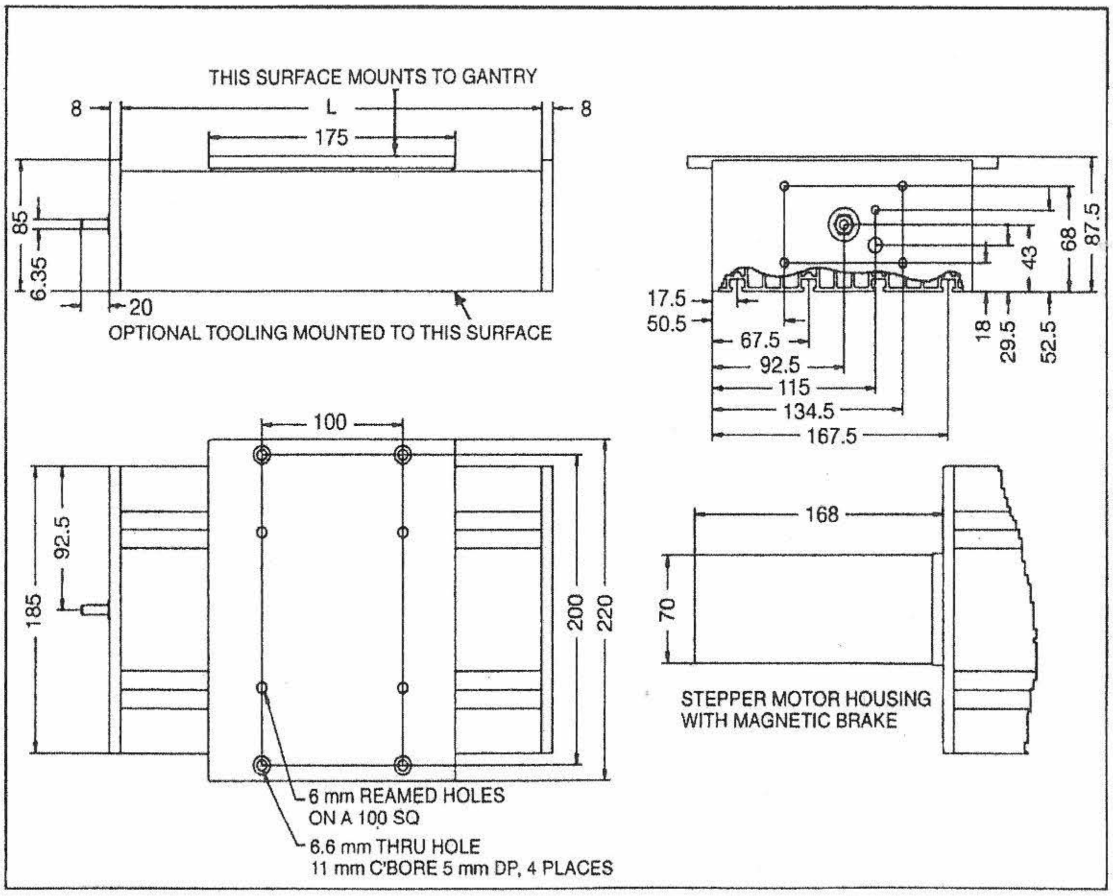


Fig. 3.5 Dimension layout of Z-axis slide for gantry

3.3. The CO_2 laser

This is without any doubt the most important feature in the sequence. The 30W CO_2 laser produces a laser beam that is perfect for this purpose.

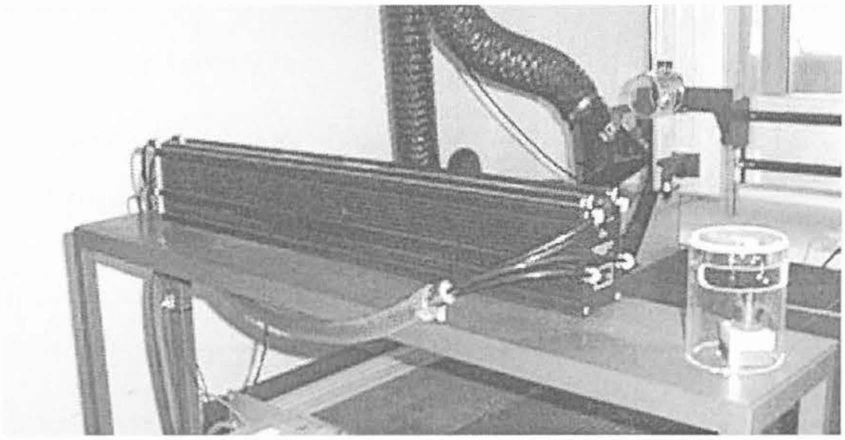


Fig. 3.6 Photo of the 30W CO_2 laser

3.3.1. Technical Specifications [26]

Table 3.6. Technical specifications on the 30W CO_2 laser

Characteristic	**Model (648-2 28W)**
Wavelength	10,57 to 10,63 microns
Power Output	30W
Power Stability	5%
Mode Quantity	TEM_{00} equivalent: 95% purity
Beam Diameter/Divergence	3,5mm/4mR
Modulation/Rise or Fall time	To 5kHz/150μsec
Electrical Control	TTL input (+3,5 V) to 20 kHz
Electrical Input	28-32 VDC, 21A max.

Table 3.6. Technical specifications on the 30W CO_2 laser (Cont'd)

Characteristic	Model (648-2 28W)
Cooling water Flow rate Temperature	 3,75 L/min 18 – 20 °C
Thermal Shutdown	60^0C ± $1,5^0$C
Beam exit	28mm from top plate
Dimensions (W x H x L)	71 mm x 99 mm x 813 mm

3.4. The Cooler

According to the specifications the laser must be water cooled with a flow rate of 3,75L/min at 18°C - 20°C. The cost of a commercial chiller was considered too high and a home made one was built. The cooler consists of a car radiator with its fan for the cooling, a centrifugal pump to produce the desired flow rate and a reservoir with the connecting pipes.

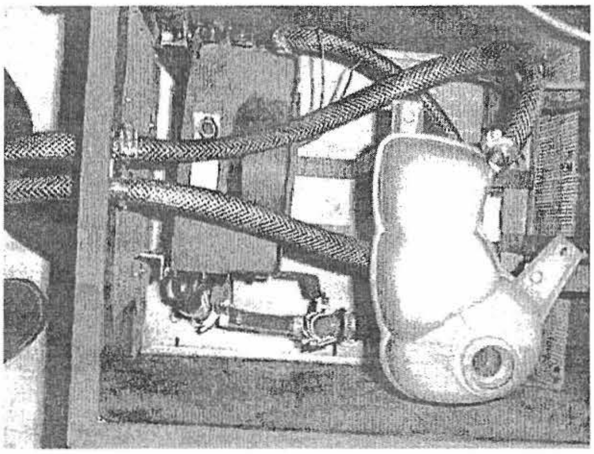


Fig. 3.7 Photo of the cooler consisting of a radiator and fan, reservoir and pump.

By connecting a reservoir to the inlet of the pump and the outlet to the laser and back to the reservoir a close-circuit continuous cycle of running water was created. By increasing the speed of the cooling fan connected to the radiator, a good cooling unit was prodused.

The cooling fan: As an adjustable DC supply is used, the current to the fan can be changed, thereby increasing or decreasing the performance of the radiator. The table below shows the results of the test.

Table 3.7. Cooling system testing data

Flow rate	Temp. in	Running Time	Temp.out	Δ Temperature	Amps.
3,75 L/min	18,7 °C	10 min	20,5 °C	1,8 °C	0 A
3,75 L/min	17,4 °C	10 min	19,5 °C	2,1 °C	1 A
3,75 L/min	18,7 °C	10 min	19,9 °C	1,2 °C	2,1 A
3,75 L/min	18,5 °C	10 min	19,8 °C	1,3 °C	3 A
3,75 L/min	18,1 °C	10 min	18,4 °C	0,3 °C	4 A
3,75 L/min	18,0 °C	10 min	18,7 °C	0,7 °C	5 A

The flow rate required is ±3,75 L/min, and temperature in is the temperature of the water at the start and temperature out is the temperature after running for the 10min. According to these results, a 5 Amp DC supply can be used.

3.4. The controller

The purpose of the controller is firstly to convert the co-ordinates from the computer software used, into understandable data for the X-Y gantry and Z-axis slide. These data must then be sent to the stepper motors, controlling the gantry and its slide. The ISEL stepper motor controller C116-4 is a complete unit, which is able to control up to three stepper motors. If the ISEL C 116-4 is used, linked to efficient user software, the dimensional positioning of the connected driver axes is made possible. Furthermore, a circular-interpolation with a constant track speed is supported. For this purpose the controller has a processor card with an eight-bit micro-controller and three performance levels with an output performance of 44 V/ 3,5 A each.

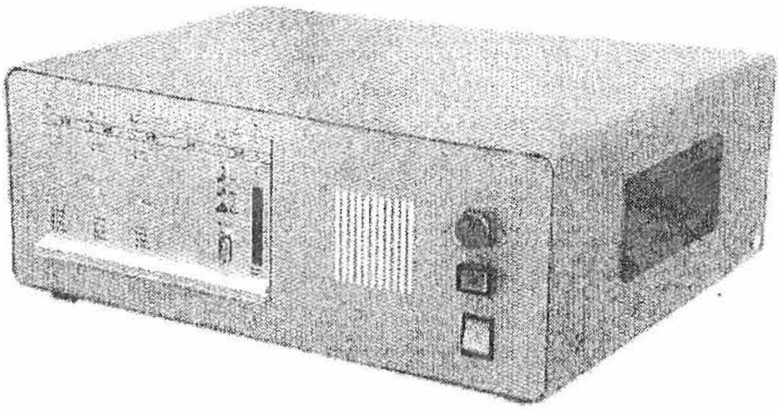


Fig. 3.8 Isel - Stepmotor – controller C116-4

Besides step calculations and impulse output at the end levels, the operation system of the processor card (Interface card UI 4C E/A) also supports the monitoring of the end location switch inside the numerical driver axes. This makes it possible to programme the card in CNC- as well as in DNC-mode. The transferred (given) data can then either be moved directly or saved in a 32-KB static RAM. By using an optical ACCU, it is possible to maintain data in RAM even after a power failure. The interface card supports the use of an exchangeable check card server (memory card 32 KB)

Connected to a steering calculator, the interface card has a serial cutting position according to RS 232. Besides pure positioning commands, the processor card makes it possible to work on eight opto-isolated signal inputs (+24 V), as well as 16 relay switch outputs (30 V/ 300 mA). The back of the controller has screw clamps where the corresponding signals can be connected. An optional DC net part (+24 V/ 2,6 A) can be built in and enables the C 166-4 to directly connect sensors, valves, etc., without additional external power supply. Three-step motor performance cards, UMS 3,5, are built into the C116-4 as performance levels. These bipolar end levels for two four-phase stepper motors have D-MOS end levels that can function with a 44 V DC power supply with a maximum of 3,5 A. The power supply of the controller replaces the power block PB 450 C, which is certified VDE 0160.

Technical specifications:

- CASING
    - System carrier: steel-metal casing; W = 475 × H = 155 × D = 410 mm.
    - In powder-coated aluminium half shell casting (anthracite).
    - 19 inch built-in casting (DIN 41494), 4HE (optional)

- ISEL INTERFACE CARD UI 4.C E/A
    - Eight-bit micro-controller with step motor operating system.
    - 2,5 dimensional linear/ circular interpolation.
    - Positioning speed maximum 10 000 steps/sec.
    - 32KB data memory (ACCU for data protection optional).
    - Eight opto-isolated signal inputs and 16 relay switch outputs ready for a check card memory 32 KB.
    - Serial cutting position according to RS 232

- ISEL STEP MOTOR PERFORMANCE CARD UMS 3,5
    - Bipolar performance and level for two four-phase stepper motors.
    - Constant power control / regulation with 18 kHz chopper frequency.
    - Phase current maximum 3,5 A short circuit proof.
    - Operational current 44 V, DC.

- ISEL POWER BLOCK
    - 450 V –Ring centre transformer with temperature monitor and electronic "switch on" current restriction.
    - Auxiliary current II +24 V/A (internal, for security circuit).
    - Security circuit according to EN 292 with emergency "on" and "off" keyboard entrance.
    - Integration of external security elements closed steel metal casing.
    - Contact through sub-D socket connector

- $W = 150 \times H = 140 \times D = 220$ mm
- Certification according to EN 50178 (VDE 160) in agreement with EN 55011 (VDE 0875 B)

- DC NET PART NT-24 (OPTIONAL , ART NR 301040)
  - Closed built-in net part with ring centre transformer.
  - Output performance +24 V /2,6 A, stabilised [14].

3.6. The Support table

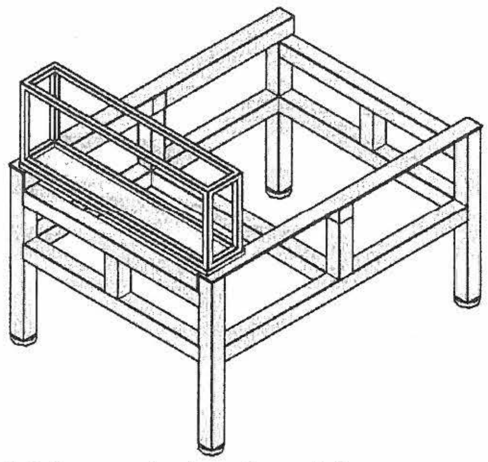


Fig. 3.9 Isometric drawing of the support table

A support table had to be built, that provided a good and solid foundation to work from. The table had to be stable enough to prevent any unnecessary vibration on the workpiece. Therefore the table was built as heavy as possible within practical limits. It was mainly manufactured from 75mm x 75mm square tubing and 80mm angle iron. Special antivibrating rubber feet (Vibrex) were fitted to reduce vibration. The dimensions of the Support table are shown in Fig. 3.10.

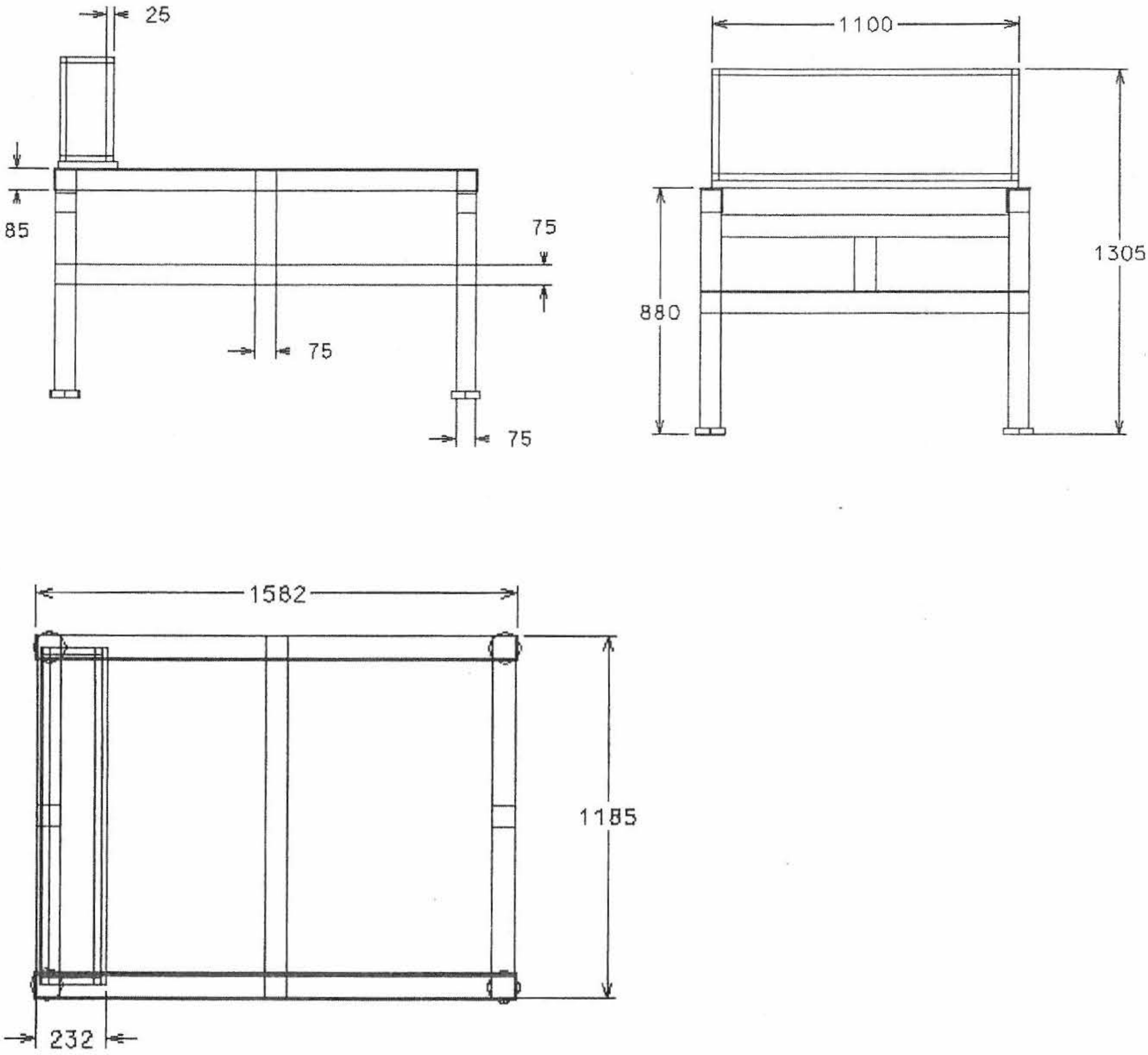


Fig. 3.10 Dimension drawing of support table (first angle)

3.7. Air purifier

The purpose of the air purifier was to extract the solid waste from the fumes generated during the cutting of the materials. The nozzle is placed as near as possible to the focus point where the cutting takes place. This is a unit that sucks and filters all the fumes while cutting. The Nederman electrostatic filter comprises a mechanical filter for coarse particles and two electrostatic cells in series capable of trapping electrically loaded particles or droplets.

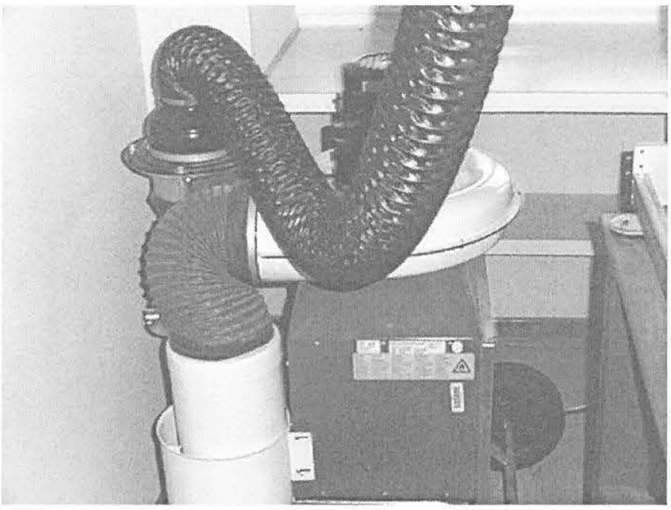


Fig. 3.11 Photo of (Nederman) Electrostatic filter

Self-contained mobile unit. Mounted on a trolley complete with fume extractor and fan, the electrostatic filter can capture welding fumes, metal dust etc. wherever and whenever required. Filtered air is vented directly from the fan outlet, without any permanent exhaust ducts, reducing the cost of space heating.

Washable filters. An advanced filter indicator gives audible and visible warning when the electrostatic cells are fully loaded. They can then be removed and washed with an aluminum-compatible detergent.

3.7.1. Specifications and technical data

Table 3.8. Technical specifications of the Air purifier [21]

Model Art.No	Filter (W)	Fan (W)	Power supply V	Capacity m^3/h	Weight kg	Dimensions HxLxW mm
612162	45	750	230	850	71	995x800x755

CHAPTER 4

Laser operation and applications

4.1. Introduction

The word *laser* is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser makes use of processes that increase or amplify light signals after those signals have been generated by other means. These processes include (1) stimulated emission, a natural effect that was deduced by considerations relating to thermodynamic equilibrium, and (2) optical feedback (present in most lasers) that is usually provided by mirrors. Thus, in its simplest form, a laser consists of a gain or amplifying medium (where stimulated emission occurs), and a set of mirrors to feed the light back into the amplifier for continued growth of the developing beam. A laser is a device that amplifies light and produces a highly directional, high-intensity beam that most often has a very pure frequency or wavelength. It comes in sizes ranging from approximately one tenth the diameter of a human hair to the size of a very large building, in powers ranging from 10^{-9} to 10^{20} W, and in wavelengths ranging from the microwave to the soft-X-ray spectral regions with corresponding frequencies from 10^{11} to 10^{17} Hz. Lasers have pulse energies as high as 10^{4} J and pulse duration as short as $6x10^{-15}$ seconds [1].

- Lasers can easily drill holes in the most durable of materials and can weld detached retinas within the human eye.
- Lasers are a key component of some of the most modern communication systems and are the "phonograph needle" of compact disc players.

- Lasers can perform heat treatment of high-strength materials, such as the pistons of automobile engines, and provide a special surgical knife for many types of medical procedures.
- They act as target designators for military weapons and provide for the rapid checkout expected at the supermarkets [25].

4.2. Definitions and description of a laser

From a practical standpoint, a laser can be considered as a source of a narrow beam of monochromatic, coherent light in the visible, infrared or ultraviolet parts of the spectrum. The power in a continuous beam can range from a fraction of a milliwatt to around 25 kilowatts (kW) in commercial lasers, and up to more than a megawatt in special military lasers. Pulsed lasers can deliver much higher peak power during a pulse, although the power average over intervals, while the laser is off and on, can be comparable to that of continuous lasers [28].

There is a broad range of laser devices. The laser medium, or material emitting the laser beam, can be a gas, liquid, glass, crystalline solid or semiconductor crystal and can range in size from a grain of salt to filling the inside of a moderately sized building. Not every laser produces a narrow beam of monochromatic, coherent light. Semiconductor diode lasers, for example, produce beams that spread out over an angle of 20^{o} to 40^{o}, hardly a pencil-thin beam. Liquid dye lasers emit a band with a narrow range of wavelengths, depending on the optics used with them. Other types emit a number of spectral lines, producing light that is neither truly monochromatic nor coherent.

Practically speaking, lasers contain three key elements. One is the laser medium itself, which generates the laser light. A second is the power supply, which delivers energy to the laser medium in the form needed to excite it to emit light. The third is the optical cavity or *resonator*, which concentrates the light to stimulate the emission of laser radiation. All three elements can be in various forms, and although they are not always immediately evident in all types of lasers, their function is essential.

There are several general characteristics that are common to most lasers which new users may not expect. Like most other light sources, lasers are inefficient in converting input energy into light. Efficiency ranges from under 0,01 to over 30 percent, but few types are much above 1 percent efficient. These low efficiencies can lead to special cooling requirements and duty-cycle limitations, particularly for high-power lasers. Operating characteristics of individual lasers depend strongly on structural components such as cavity optics, and in many cases a wide range is possible. Packing can also have a strong impact on laser characteristics and the use of lasers for certain applications [13].

4.3. Commercial Lasers.

There is a big difference between the world of laser research and the world of the commercial laser industry. Unfortunately, many text and reference books fail to differentiate between types of lasers that can be built in the laboratory and those which are readily available commercially. That distinction is a crucial one for laser users. Laser emission has been obtained from hundreds of materials at many thousands of emission lines in laboratories around the world. However, most of these laser lines are of purely academic interest. Many are weak lines close to much stronger lines, which dominate the emission in practical lasers. Most of the lasers that have been demonstrated in the laboratory have proved to be cumbersome to operate, low in power, inefficient, and/or simply less practical to use than other types.

Only a couple of dozen types of lasers have proved to be commercially viable on any significant scale. Some of these types, notably the ruby and helium-neon lasers, have been around since the beginning of the laser era. Others, such as vibronic solid-state, are promising newcomers. The family of commercial lasers is expanding slowly, as new types such as titanium-sapphire come on the market, but with the economics of production a factor to be considered, the number of commercially viable lasers will always be limited.

There are many possible reasons why certain lasers do not find their way onto the market. Some require exotic operating conditions or laser media, such as high temperatures or highly reactive metal vapors. Some emit only feeble powers. Others have only limited applications, particularly lasers emitting low powers in the far-infrared, or in parts of the infrared where the atmosphere is opaque. And some simply cannot compete with materials already on the market. For our purposes, gaseous (low-density) gain media are used in all our applications. In the table below a summary of the lasers that are commercially available, can be seen.

Table 4.1. Summary on laser specifications [13]

Laser type	Wave length (λ)	Power output
Helium Neon	632,8nm – 543,5nm	0,5 – 100mW
Argon Ion	488nm – 514,5nm	100mW – 50W
Helium - Cadmium	441,6nm; 353,6nm; 325nm	10 – 200mW
Copper Vapour	510,5nm – 578,2nm	1MW/pulse, 20kHz rep.rate
Carbon Dioxide	10,6μm – 9,4μm	1 – 10,000 W
Excimer	XeF, 351nm; XeCl, 308nm; KrF, 248nm; ArF, 193nm	1J/pulse at 100Hz = 100W
Nitrogen	337,1nm	250kW – 1MW
Far - Infrared	28 transitions, ranging from 99 to 373 μm	1kW (pulsed), and up to 100MW (cw)
X-ray	3,56 – 46,9μm	1 – 2MW
Free - Electron	248nm – 8mm	1GW (pulsed), up to 10W (cw)

Over 25 million semiconductor diode lasers were sold in 1990, representing 98 percent of the total number of lasers. However, diode lasers accounted for less than 30 percent of the dollar volume of sales. Conversely, some 4000 carbon dioxide gas lasers accounted for 21 percent of 1990 laser sale's dollars. The two largest laser makers, Spectra-Physics and Coherent Inc., for many years concentrated on gas and dye lasers, but both now offer broader product lines. Both are nominally based in the United States [13].

4.4. Laser safety

For the uninitiated, the thought of working with lasers means wearing dark goggles, heavy gloves and extra protecting overcoats. On the contrary, the kinds of lasers available to the electronics hobbyist are so low in power that protective measures are practically unnecessary. The light radiation emitted by a helium-neon laser is not even strong enough to be felt on the skin.

Of course precautions must still be taken, but for the most part, experimenting with lasers can be done in the comfort of the family living room. This doesn't mean hobby lasers are completely harmless. As with all electrical devices, some dangers exist, and it is vitally important that these dangers are understood and the user knows how to avoid them [13]. Lasers that are sold and used commercially, are subject to compliance with a strict set of laws enforced by the Centre for Devices and Radiological Health (CDRH, formerly the Bureau of Radiological Health, or BRH). The CDRH, a department of the Food and Drug Administration, serves a similar purpose as the Federal Communications Commission namely to ensure that these products comply with recognised standards and that the dangers of laser radiation are kept to a minimum.

For regulatory purposes, the CDRH has divided lasers into six groups, or classes. The classification of lasers depends on their power output (in joules or watts), their emission duration, and their wavelength. The classification is then affixed as a sticker to the laser. We work with a class four laser.

- Class IV represents the "laser brutes." In these devices, the limits of the other classes are exceeded. The CDRH classifies a laser as a Class IV device if it produces light radiation (visible or invisible) that is dangerous to eyes and flesh whether or not the beam is direct, reflected, or diffused. $C0_2$, ruby, Nd: glass, and multi-watt gas lasers (such as 3-to 5-watt argon) fall within the Class IV classification.

Laser safety has been controversial since lasers began appearing in laboratories. The two major concerns are exposure to the beam (which presents much more danger to the eyes than to the rest of the body) and high voltages within the laser and power supply. Many standards have been developed covering either the performance of laser equipment or the safe use of lasers. Some developed by government agencies have legal status, while others are recommended by voluntary organisations [16].

High-power laser beams can burn the skin, but the most important hazards of laser beams are to the eyes, which are the part of the body most sensitive to light. Like sunlight, laser light arrives in parallel rays, which the eye focuses to a point on the retina, the layer of cells that responds to light. Just as staring at the sun can damage vision, exposure to a laser beam of sufficient power can cause permanent eye damage. Eye hazards have attracted considerable attention from standards writers and regulators. They depend on parameters such as laser wavelength, average power over a long interval, peak power in a pulse, beam intensity, and distance from the laser. Wavelength is important because only certain wavelengths (those between about 0,4 and 1,5 micrometers (μm)) can penetrate the eye well enough to damage the retina.

Ultraviolet light can damage surface layers of the eye (and some can penetrate to the retina, especially in people whose natural ocular lens has been removed). Infrared light also can damage the surface of the eye, although the damage threshold is higher than that for ultraviolet light. Eye response also differs within the range that penetrates the eyeball, because the eye has a natural aversion response, which makes it turn away from a bright visible light which is not triggered by infrared wavelengths longer than 0,7 μm.

People working where they cannot avoid exposure to laser beams that pose eye hazards, should wear safety glasses or goggles. Special filters in the safety goggles block light at certain laser wavelengths, while transmitting enough other light to enable the worker to see. The proper goggles should be used for work with each type of laser. It does no good to block the blue-green light from an argon laser when working with a red helium-neon laser. Users can select general-purpose goggles that fit over the eyes and spectacles, or can have prescription spectacles made from laser blocking filter glasses. Goggles should block all possible paths for laser light to reach the eye, because hazardous pulses can be reflected from any shiny surface and arrive from unexpected angles.

Much of the laser components available on the surplus market do not comply with CDRH standards, although a few do. If they are in compliance, they will display a sticker, affixed somewhere on the device. Note that individual components may not in themselves comply with the CDRH regulations, even though the device from which they were taken, meets the standards.

Most of the CDRH regulations pertain to such simple functions as:

- Placing the proper sticker(s) on the device.
- Covering the power supply during operation.
- Providing a power supply interlock that shuts the supply off if the case is opened.
- Inserting a key switch in the power supply mains to prevent unauthorised use.
- Adding a cover or slide to the output mirror to prevent accidental exposure to the beam when the laser is operating.
- Providing adequate instructions for the user. In all cases, user information and basic service information are required.

4.5. The carbon dioxide laser

4.5.1. Operation

The carbon dioxide laser is one of the most versatile types on the market today. It emits infrared radiation between 9 and 11 micrometers (μm), either at a single line selected by the user or on the strongest lines in untuned cavities. It can produce continuous output powers ranging from well under 1 watt (W) for scientific applications to many kilowatts for materials working. It can generate pulses from the nanosecond to millisecond regimes. Custom-made $C0_2$ lasers have produced continuous beams of hundreds of kilowatts for military laser weapon research or nanosecond-long pulses of 40 kilojoules (kJ) for research in laser-induced nuclear fusion.

This versatility comes from the fact that there are several distinct types of carbon dioxide lasers. While they share the same active medium, they have important differences in internal structure and, more important to the user, in functional characteristics. In theory, the structural variations could range over a nearly continuous spectrum, but manufacturers have settled on a few standard configurations, which meet most user needs. Thus users see several distinct types, such as waveguide, low-power sealed-tube, high-power flowing-gas, and pulsed transversely excited $C0_2$ lasers [29].

The active medium in a $C0_2$ laser is a mixture of carbon dioxide, nitrogen, and (generally) helium. Each gas plays a distinct role. Carbon dioxide is the light emitter. The $C0_2$ molecules are first excited so that they vibrate in an asymmetrical stretching mode. The molecules then lose part of the excitation energy by dropping to one of two other, lower-energy vibrational states as shown in Fig. 4.2. These two decay paths are the two principal laser transitions: a shift to a symmetrical stretching mode accompanied by emission of a 10,6 μm photon, or a shift to a bending mode accompanied by emission of a 9,6 μm photon. Superposition of changes in the molecules' rotational states on the vibrational transitions yields large families of laser lines surrounding the 9,6- and 10,6-μm transitions. Once the molecules have emitted their laser photons, they continue to drop down the energy-level ladder until they reach the ground state.

The nitrogen molecules help to excite $C0_2$ to the upper laser level. The lowest vibrational state of N_2 is only 18 inverse centimetres lower in energy than the asymmetric stretching mode of $C0_2$, a difference that is less than one-tenth the mean thermal energy of room-temperature molecules, and hence insignificant from a practical standpoint. This lets the nitrogen molecules absorb energy and transfer it to the carbon dioxide molecules, thereby raising them to the upper laser level.

Carbon dioxide molecules can also reach the upper laser level in other ways. They can directly absorb energy from electrons inserted into the gas in a discharge or electron beam. An alternative way of producing the population inversion needed for laser operation is to rapidly expand hot, high-pressure laser gas into a cool near-vacuum; this is the basic principle behind the gas-dynamic carbon dioxide laser. In practice, the presence of N_2 significantly enhances laser operation, and that gas is almost always present in $C0_2$ lasers. Helium plays a dual role. It serves as a buffer gas to aid in heat transfer and helps the $C0_2$ molecules drop from the lower laser levels to the ground state, thus maintaining the population inversion needed for laser operation. The optimum composition and pressure for the gas in a $C0_2$ laser vary widely with the laser design. In a typical flowing-gas $C0_2$ laser, the total pressure might be around 15 torr {2000 pascals (Pa)}, with 10 percent of the gas CO_2, 10 percent N_2, and the balance helium.

In general, the concentrations of nitrogen and carbon dioxide are comparable, but much lower than that of helium. Low pressures are needed for continuous operation, but pulsed $C0_2$ lasers can be operated at pressures well above 1 atm.

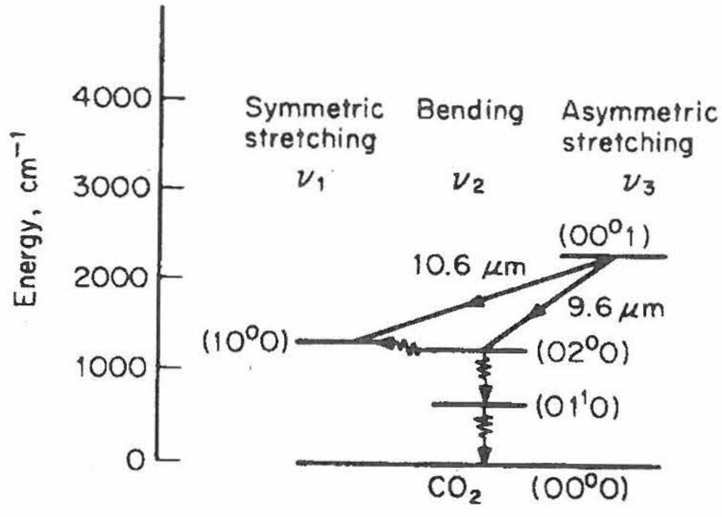


Fig. 4.2 Energy level structure in the CO_2 laser, showing the relevant vibrational modes of the CO_2 molecule[1].

The discharge breaks down some $C0_2$ into carbon monoxide and oxygen. In some cases, other gases may be added to the laser mixture to improve performance or prevent degradation of tube components by free oxygen. For example, hydrogen or water can be added to promote regeneration of $C0_2$ during operation of a sealed-tube laser, and sometimes carbon monoxide is added for similar reasons. It is even possible to operate pulsed lasers with a 50:50 mixture of air and carbon dioxide, albeit at reduced output power. However, too much water vapour can absorb enough infrared light to reduce laser gain. Performance of the $C0_2$ laser depends on temperature because of its energy-level structure. As can be seen in Fig.4, the lower laser levels are only about 1200 inverse centimetres above the ground state. As the gas is heated above room temperature, the

[1] *Numbers in parentheses indicate the excitation levels of the symmetric stretching, bending, and asymmetric stretching vibrational modes, respectively, of the molecule.*

populations of these levels increases. To keep gain at high levels, the temperature must be kept below about 150^0C [13].

4.5.2. Cooling

Forced-air cooling is used in some small $C0_2$ lasers. Higher-power lasers require water cooling, and the largest devices have sophisticated multicycle cooling systems. Typical water-flow requirements are 2 litres per minute (L/min) for a 150-W slow axial-flow laser and 20 to 40 L/min for a 1,5-kW fast axial-flow laser.

4.5.3. Efficiency

The overall efficiency of carbon dioxide lasers typically runs between 5 and 20 percent, which is not good when compared to other types of electrical equipment, but higher than most other lasers. Efficiencies are lower if operation is on a single line, if the electrical power supply is inefficient, or if the optics are particularly inefficient in extracting energy from the laser cavity. Users concerned with efficiency should make sure that it is defined explicitly. Wall-plug efficiency is always lower than efficiency in converting energy deposited in the active medium into laser emission.

4.5.4. Operating Conditions and Temperature

Carbon dioxide lasers are designed to operate at room temperature and can function well in normally clean environments. Many models are intended for industrial use. Extremes of dirt and/or vibration in factories have caused problems in some cases, and such protective measures, as air filters may be needed in particularly severe environments.

4.5.5. Reliability and Maintenance

Laser lifetime: Different factors limit operating lifetimes of different types of $C0_2$ laser, including gas lifetime in sealed lasers and degradation of optics and power supplies in all types. Sealed continuous-output $C0_2$ lasers are designed to operate from one to several thousand hours on a single gas fill. Transversely exited atmospheric (TEA) lasers can deliver millions of shots from a single gas fill. Output power drops gradually if the gas is not changed, but refilling (and in some cases cleaning) the tube should restore the laser to original output levels. Lifetimes of flowing-gas $C0_2$ lasers normally are not specified, and in practice depend heavily on environmental factors, such as contamination of optics, which may require periodic replacement in materials-working applications. Some lasers can last a long time. One company reports that two 3-kW lasers have survived 14 years of continuous use [13].

Maintenance and Adjustments: A few basic types of maintenance are common for $C0_2$ lasers:

- Replacement of optics subject to degradation;
- Replacement of gas in sealed-tube lasers after 1000 hours or more of operation;
- Replacement of high-voltage components such as spark gaps;
- Lubrication and other upkeep of essential accessories such as vacuum pumps.

4.6. Applications of the CO_2 laser

Carbon dioxide lasers can serve many functions, from a comparatively inexpensive source of laser photons to an emitter of precise infrared wavelengths. This versatility has opened up many applications for $C0_2$ lasers in both industrial and laboratory environments. Some of the major applications of $C0_2$ lasers and their principal requirements are summarized briefly below [13].

- *Materials processing:* $C0_2$ lasers are used for materials processing, primarily cutting and welding of metals and non-metals. Non-metals such as plastics, ceramics, cloth, and rubber are much more efficient absorbers than metals at 10 μm, so lower laser powers are required. Despite reflectivities that can exceed 90 percent at 10 μm, $C0_2$ laser metal working is growing, because no other commercially available laser can generate as intense continuous-wave output. Cutting and welding generally require continuous-wave powers of 50 W and up, with much higher powers needed for most metals except titanium, which absorbs more 10-μm radiation than other metals and is hard to cut with mechanical saws. $C0_2$ lasers are sometimes used for drilling, but that task is more often done with pulsed neodymium lasers, which produce high peak powers at about 1 μm.
- *Heat treating:* To alter the characteristics of metal surfaces, $C0_2$ lasers are used for heat treating, generally improving the durability of the metal. This requires a continuous beam, which for the sake of efficiency should contain a high power that can be spread over a large area.
- *Marking letters or symbols:* Pulsed TEA lasers can etch a stencil-like image onto a workpiece in a single (or sometimes multiple) shot, a non-contact technique for permanent marking that is used in a variety of industries. A pulsed laser can write

alphanumeric characters as series of dots, but that is generally done with pulsed neodymium lasers.

- *Spectroscopy and photochemistry:* CO_2 lasers can generate narrow-band output in the 10-μm range for spectroscopic applications, and/or high powers for studies of laser-induced chemistry. TEA or waveguide lasers are the commonest types for these applications.
- *Range finding:* For military applications, use of waveguide CO_2 lasers as range finders is in the development and demonstration stages [18].
- *Laser radar or "lidar":* CO_2 lasers can be used in systems which generate 10μm pulses and analyse the returns, much as an ordinary radar system in the microwave range. Alternatively, returns from the atmosphere can be analysed spectroscopically to determine concentrations of various species in the atmosphere.
- *Surgery:* Surgery can be performed with 10μm powers in the 50W range because water in living tissue absorbs that wavelength strongly. Continuous-wave lasers are used, with waveguide lasers becoming increasingly popular because of their compact size, good beam quality, and low cost.
- *Generation of far-infrared or submillimetre radiation:* A CO_2 laser can be used to optically pump or energise another gas so that the second gas can emit a laser beam at longer wavelengths. The use of different gases makes it possible to generate many wavelengths in the far-infrared and submillimetre regions.
- *Plasma production:* An intense pulse from a TEA laser (often modelocked) can deposit energy quickly onto a small spot to produce plasma. One specific application has been laser fusion research, although most work in that field is with shorter-wavelength lasers.

•*Directed-energy weapons:* Weapon experiments have been conducted with carbon dioxide lasers. However, interest in $C0_2$ laser weapons has decreased in recent years.

4.7. Summary

The 30W CO_2 laser we have, is used mainly to cut materials. The CO_2 laser is a low-powered one that is easily maintained. The laser is perfect for the cutting thin layers of wood, paper, plastics and carton. The next chapter will go into it in more detail. By connecting the laser beam to an X-Y plotter we replaced the ink with the laser beam and cut the figure out.

CHAPTER 5

Materials

The material choice is important right from the start, at the design phase. First of all the question may be asked, whether or not the material can be cut with CO_2 laser, what thickness can be cut and what is the minimum distance two lines can be apart before any deformation occurs. These parameters are important and are used in the design phase. Furthermore in some cases thicker sliced pieces will look better, depending on whether the laser will be able to do the cutting.

5.1. Laser interaction on materials

5.1.1. Spatial Mode

Resonator design is crucial for the production of the proper wavelength of light. The phase of the electromagnetic wave may differ by resonator design, resulting in changes in the laser beam spatial profile. The beam profile can be characterised by its *Transverse Electromagnetic Mode* (TEM). TEM modes are normally written in the form of TEMnm. The subscripts n and m denote the number of nodes in directions orthogonal to the beam propagation, such as TEM_{00} or TEM_{01}. TEM_{00} has a Gaussian spatial distribution and is usually considered the best mode for laser machining because the phase front is uniform and there is a smooth drop off of irradiance *from* the beam centre. This minimises diffraction effects during focussing and allows the generation of small spot sizes. The ideal for our purpose is to make sure that we have the smallest spot diameter to create the thinnest cut.

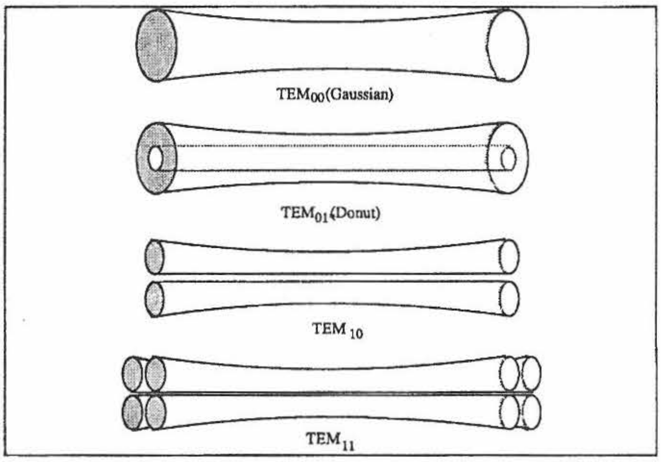


Fig. 5.1 Different beam profiles (TEM_{nm} modes)

5.1.2. Focal Spot Size

In materials processing, *irradiance (power per unit area)* of the laser beam at the material surface is of prime importance. Irradiances can be great enough to melt or vaporise any material and it can be generated by focussing a laser beam. The maximum irradiance is obtained at the focal point of a lens, where the beam is at its smallest diameter. The location of this minimum diameter is called the *focal spot*. Irradiance values of billions of watts per square centimetre can be obtained at the focal spot. The imperfections of the optical components and diffraction effects limit the size of the obtainable focal spots. Several such factors influence focal spot size. Firstly, focal spot size is directly related to the quality of the incoming beam, which can be quantified by the divergence of the beam (Fig. 5.2). A laser beam with a small divergence can be focussed to a smaller spot than a beam with high divergence. Second, focal spot size is influenced by diffraction. When focussing a diffraction-limited laser beam with a lens, a longer focal length or higher f-number corresponds to a larger focussed spot diameter. Finally, the diameter of the incoming laser beam affects the focal spot size. When restricted to specific optics, the only method of producing smaller focal spot sizes is to *increase* the incoming laser beam diameter [4].

5.1.3. Laser Capabilities

It is important to determine what kind of materials is cuttable with a 30W CO_2 laser. High-powered lasers are well known in the industries and a lot of literature is available (see table 5.1.). It is clear that high-powered lasers (specifically CO_2 lasers) are able to cut thicker materials successfully. The applications of low-powered lasers are still to be investigated.

Calculations on our laser capabilities can tell what the outcome will be. The answers can be used to compare with more powerful lasers. Important parameters such as power density, spot diameter and depth of focus can be determined, and compared with the literature available. Possible materials (together with their thicknesses) can then be chosen.

Table 5.1. Laser capabilities [4]

Laser type	Material	Laser power	Material width
Nd:YAG	Aluminum	200W	2mm
Nd:YAG	Copper	120W	3mm
CO_2	Mild Steel	250W	0,5mm
CO_2	Mild Steel	4kW	10mm
CO_2	Titanium	375W	1,5mm-3,2mm
Nd:YAG	Aluminum Oxide	$50MW/cm^2$	15mm
CO_2	Aluminum Oxide	$100MW/cm^2$	0,63mm
CO_2	Silicon Nitride	1-2kW	0,51mm
Nd:YAG	Silicon Nitride	$10MW/cm^2$	3mm
CO_2	Poly-carbonate	400W	3,175mm-12,7mm
CO_2	Poly-ethylene	400W	3,175mm-12,7mm
CO_2	Poly-styrene	400W-1300W	0,635mm-7,5mm
CO_2	Glass/ Epoxy	1kW	5mm
CO_2	Graphite/ Epoxy	300W	1mm
CO_2	Kevlar/ Epoxy	150W-950W	3,2mm-9mm
CO_2	Wood (Soft Maple)	250W	13mm
CO_2	Plywood	400W	19mm
CO_2	Glass	250W	1mm

Important laser parameters:

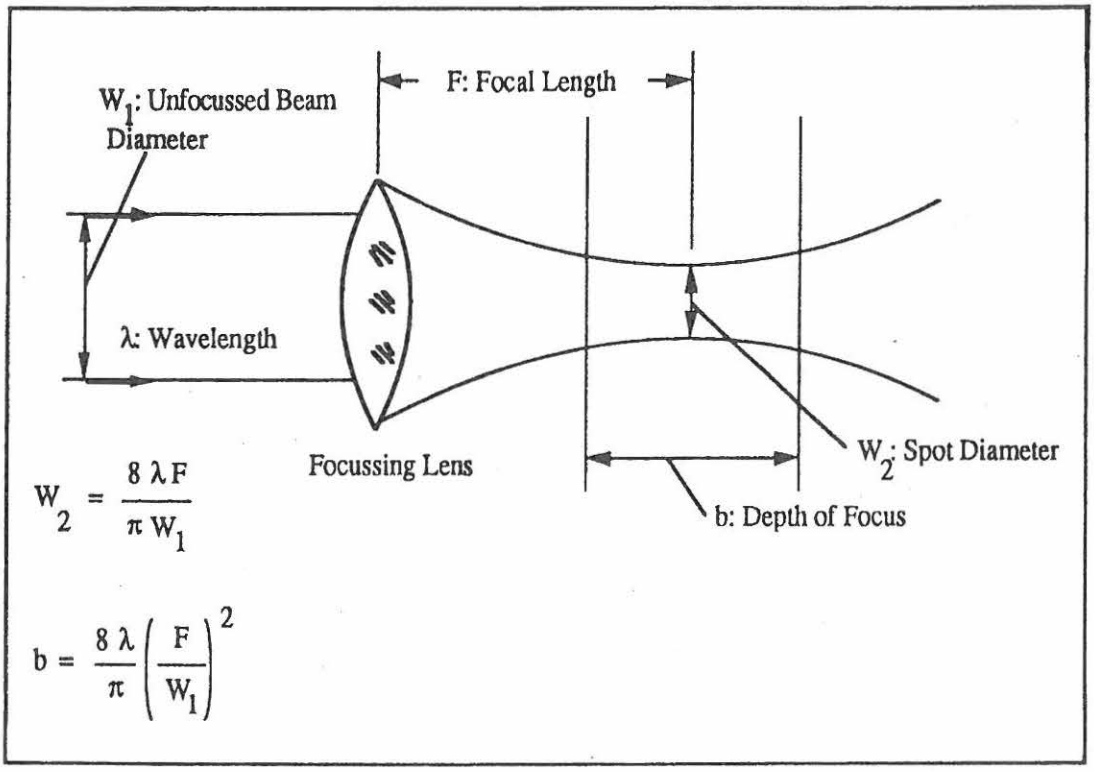


Fig. 5.2 Dimensions on laser beam

The most important parameters of the 30W CO_2 laser are the spot diameter (W_2), depth of focus (b) and power density (ϕ), where:

$$W_2 = \frac{8 \lambda F}{\pi W_1}$$

$$b = \frac{8 \lambda F^2}{\pi W_1^2}$$

$$\phi = \frac{I}{(\pi W_2^2 / 4)}$$

The parameters used on our 30W CO_2 laser are as follows:

W_1 = Unfocussed beam diameter = 6mm

F = Focal length = 38mm

λ = Wavelength = 10,6μm

Spot diameter

Spot diameter is the smallest diameter of the focussed beam, and it therefore implies the highest intensity of the beam power is on that exact spot. The spot diameter should determine the width of the cut. For our laser:

$$W_2 = \frac{8 \lambda F}{\pi W_1}$$

$$= \frac{8 \times 10{,}6 \times 10^{-6} \times 38 \times 10^{-3}}{3{,}14 \times 6 \times 10^{-3}}$$

$$= \underline{0{,}17 \text{ mm } (170\mu m)}$$

Depth of Focus

The depth of focus determines the thickness that the laser is able to cut easily. In that region the beam is focussed to achieve the best power transfer. For our laser:

$$b = \frac{8 \lambda F^2}{\pi W_1^2}$$

$$= \frac{8 \times 10{,}6 \times 10^{-6} \times (38 \times 10^{-3})^2}{3{,}14 \times (6 \times 10^{-3})^2}$$

$$= \underline{1{,}1 \text{ mm}}$$

It thus implies that material thicknesses of at least 1,1mm can be cut on our system.

Power density

Unfortunately from the literature (Table 5.1.), data on power density is scarce. For our laser, with maximum output power of I = 30W

$$\phi = \frac{I}{(\pi W_2{}^2 / 4)}$$

$$= \frac{30}{(3{,}14 \times 0{,}017^2/4)}$$

$$= \underline{132 \text{ kW/cm}^2}$$

With the correct focussing, it should be possible to play in the same ball park as more powerful lasers.

5.1.4. Summary

The power density of the 30W CO_2 laser is 132kW/cm^2 with a depth of focus of 1,1mm. With only about 1,1mm to ±3,5mm of depth cuttable, the laser is restricted to materials such as Wood, Plastics and Carton. For rapid prototyping the low-powered lasers are perfect. In this study, from a viewpoint of economy and availability, materials such as Ultra-high impact plastics (UHI), Acrylic glass and masonite were investigated.

5.2. Material processing parameters

Different materials and thicknesses were cut to find out whether or not the laser can cut the thickness with the given speed and power. The results were displayed graphically. The graphs provide selection of the correct cutting speed at a desired power. This will enhance the cutting speed and improve the product costs. *(In the **results** row, the Y stands for "yes, it cut through" and N stands for "no, it did not cut through".)*

5.2.1. Ultra-high Impact Plastic (UHI)

Table 5.2. Results on UHI (3mm thickness)

Material	U H I																	
Thickness	3mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 2	y	y	n	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 3	y	y	n	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Ave. Results	**y**	**y**	**n**	**n**	**n**	**n**	**n**	**y**	**y**	**n**	**n**	**n**	**n**	**y**	**n**	**n**	**n**	**n**

Table 5.3. Results on UHI (2mm thickness)

Material	U H I																	
Thickness	2mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	y	y	n	n	y	y	y	y	y	n	y	y	y	n	n
Results 2	y	y	y	y	y	n	n	y	y	y	y	n	n	y	y	n	n	n
Results 3	y	y	y	y	y	n	n	y	y	y	y	n	n	y	y	y	n	n
Ave. Results	**y**	**y**	**y**	**y**	**y**	**n**	**n**	**y**	**y**	**y**	**y**	**n**	**n**	**y**	**y**	**y**	**n**	**n**

Table 5.4. Results on UHI (1,5mm thickness)

Material	U H I																	
Thickness	1,5mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	y	y	y	n	y	y	y	y	y	n	y	y	y	n	n
Results 2	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y	y	y	n
Results 3	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y	y	y	y
Ave. Results	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y	y	y	n

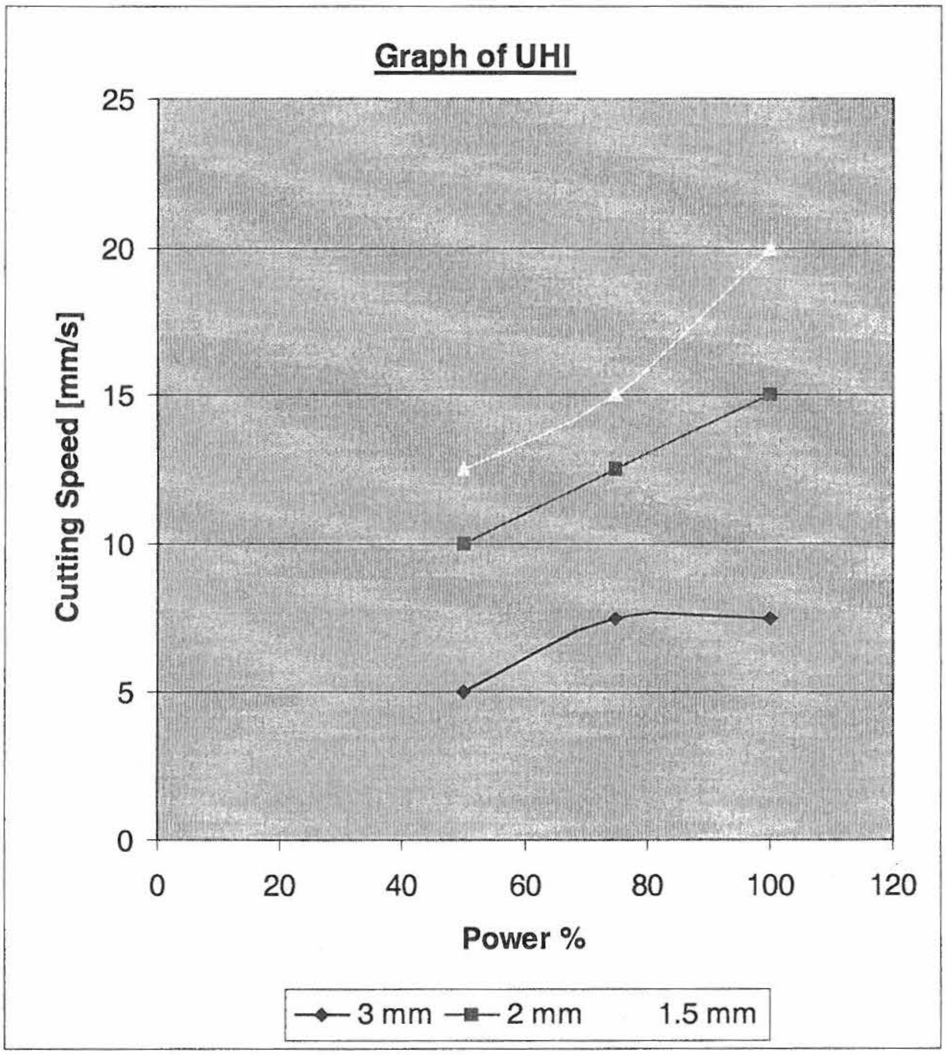


Fig. 5.3 Graph on UHI

5.2.2. Acrylic Glass

Table 5.5. Results on A.C. glass (3mm thickness)

Material	A.C. glass																	
Thickness	3mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 2	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 3	y	y	n	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Ave. Results	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n

Table 5.6. Results on A.C. glass (2mm thickness)

Material	A.C. glass																	
Thickness	2mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	y	n	n	n	y	y	y	n	y	n	y	y	n	n	n
Results 2	y	y	y	y	n	n	n	y	y	y	y	n	n	y	y	n	n	n
Results 3	y	y	y	y	n	n	n	y	y	y	n	n	n	y	y	y	n	n
Ave. Results	y	y	y	y	n	n	n	y	y	y	n	n	n	y	y	n	n	n

Table 5.7. Results on A.C.glass (1,5mm thickness)

Material	A.C.glass																	
Thickness	1,5mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	Y	y	y	n	y	y	y	y	y	n	y	y	y	n	n
Results 2	y	y	y	Y	y	y	n	y	y	y	y	y	n	y	y	y	y	n
Results 3	y	Y	y	Y	n	n	n	y	y	y	y	y	n	y	y	y	y	n
Ave. Results	y	y	y	y	y	y	n	y	y	y	y	y	n	y	y	y	y	n

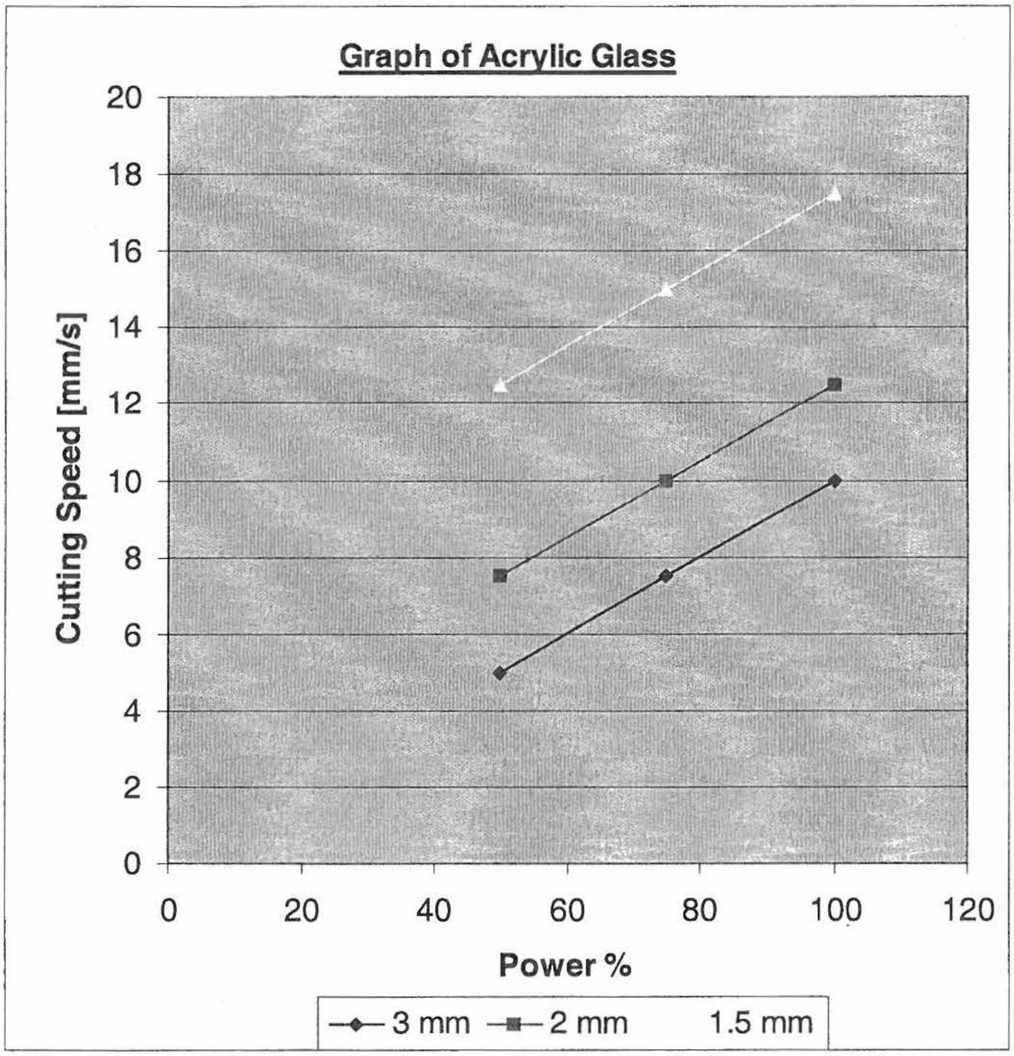


Fig. 5.4 Graph on Acrylic Glass

5.2.3. Masonite

Table 5.8. Results on Masonite (3mm thickness)

Material	Masonite																	
Thickness	3mm																	
Power	100%							75%						50%				
Speed mm/sec	5	7,5	10	12,5	15	17,5	20	5	7,5	10	12,5	15	17,5	5	7,5	10	12,5	15
Results 1	y	y	y	y	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 2	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Results 3	y	y	y	n	n	n	n	y	y	n	n	n	n	y	n	n	n	n
Ave. Results	**y**	**y**	**y**	**n**	**n**	**n**	**n**	**y**	**y**	**n**	**n**	**n**	**n**	**y**	**n**	**n**	**n**	**n**

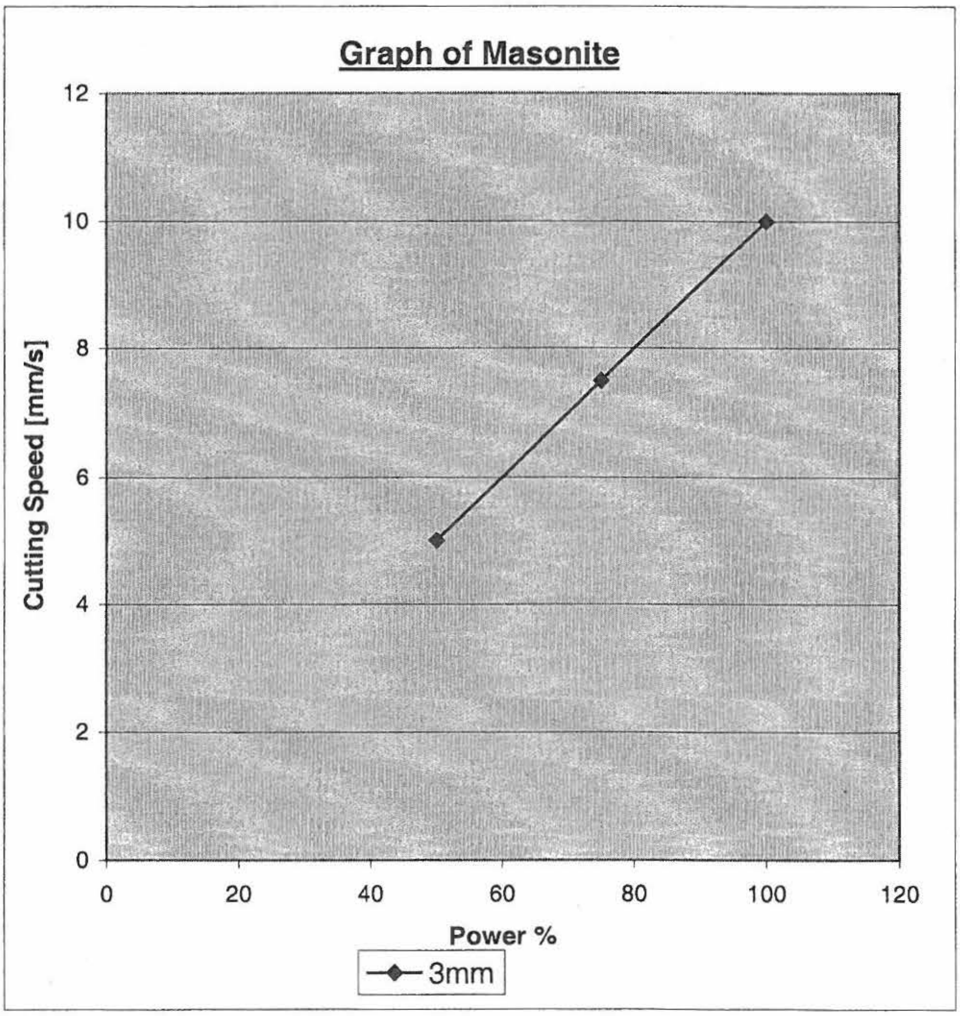


Fig. 5.5 Graph on Masonite

5.3. Material choice

One of the most important variables to take into consideration when choosing a suitable material, is minimum distance between cuts. The following results will indicate the nearest two lines that can be cut next to each other, before any deformation occurs. It is necessary to have this data when busy with a design or when a model has to be rescaled. A test piece of lines, 1mm, 0,8mm, 0,6mm, 0,4mm and 0,2mm apart, was cut and the following was found.

5.3.1. Minimum distances, first test

Table 5.9. Results on first test (minimum distances)

Material	Thickness	1mm apart	0,8mm apart	0,6mm apart	0,4mm apart	0,2mm apart
UHI	3mm	G	G	D	B	B
UHI	2mm	G	G	D	B	B
UHI	1,5mm	G	G	G	B	B
ACROGLAS	3mm	G	G	G	D	B
ACROGLAS	2mm	G	G	G	D	B
ACROGLAS	1,5mm	G	G	G	B	B
MASONITE	3mm	G	G	G	G	B

G - Good

D - Deformed

B - Bad, broken

5.3.2. Minimum distances, second test

Table 5.10. Results on second test (minimum distances)

Material	Thickness	1mm apart	0,8mm apart	0,6mm apart	0,4mm apart	0,2mm apart
UHI	3mm	G	G	D	B	B
UHI	2mm	G	G	G	B	B
UHI	1,5mm	G	G	G	D	B
ACROGLAS	3mm	G	G	G	B	B
ACROGLAS	2mm	G	G	G	D	B
ACROGLAS	1,5mm	G	G	G	B	B
MASONITE	3mm	G	G	G	G	B

5.3.3. Minimum distances, third test

Table 5.11. Results on third test (minimum distances)

Material	Thickness	1mm apart	0,8mm apart	0,6mm apart	0,4mm apart	0,2mm apart
UHI	3mm	G	G	D	B	B
UHI	2mm	G	G	D	B	B
UHI	1,5mm	G	G	G	D	B
ACROGLAS	3mm	G	G	G	B	B
ACROGLAS	2mm	G	G	G	B	B
ACROGLAS	1,5mm	G	G	D	B	B
MASONITE	3mm	G	G	G	B	B

5.3.4. Results on minimum distances, Average values

Table 5.12. Final results on minimum distances

Material	Thickness	1mm apart	0,8mm apart	0,6mm apart	0,4mm apart	0,2mm apart
UHI	3mm	G	G	D	B	B
UHI	2mm	G	G	G	B	B
UHI	1,5mm	G	G	G	D	B
ACROGLAS	3mm	G	G	G	B	B
ACROGLAS	2mm	G	G	G	D	B
ACROGLAS	1,5mm	G	G	G	B	B
MASONITE	3mm	G	G	G	G	B

5.4. Summary

From these graphs a comparison between the cutting speed and laser power for every material (with its different thicknesses) that we used, is possible. To reduce time and product costs the maximum values is of importance. So, for 100% laser power, a maximum speed of 20mm/s is possible to ensure a clean cut for 1,5mm thick UHI. At 100% power, speeds of 15mm/s and 7,5mm/s for 2mm and 3mm UHI, respectively, are achievable. The same with Acrylic glass: with maximum power, speeds of 17,5mm/s, 12,5mm/s and 10mm/s are cuttable on 1,5mm, 2mm and 3mm thick Acrylic glass, respectively. On the plastics, it is pertinent to note that the thinner the thickness of the material, the quicker it will start to deform. Despite that, lines can be placed up to 0,8mm apart and still come out without any deformation.

According to these results Masonite gives the cleanest cut, this material will not deform and a clear cut up to 0,4mm apart is possible. When something with high detail must be built, Masonite will be the best choice. With Masonite, at 100% power, a clean cut at 10mm/s is possible.

CHAPTER 6

Lamination

6.1. Locating methods

A method of referencing the different slices to each other had to be found. A model such as a horse consisting of forty parts must be aligned one hundred percent to achieve an accurate prototype. The introduction of reference holes came to the rescue. The idea is to cut out a hole on every layer that is aligned with each other. In the computer drawing, a pin that passes through all the different layers, some times more than one, is subtracted from the solid model, resulting in a reference hole for a pin.

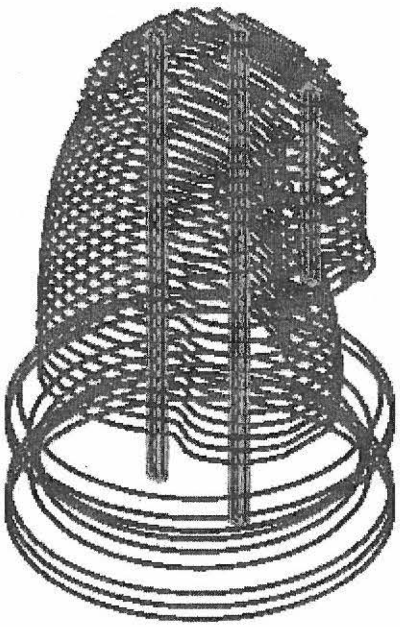


Fig. 6.1 Sliced model of a horse with reference pins

The size of the hole must be adjusted by the designer according to the size of the model. In the cases examined, a size of 3mm x 2mm was used in most cases. This 3mm x 2mm was cut out of the 3mm material was used. This ensures that a model consists of only one material with the same color. In other cases, a standard round reference pin can be used. This results in a perspex model with standard diameter wood, steel or brass rod etc. reference pin. The size of the pins depends on the contours of the model.

A few examples are given of the chess piece (horse) sliced in the X, Y and Z directions.

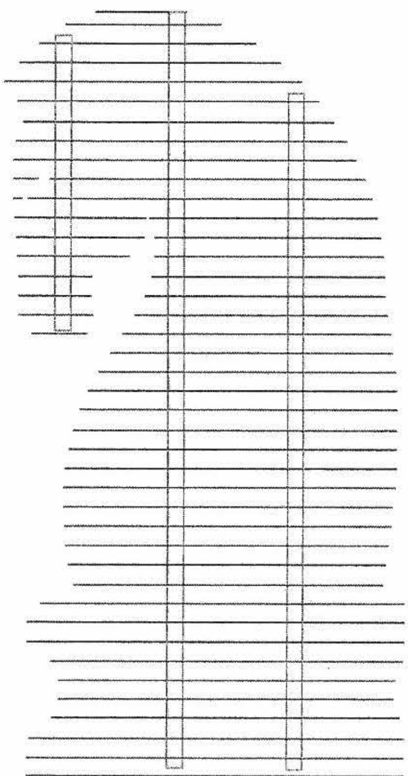


Fig. 6.2 3mm x 2mm ref. pins (Z-sliced)

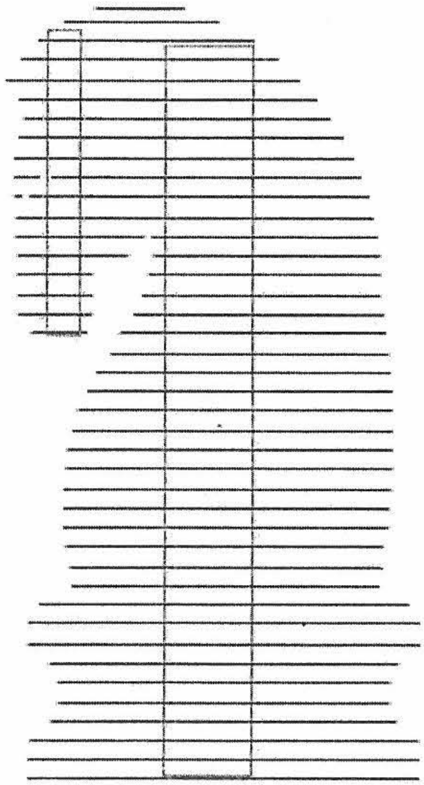


Fig. 6.3 10mm and 5mm ref. pins (Z-sliced)

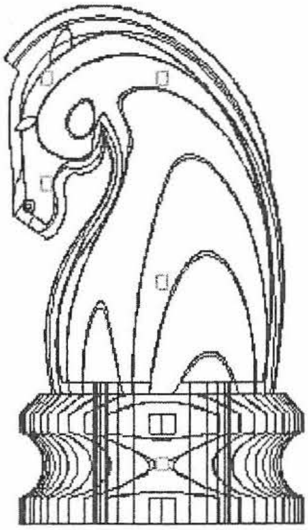


Fig. 6.4 3mm x 2mm ref. pins (X-sliced)

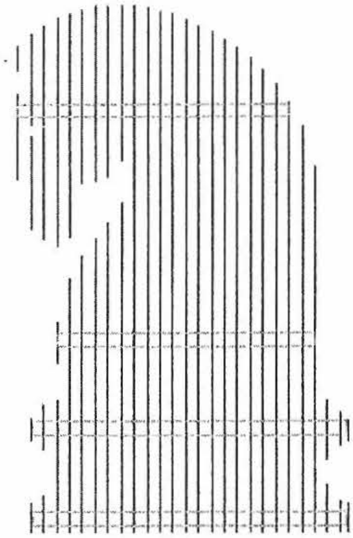


Fig. 6.5 3mm x 2mm ref. pins (Y-sliced)

6.2. Encoding

This step is optional, as it only helps the person to laminate the layers in the correct sequence. Furthermore, the numbering of the layers not only ensures the correct sequence, but enables a second person to do the lamination without seeing the design.

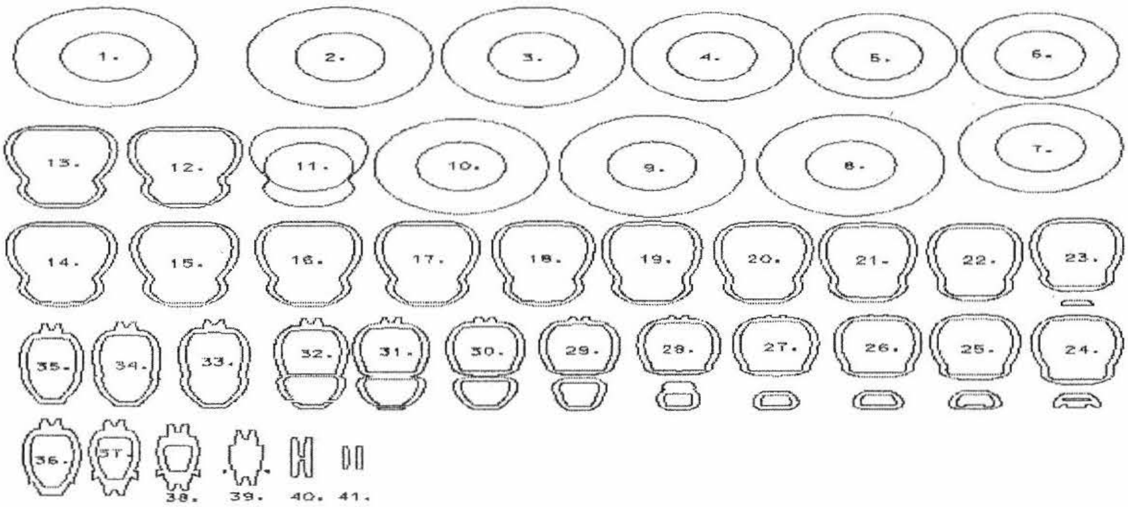


Fig. 6.6 Plot layout with numbering

This enforces a second step to the cutting procedure. At first the numbers are engraved into the material. This is achieved by defining the sequence, selecting only the numbers and using only about 30% of the laser power. The numbers are now engraved on the material.

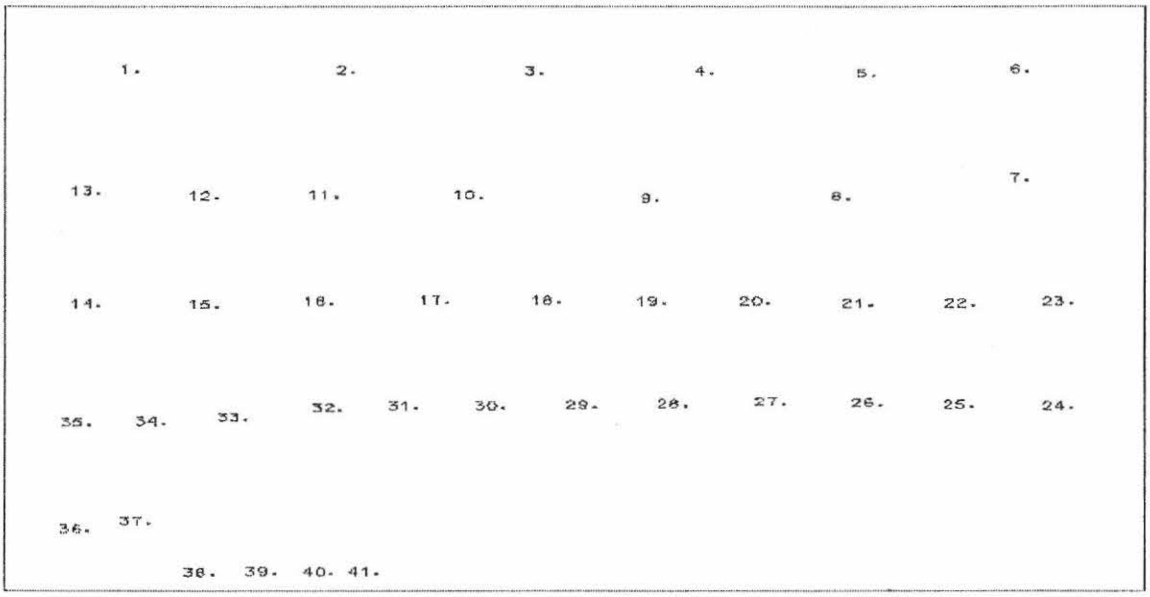


Fig. 6.7 Numbers engraved on the material

Setting the laser power to the maximum for cutting ensures that the sliced pieces can be cut. The second cut only includes the cut of the sliced model.

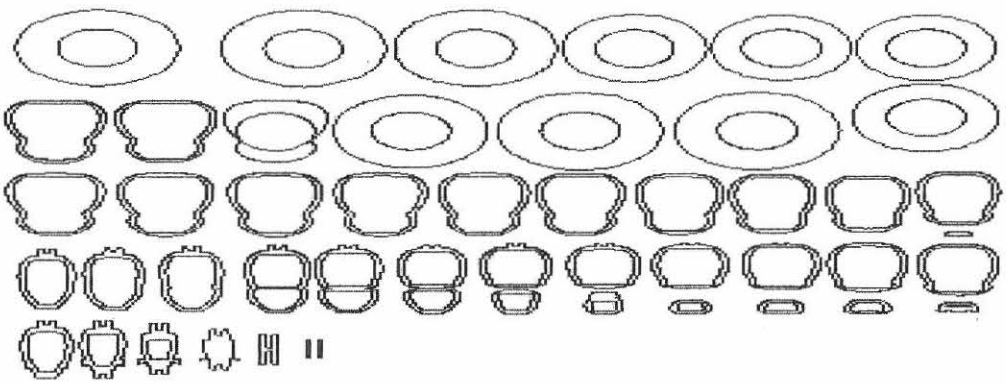


Fig. 6.8 Plot layout of the second cut

It is important to realise that the material on the X-Y gantry should not be moved after the first cut. That will result in inaccurate cutting and numbering.

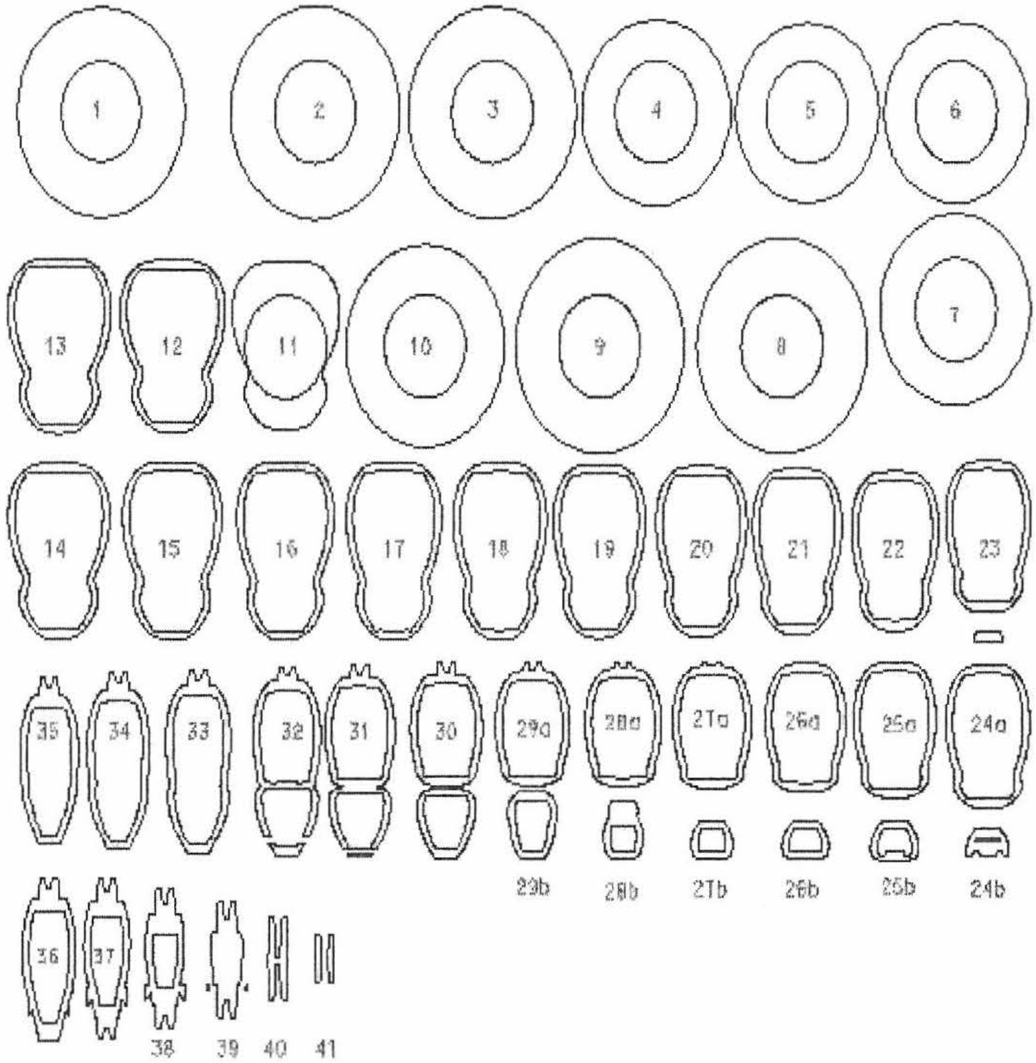


Fig. 6.9 Complete layout of the horse model with proper encoding

6.3. Adhesives

It is important to have a look at bonding substances to ensure that the time spent on the model so far is not wasted. The glues looked at, were mainly those ideal for the materials used namely Acroglass, UHI and Masonite, categorised under wood and plastics. For the best results, it is important to know which type of glue to use for every crafting project. No matter what materials are glued together, the selected adhesive should bond well and last for a long time.

In general, adhesives other than hot melts fall into two categories, namely water-based and solvent-based. The water-based glues are usually non-flammable, non-polluting, and non-toxic, and they may or may not wash out (depending on the formula). The solvent-based glues have a faster drying time and are not water-soluble. They may be flammable or non-flammable, depending on the composition, and bond well to many surface types [15].

6.3.1. Glues for Wood

For wood working substances such as Epoxies and Resorcinol types, can be considered but, due to accessibility and price, only the following substances are discussed:

White Glues

The white glues sometimes used in woodcrafting are polyvinyl acetate (PVA) based. These glues should be used only for projects that will be subjected to little stress during use and the finished item should not be exposed to water or dampness. These glues are ideal for architectural prototypes. When using white glue for woodworking, the setting time will be at least one hour and in most brands it is recommended that the project be left clamped for at least 24 hours, until it completely cures. The problem with this glue is the curing time [32, 19].

Aliphatic resins (Yellow Wood Glues)

The most common type of woodcrafting glue used today is a white glue mixed with a resin to produce a stronger bond and a faster setting time, namely 30 minutes or less. This will speed up the curing process. It works well on both soft and hard woods.

Like white glues, yellow wood glues are non-toxic and odourless. They are cleaned with warm water before drying. Never use these glues on outdoor furniture or any item that will be exposed to moisture. Instead of drying clear, like white glues, yellow glues will probably retain some of their yellow colour when dried. Others are specially formulated to dry darker for use with darker woods. There are several advantages attached to using a yellow wood glue instead of other wood glues. It has good heat resistance and is not affected by solvents from paint or finishes. When used at cooler temperatures (down to 7.2°C), the glue will still form a good bond, although the curing time will be longer. Yellow wood glue comes in an easy-to-use liquid form and, probably most important, it can be sanded after drying [32].

6.3.2. Glues for UHI and Acroglass

The different types that are named are the most important. There is a warning, however, with regard to the Epoxy types. Epoxies are not recommended for polyethylene (clear lightweight plastic), polypropylene, plastic foam, or soft wood (because it will be stronger than the wood, it will have no flexibility and can cause splitting).

Acrylic adhesive

A recently discovered two-part crafting adhesive has been developed. It is not an epoxy but is acrylic-based. It is ideal for model making, especially when layering several pieces in the same project. To use acrylic adhesives, brush the activator onto both surfaces being joined. Then put the adhesive on only one surface and join the two pieces together. Only 20 seconds for repositioning is allowed, and the adhesive will set in 30 seconds. There is hardly any waiting for each part to set before layering another over it [32].

Super glue gels

Super glue (chemically a cyanoacrylate) is a power-bonding agent. This liquid super glue is an instant adhesive, but it works much better on smooth surfaces that fit together tightly. The biggest advantage of any super glue is that it forms a powerful bond in seconds (although the bond will not be as durable as many of the high-tech adhesives). On the flip side, the quick bond does not allow for repositioning if the components are not aligned perfectly. Super glue gel is water-resistant, but it is not the best choice for washable projects. Although super glue gel is relatively expensive, only a small drop per square cm is needed. Using more glue will actually weaken the bond.

All-purpose cement

In general, all-purpose cements are strong, but they are not the strongest adhesives available. They have greater holding power than white glues, but less than epoxies or many of the high-tech adhesives. They have a slower setting time and drying time than most other adhesives, but they still dry faster than a water-based glue. When dry, all-purpose cements are invisible, water-resistant, and unaffected by weather and temperature changes [32].

CHAPTER 7

Results and Rapid Prototyping products

The results are categorised into two main groups, architectural prototypes and engineering prototypes. The purpose was to find a conclusion about the two different prototypes concerning first the type of cut "slicing direction" and also the choice of material.

The way a model is sliced has a significant influence on the time and overall neatness of the product. Two models, a typical engineering model, i.e. an impeller, and a typical architectural model, a simple townhouse, were cut with different material thicknesses, to get a clearer picture of the prototypes to be manufactured. Concerning the material choice, some results are applicable to both the engineering and the architectural models.

In the end, all this data was used to manufacture the best laser cut prototypes, three engineering and three architectural models. These models were then compared with models obtained by means of other rapid prototyping techniques.

7.1. The Architectural Prototype

A simple townhouse is examined in Fig. 7.1, comparing the different results on the X-Y- and Z-sliced directions with the different material thicknesses. The results are shown and summarised in the conclusion.

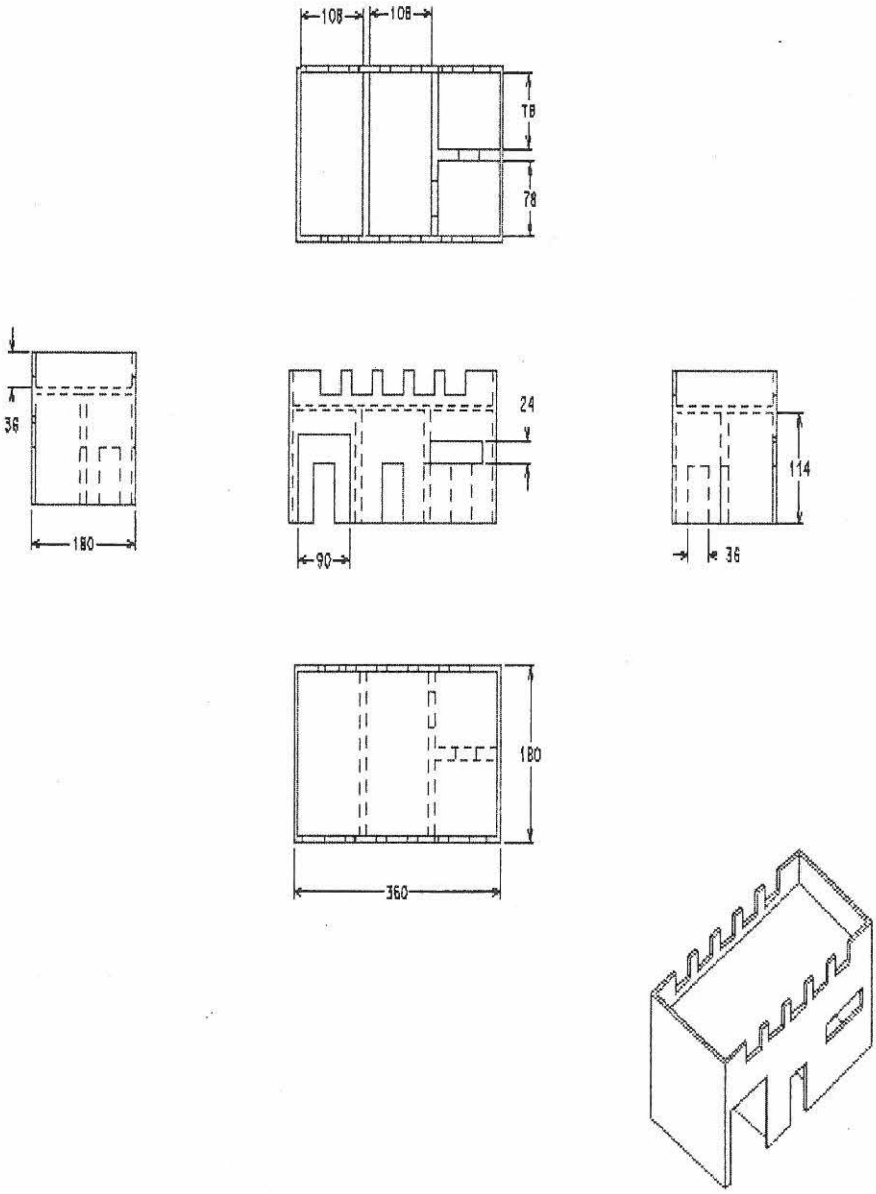


Fig. 7.1 A townhouse with dimensions

7.1.1. The townhouse

Sliced: (X-Y directions)

Thickness: 1mm

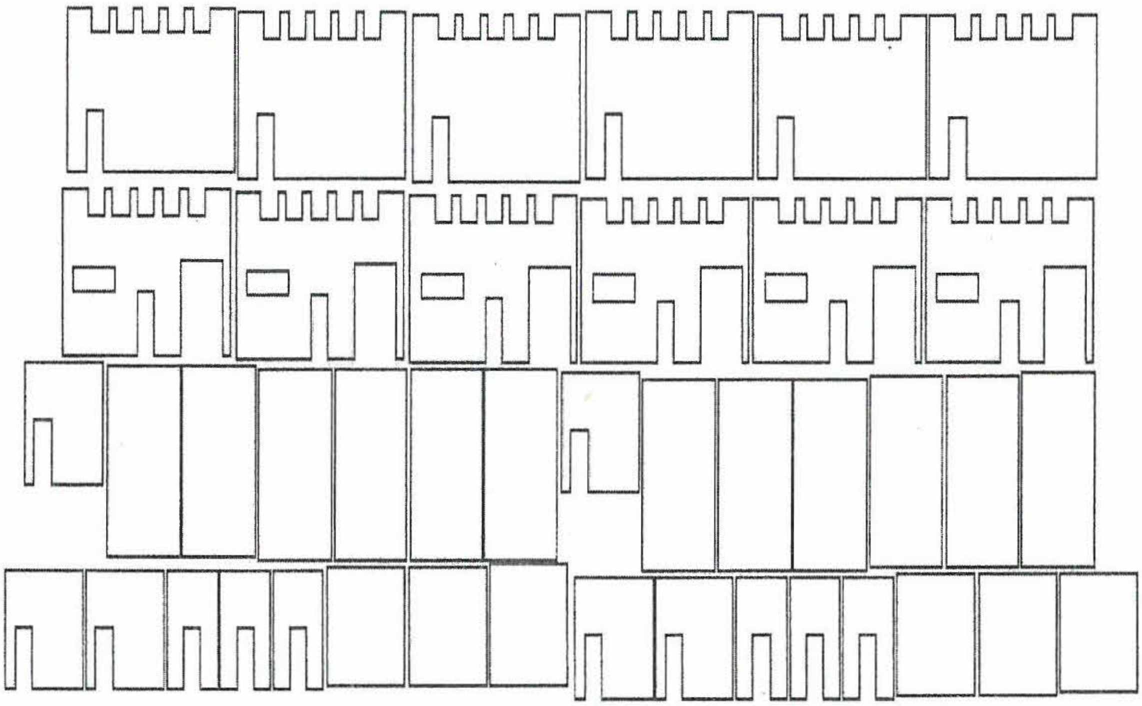


Fig. 7.2 Plot layout of townhouse: 1mm thickness (X-Y- sliced)

Table 7.1. Results on townhouse X-Y- sliced (1mm thickness)

Circumference cut	m	34,07
Area required	m^2	1,671
Area used	m^2	0,982
Area wasted	m^2	0,689
Cutting time	sec.	6813,956
Computer time	sec.	728,868
Lamination	sec.	924

7.1.2. The townhouse

Sliced: (X-Y directions)

Thickness: 2mm

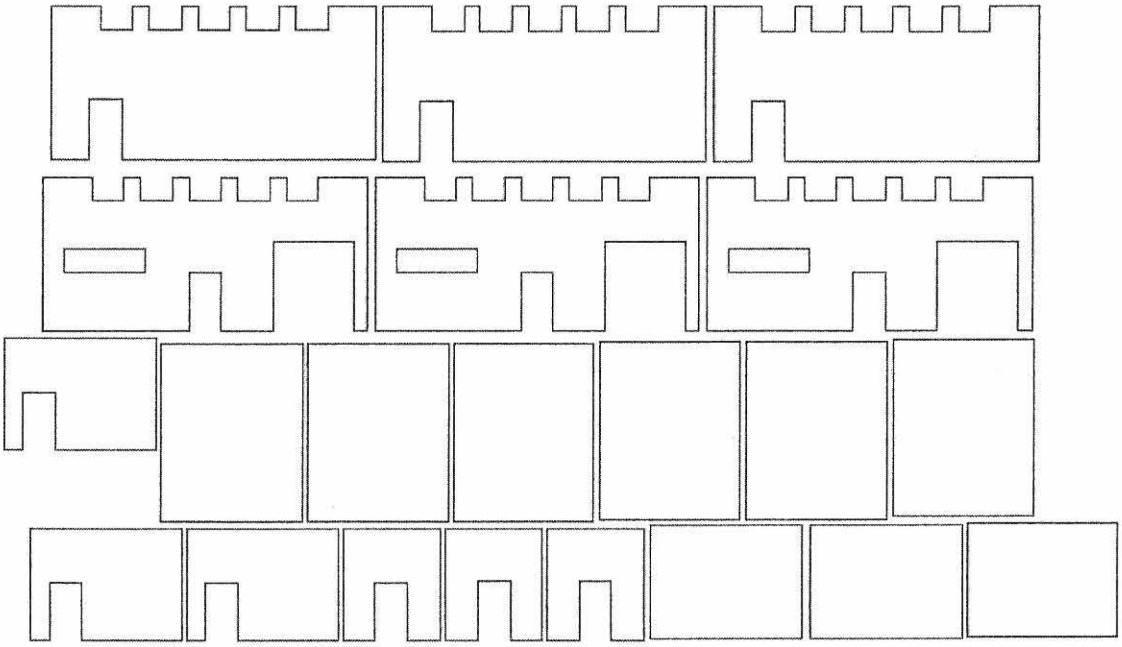


Fig. 7.3 Plot layout of townhouse: 2mm thickness (X-Y- sliced)

Table 7.2. Results on townhouse X-Y- sliced (2mm thickness)

Circumference cut	m	17,035
Area required	m^2	0,843
Area used	m^2	0,491
Area wasted	m^2	0,352
Cutting time	sec.	3406,978
Computer time	sec.	364,434
Lamination	sec.	462

7.1.3. The townhouse

Sliced: (X-Y directions)

Thickness: 3mm

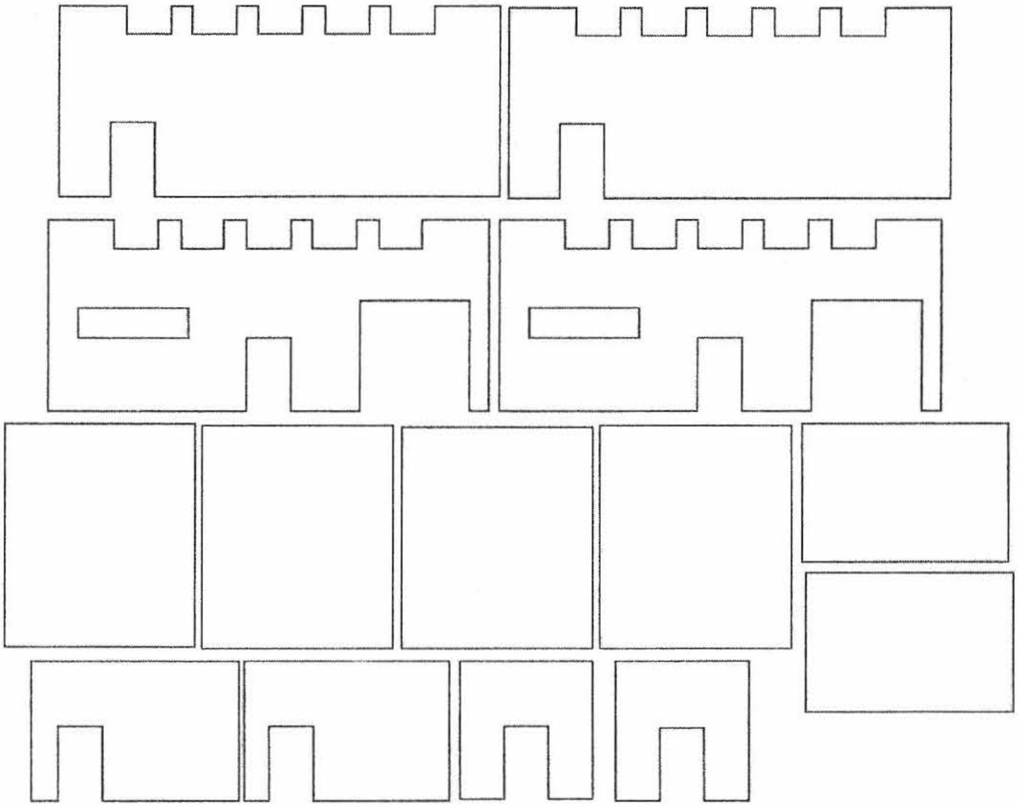


Fig. 7.4 Plot layout of townhouse: 3mm thickness (X-Y- sliced)

Table 7.3. Results on townhouse X-Y- sliced (3mm thickness)

Circumference cut	m	11,357
Area required	m^2	0,569
Area used	m^2	0,327
Area wasted	m^2	0,242
Cutting time	sec.	2271,319
Computer time	sec.	242,956
Lamination	sec.	308

7.1.4. The townhouse

Sliced: (Z directions)

Thickness: 1mm

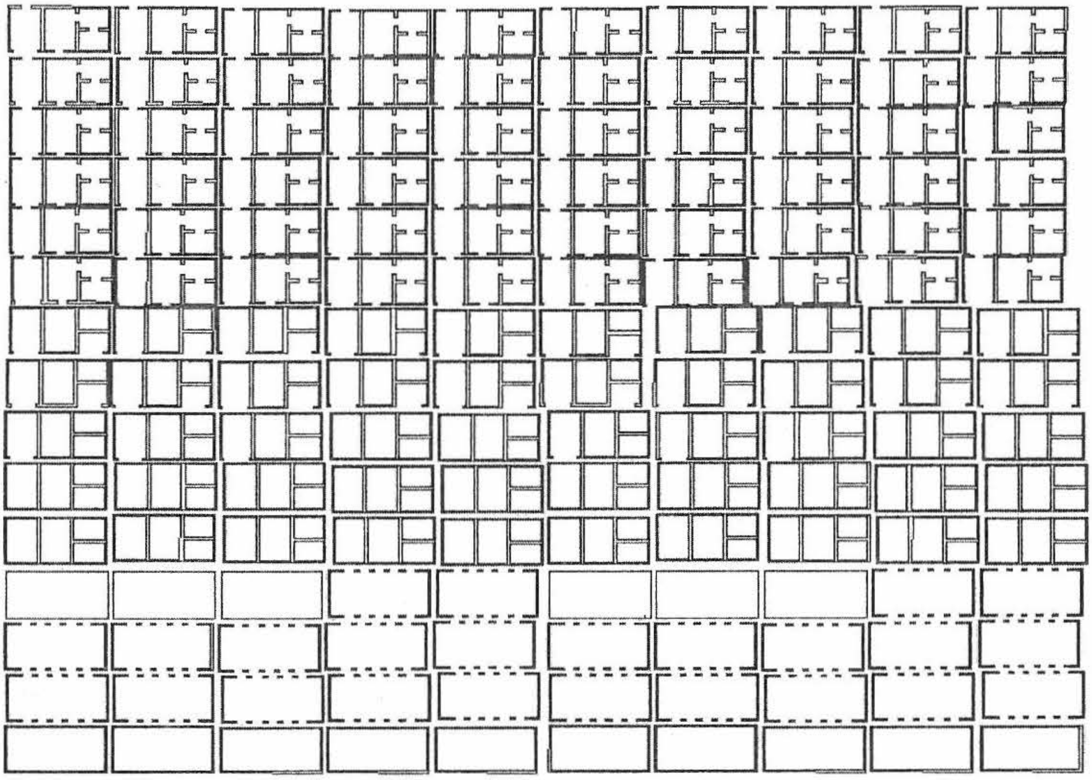


Fig. 7.5 Plot layout of townhouse: 1mm thickness (Z- sliced)

Table 7.4. Results on townhouse Z-sliced (1mm thickness)

Circumference cut	m	355,197
Area required	m^2	11,791
Area used	m^2	1,668
Area wasted	m^2	10,123
Cutting time	sec.	71039,498
Computer time	sec.	2603,100
Lamination	sec.	3300

7.1.5. The townhouse

Sliced: (Z directions)

Thickness: 2mm

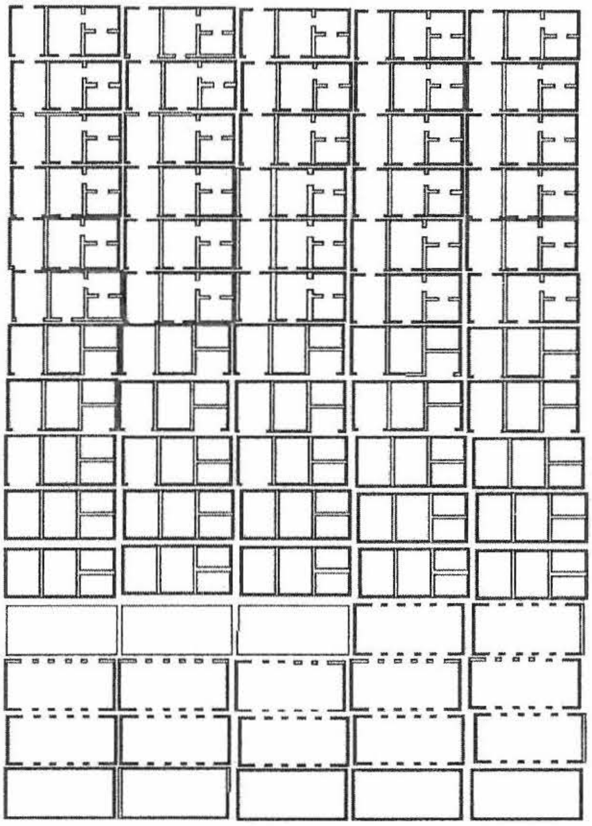


Fig. 7.6 Plot layout of townhouse: 2mm thickness (Z-sliced)

Table 7.5. Results on townhouse Z-sliced (2mm thickness)

Circumference cut	m	177,599
Area required	m^2	5,734
Area used	m^2	0,834
Area wasted	m^2	4,9
Cutting time	sec.	35519,749
Computer time	sec.	1301,55
Lamination	sec.	1650

7.1.6. The townhouse

Sliced: (Z directions)

Thickness: 3mm

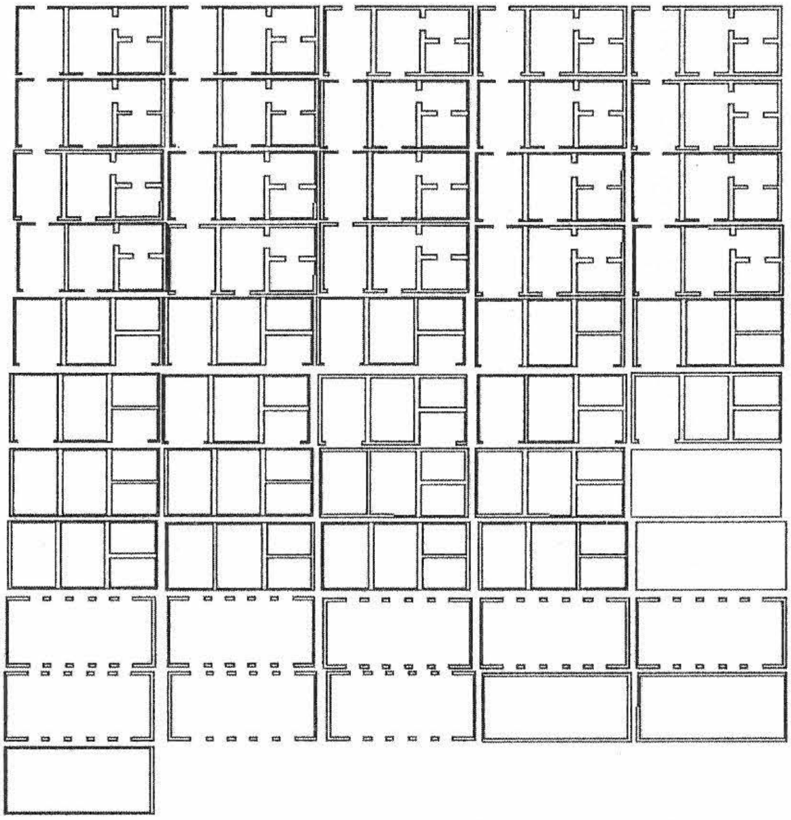


Fig. 7.7 Plot layout of townhouse: 3mm thickness (Z-sliced)

Table 7.6. Results on townhouse Z-sliced (3mm thickness)

Circumference cut	m	121,151
Area required	m^2	4,211
Area used	m^2	0,567
Area wasted	m^2	3,644
Cutting time	sec.	24230,231
Computer time	sec.	885,054
Lamination	sec.	1122

7.1.7. Summary of the data obtained from the townhouse:

Table 7.7. Summary on the townhouse

	X-Y cut (1mm)	Z cut (1mm)	X-Y cut (2mm)	Z cut (2mm)	X-Y cut (3mm)	Z cut (3mm)
Circumference cut (m)	34,07	355,2	17,05	177,6	11,36	121,15
Area required m^2	1,67	11,79	0,843	5,73	0,57	4,21
Area used m^2	0,98	1,67	0,49	0,83	0,33	0,57
Area wasted m^2	0,69	10,12	0,353	4,9	0,24	3,64
Cutting time (hrs.)	1,89	19,73	0,95	9,87	0,63	6,73
Computer time (min.)	12,15	43,39	6,07	21,69	4,05	14,75
Lamination (min.)	15,4	55	7,7	27,5	5,13	18,7

7.2. The Engineering prototype

An engineering impeller is examined in Fig. 7.8, where the different results on the X-Y- and Z-slice directions with different material thicknesses are compared. Because the results of the slicing direction are not so conclusively in favour of the X-Y- slicing choice as in the architectural model, a second engineering model, namely a chess piece (horse) was introduced. The chess piece was expected to provide more information on material usage and cutting time.

Model 1: The impeller

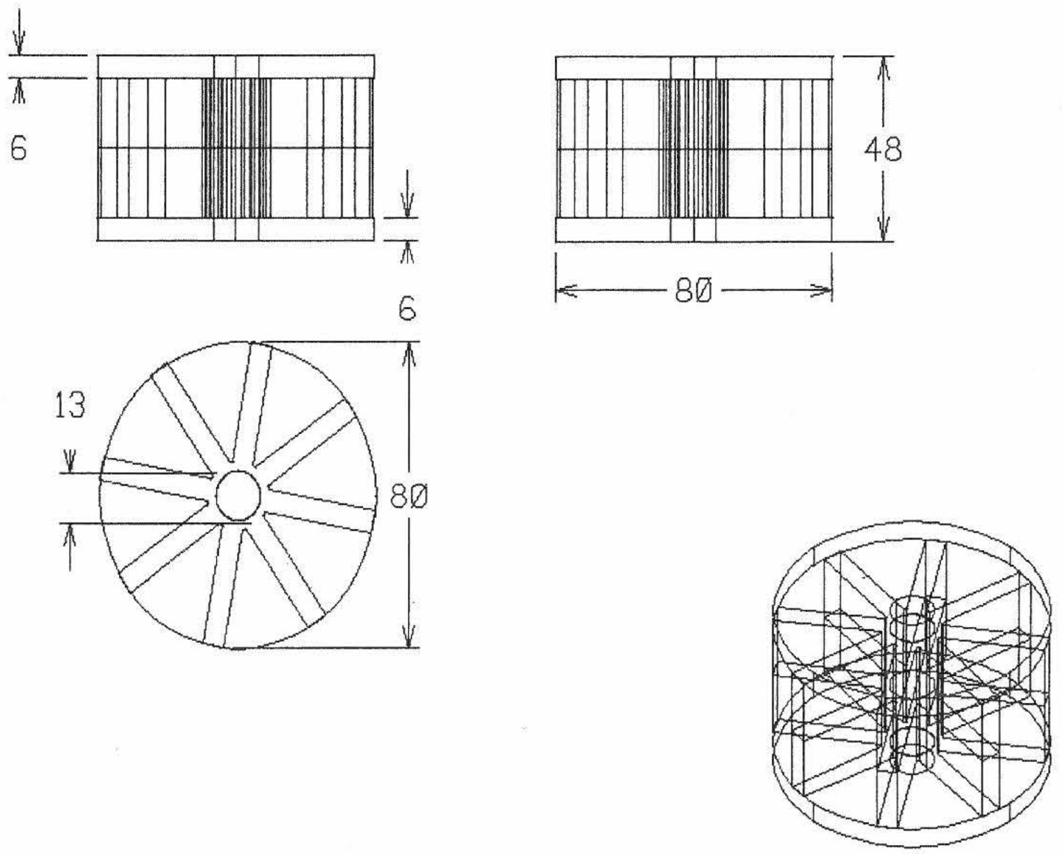


Fig. 7.8 An engineering impeller

7.2.1. The impeller

Sliced: (X-Y directions)

Thickness: 1mm

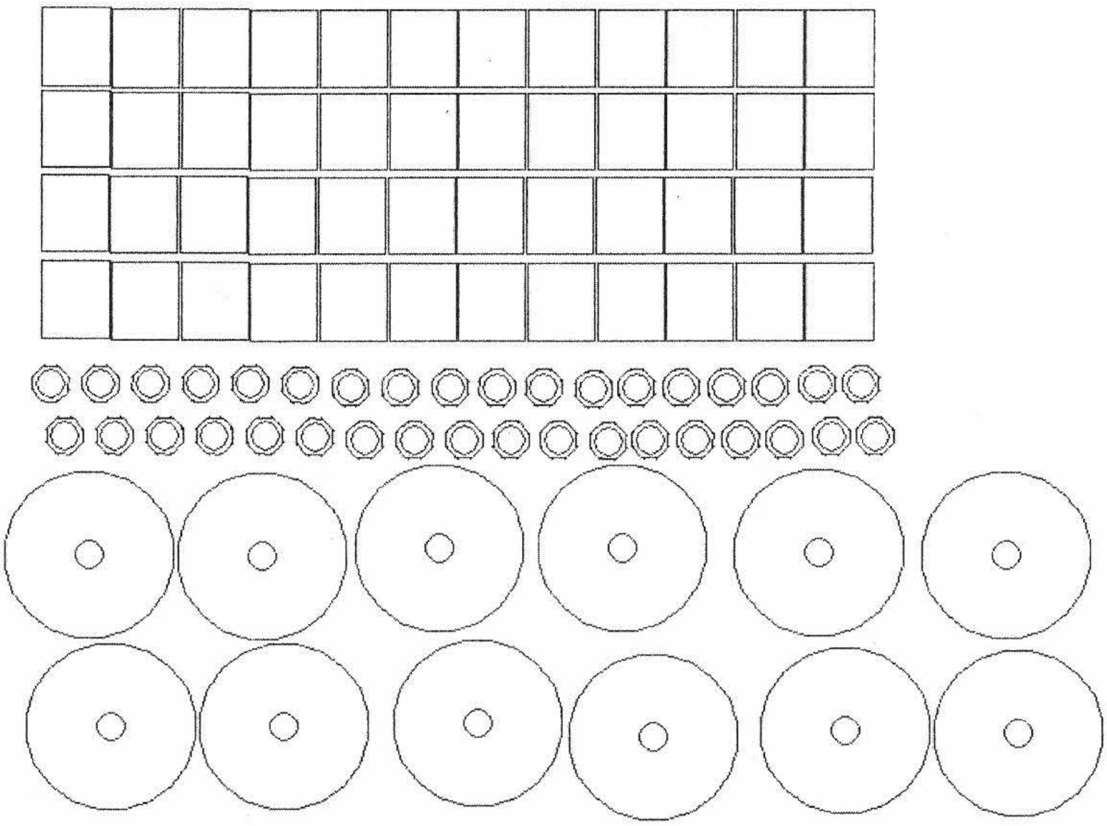


Fig. 7.9 Plot layout of impeller: 1mm thickness (X-Y- sliced)

Table 7.8. Results on impeller X-Y- sliced (1mm thickness)

Circumference cut	mm	13,473
Area required	m^2	0,215
Area used	m^2	0,117
Area wasted	m^2	0,098
Cutting time	sec.	2694,647
Computer time	sec.	1665,984
Lamination	sec.	2112

7.2.2. The impeller

Sliced: (X-Y directions)

Thickness: 2mm

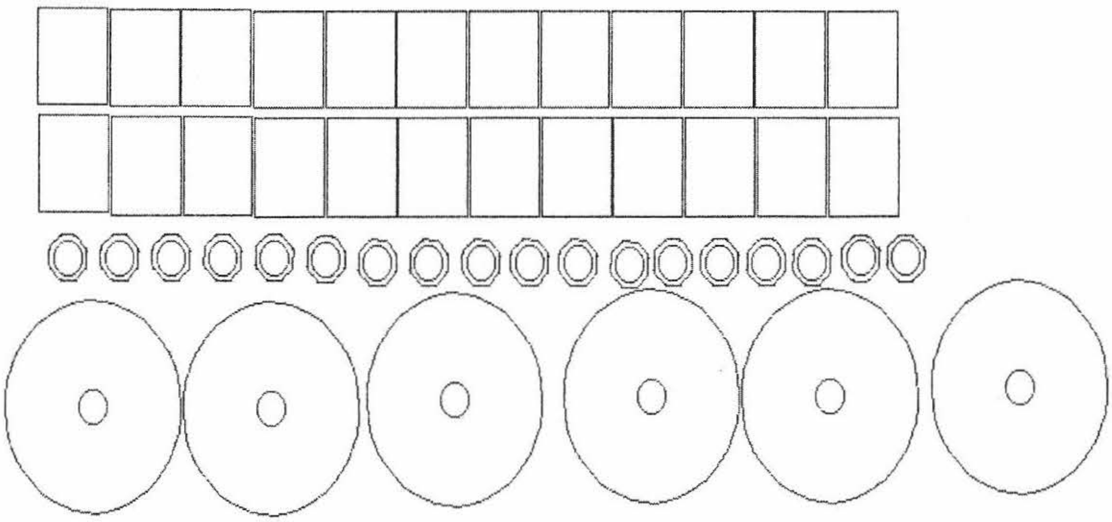


Fig. 7.10 Plot layout of impeller: 2mm thickness (X-Y- sliced)

Table 7.9. Results on impeller X-Y- sliced (2mm thickness)

Circumference cut	m	6,737
Area required	m^2	0,11
Area used	m^2	0,058
Area wasted	m^2	0,052
Cutting time	sec.	1347,332
Computer time	sec.	832,992
Lamination	sec.	1056

7.2.3. The impeller

Sliced: (X-Y directions)

Thickness: 3mm

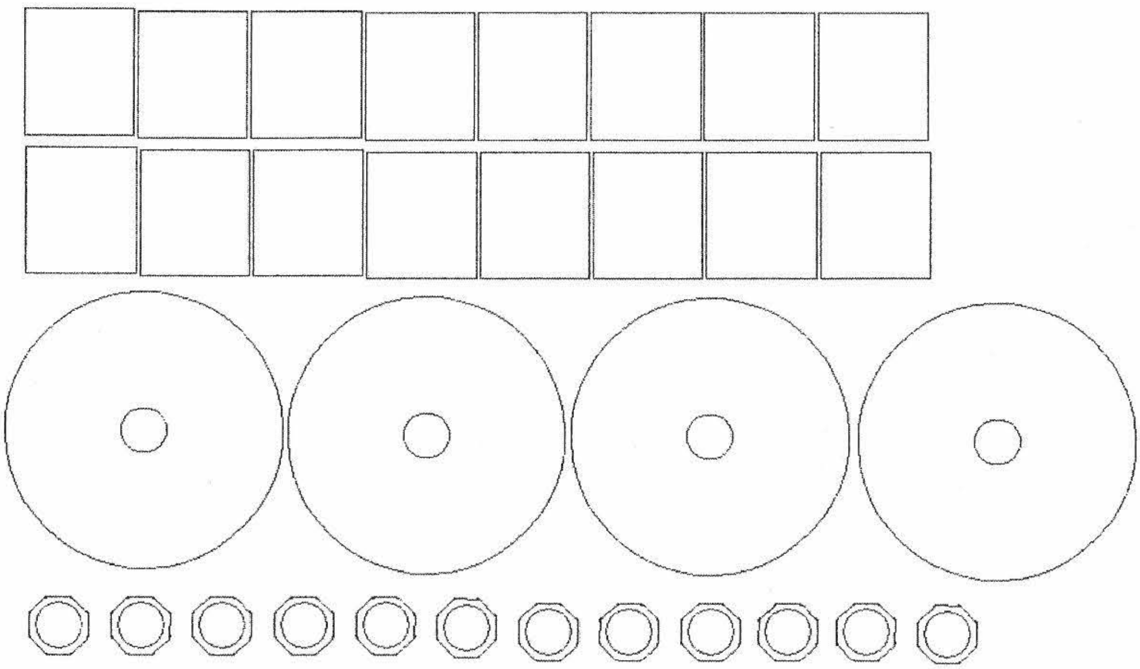


Fig. 7.11 Plot layout of impeller: 3mm thickness (X-Y- sliced)

Table 7.10. Results on impeller X-Y- sliced (3mm thickness)

Circumference cut	m	4,491
Area required	m^2	0,067
Area used	m^2	0,039
Area wasted	m^2	0,028
Cutting time	sec.	898,221
Computer time	sec.	555,328
Lamination	sec.	704

7.2.4. The impeller

Sliced: (Z directions)

Thickness: 1mm

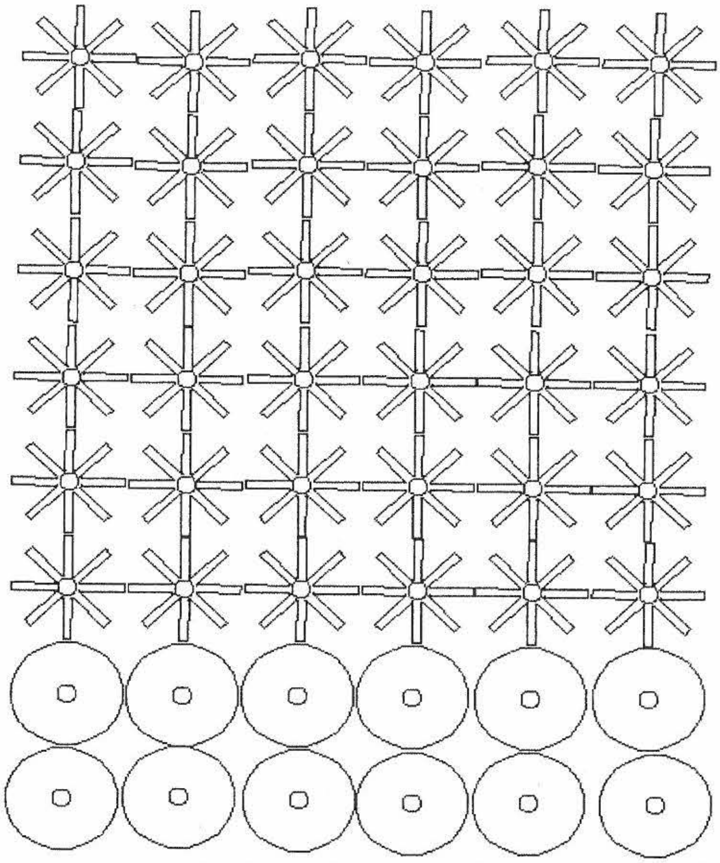


Fig. 7.12 Plot layout of impeller: 1mm thickness (Z-sliced)

Table 7.11. Results on impeller Z-sliced (1mm thickness)

Circumference cut	m	25,103
Area required	m^2	0,34
Area used	m^2	0,117
Area wasted	m^2	0,223
Cutting time	sec.	5020,581
Computer time	sec.	832,992
Lamination	sec.	1056

7.2.5. The impeller

Sliced: (Z directions)

Thickness: 2mm

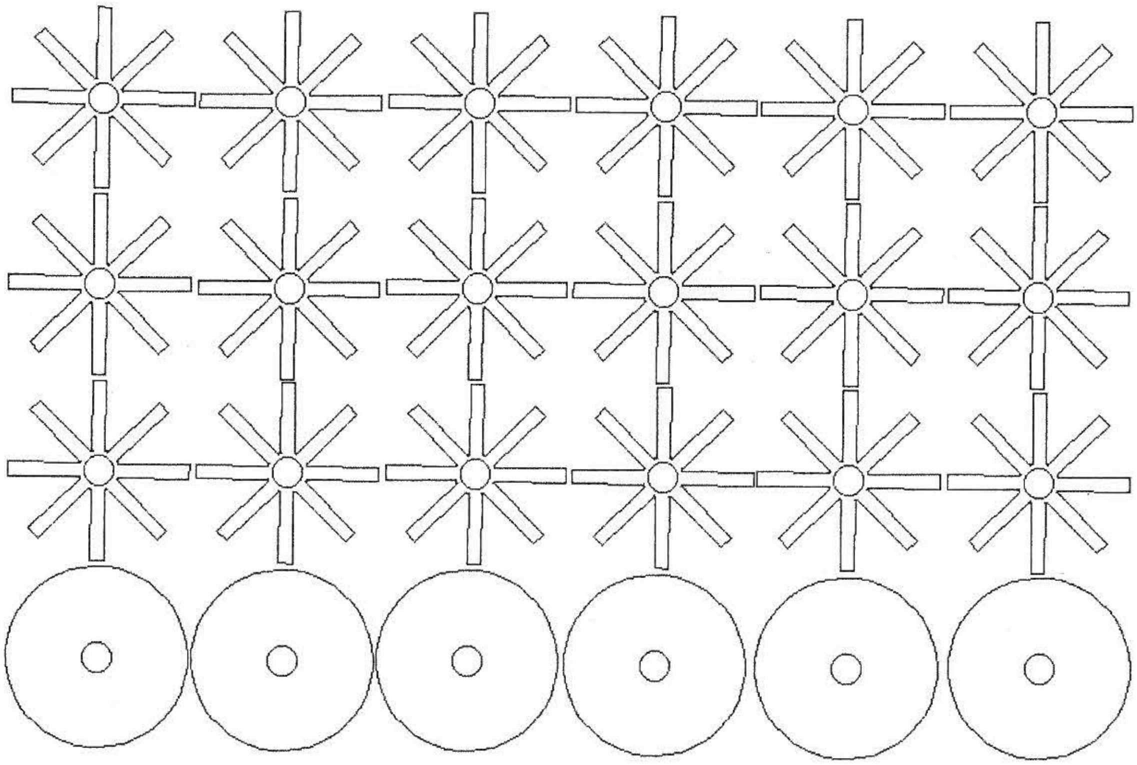


Fig. 7.13 Plot layout of impeller: 2mm thickness (Z-sliced)

Table 7.12. Results on impeller Z-sliced (2mm thickness)

Circumference cut	m	12,551
Area required	m²	0,167
Area used	m²	0,059
Area wasted	m²	0,108
Cutting time	sec.	2510,290
Computer time	sec.	416,496
Lamination	sec.	528

7.2.6. The impeller

Sliced: (Z directions)

Thickness: 3mm

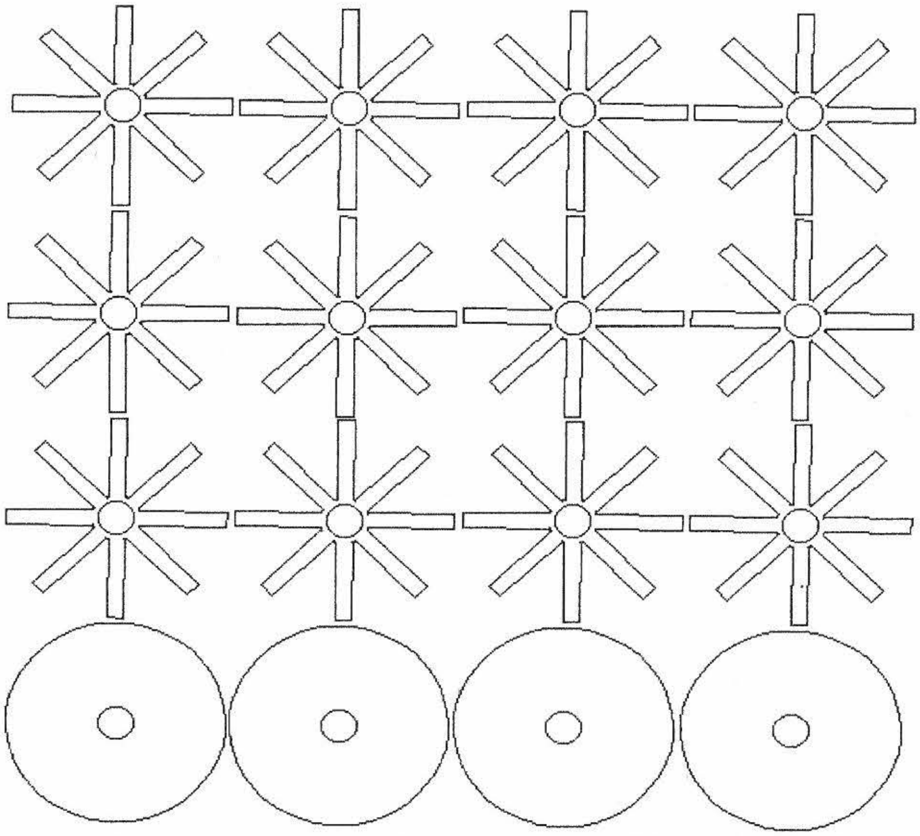


Fig. 7.14 Plot layout of impeller: 3mm thickness (Z-sliced)

Table 7.13. Results on impeller Z-sliced (3mm thickness)

Circumference cut	m	8,368
Area required	m^2	0,116
Area used	m^2	0,039
Area wasted	m^2	0,077
Cutting time	sec.	1673,527
Computer time	sec.	277,664
Lamination	sec.	352

7.2.7. Summary of the data obtained from the impeller:

Table 7.14. Summary of the impeller

	X-Y cut (1mm)	Z cut (1mm)	X-Y cut (2mm)	Z cut (2mm)	X-Y cut (3mm)	Z cut (3mm)
Circumference cut (m)	13,47	25,1	6,74	12,55	4,49	8,37
Area required m^2	0,21	0,34	0,11	0,17	0,067	0,12
Area used m^2	0,12	0,12	0,06	0,06	0,04	0,04
Area wasted m^2	0,09	0,22	0,05	0,11	0,027	0,08
Cutting time (hrs.)	0,75	1,39	0,37	0,7	0,25	0,46
Computer time (min.)	27,77	13,88	13,88	6,94	9,26	4,63
Lamination (min.)	35,2	17,6	17,6	8,8	11,73	5,87

Model 2: The chess piece (horse)

This model was chosen to illustrate a better comparison if any, in the slicing direction in engineering models, not only for cutting time and material usage, but for the final appearance as well.

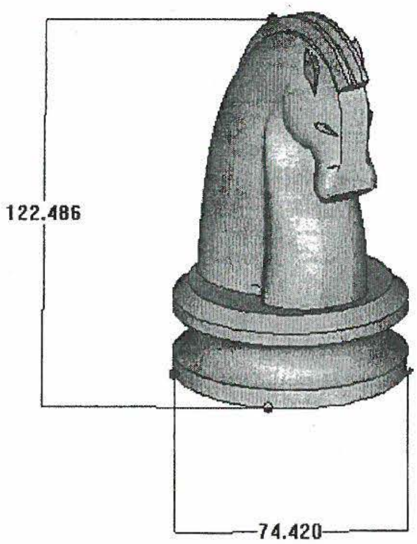


Fig. 7.15 Dimensional drawing of the horse

Photos are shown of the horse sliced in each direction to indicate the final appearances.

7.2.8. The Horse cut in the X direction.

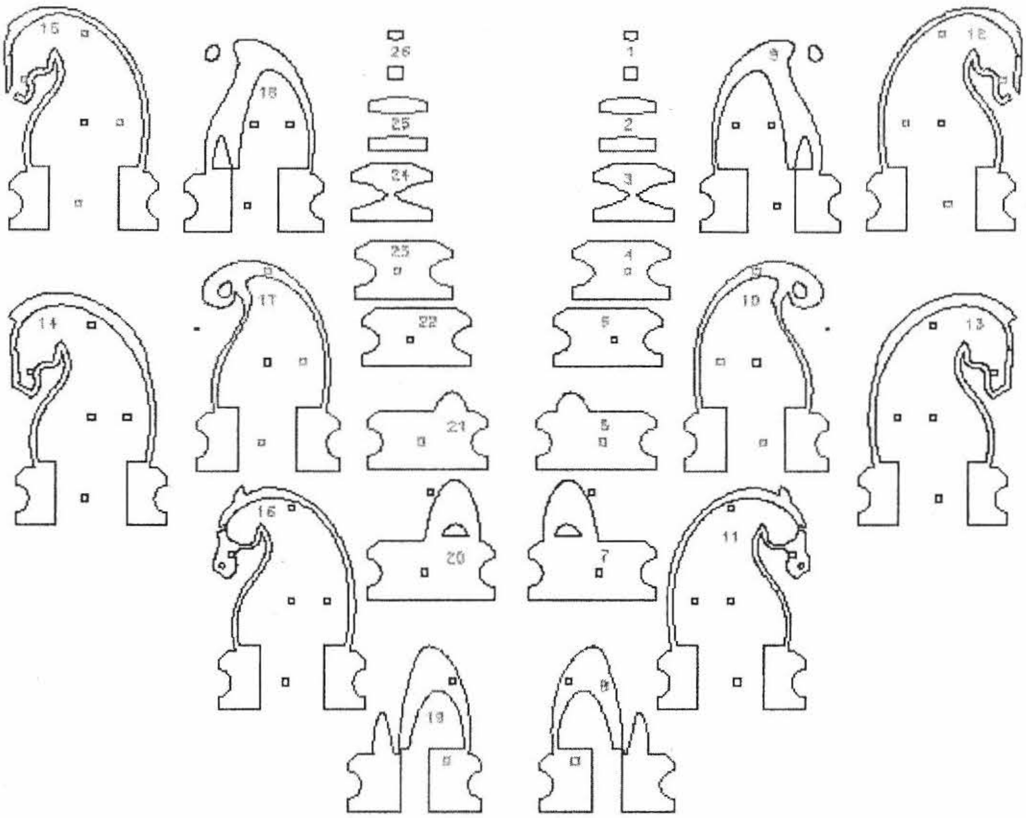


Fig. 7.16 Plot layout of the Horse sliced in the X direction

Table 7.15. Results of the horse cut in the X direction

Computer time	45min
Material thickness	3mm (X direction)
Area Required (Material)	0,253m²
Cutting time	40min 12sec

7.2.9. The Horse cut in the Y direction.

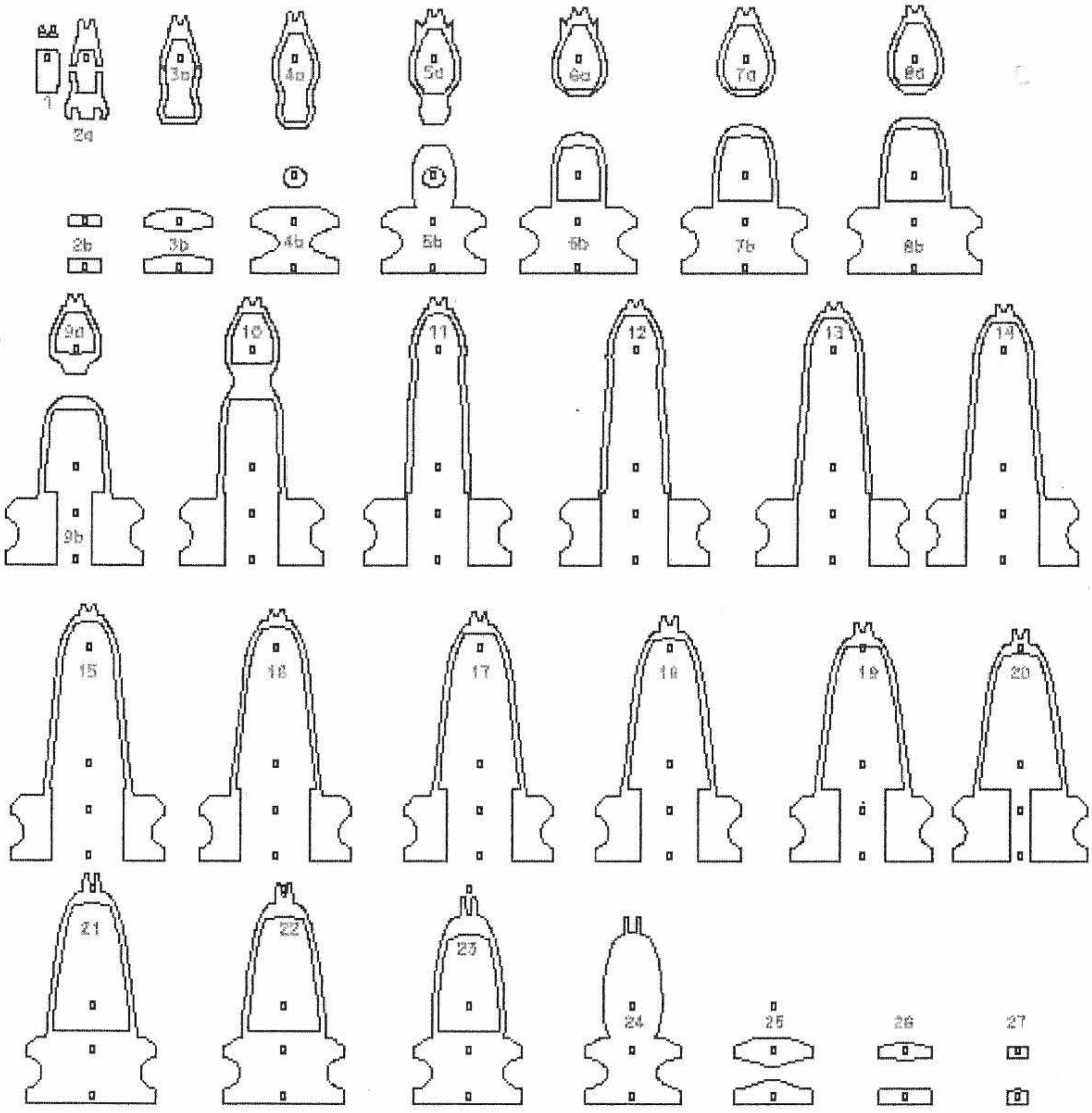


Fig. 7.17 Plot layout of the Horse sliced in the Y direction

Table 7.16. Results of the horse cut in the Y- direction

Computer time	40,5min
Material thickness	3mm (Y direction)
Area Required (Material)	0,28m²
Cutting time	41min 21sec

7.2.10. The Horse cut in the Z direction.

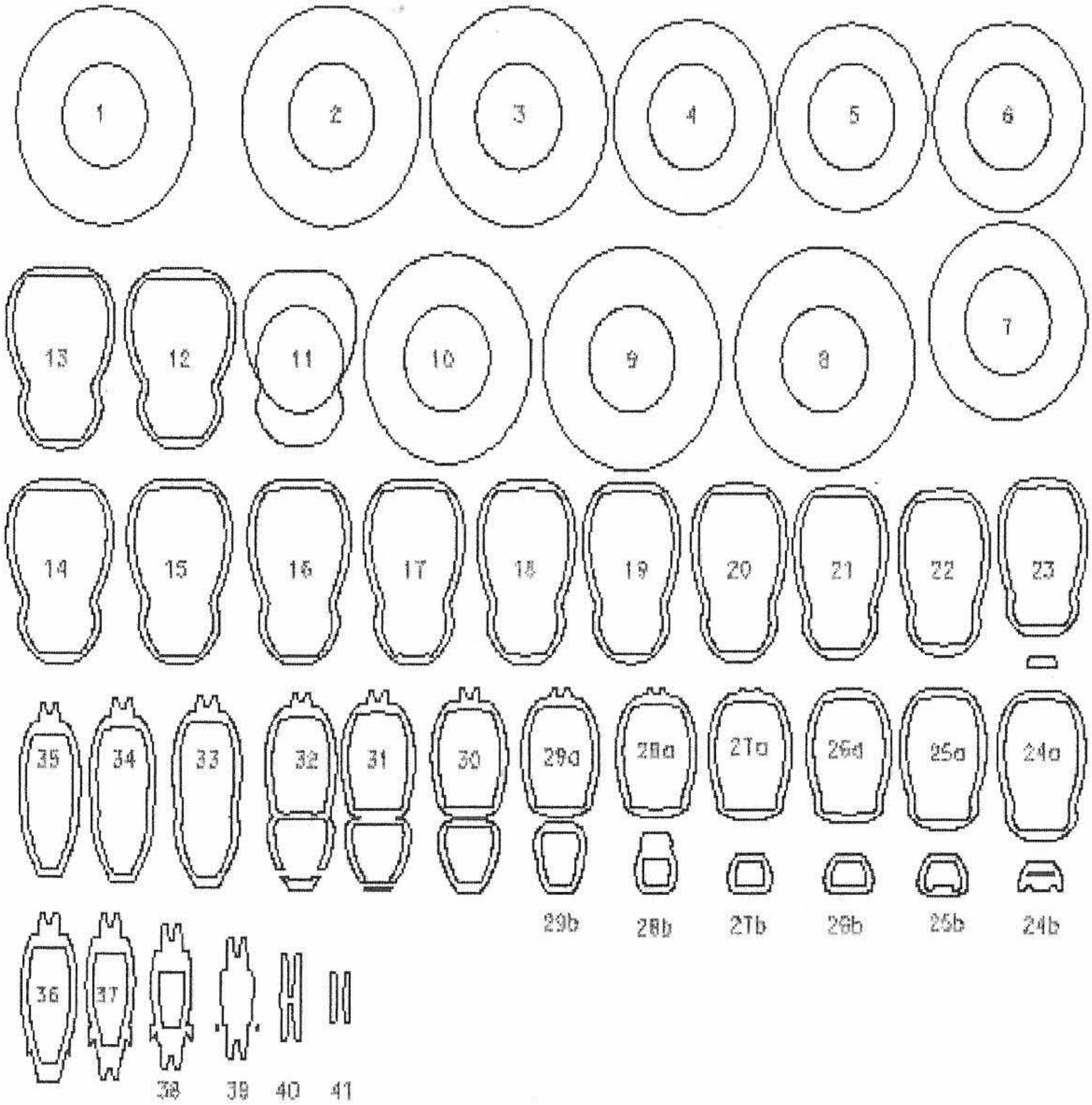


Fig. 7.18 Plot layout of the Horse sliced in the Z direction

Table 7.17. Results of the horse cut in the Z direction

Computer time	61,5min
Material thickness	3mm (Z direction)
Area Required (Material)	0,178m²
Cutting time	33min 57 sec

7.2.11. Results of the horse model

Table 7.18. Summary on different slice directions

Layout	X direction	Y direction	Z direction
Computer time	45min	40,5min	61,5min
Material thickness	3mm	3mm	3mm
Area Required (Material)	0,253m²	0,28m²	0,178m²
Cutting time	40min 12sec	41min 21sec	33min 57 sec

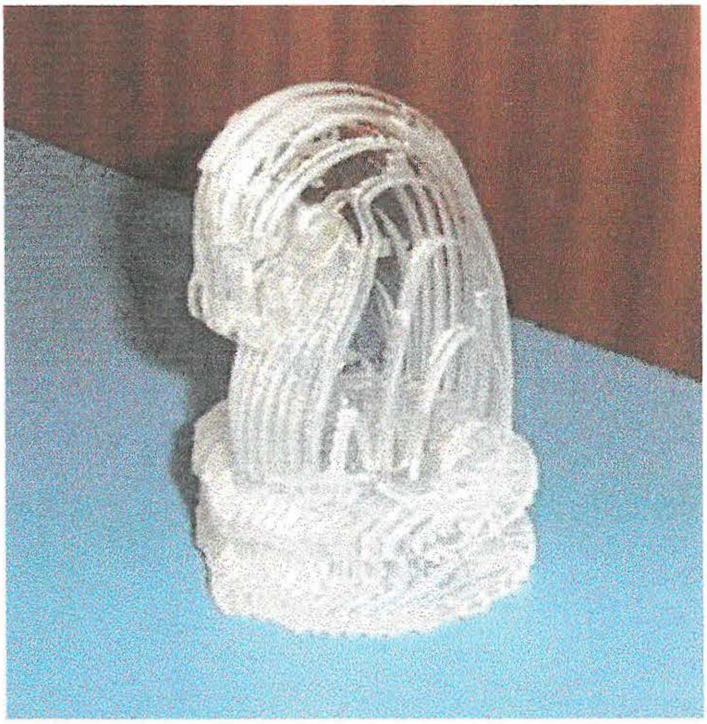


Fig. 7.19 Photo of the horse model sliced in the X direction

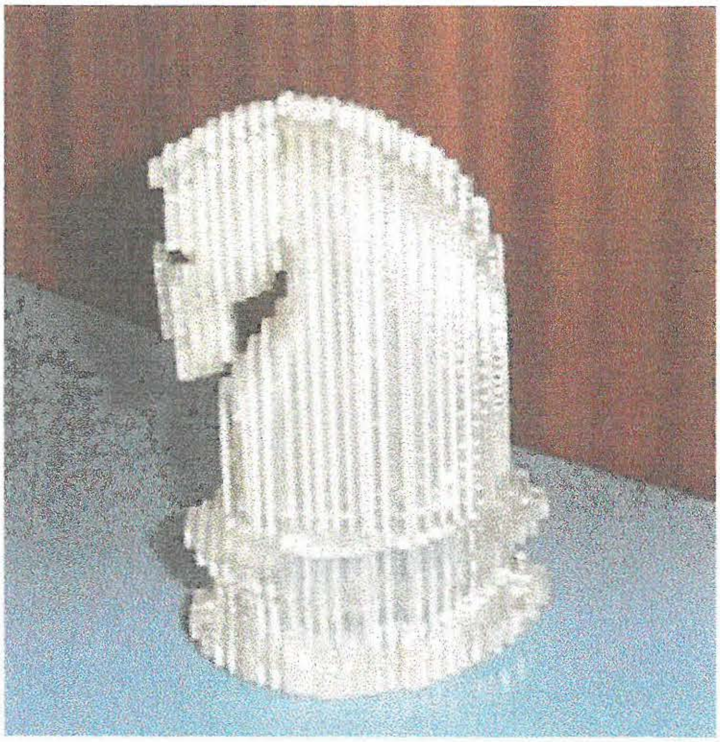


Fig. 7.20 Photo of the horse model sliced in the Y direction

Fig. 7.21 Photo of the horse model sliced in the Z direction

7.3. Laser-cut prototypes compared to other rapid prototyping methods.

Six models were build, 3 engineering prototypes and 3 architectural houses on four different machines, namely the SLS (DTM sinterstation 2000), SLA (SLA 250), Sanders SPI modelmaker II and the laser cutter. Comparisons were made and set out as follows:

Computer time

Laser cutter: The complete time layout for every step was recorded for every software used.

SLA, SLS: The computer time for the RP machines is an approximated time received from the Rapid Prototyping and Manufacturing Centre.

Sanders: The time was recorded for every model.

Manufacturing time

Laser cutter: The complete time layout for every step of cutting and manufacturing is shown (Appendix A).

SLA: The software, Magics, gives a time estimate on how long the machine takes to build the specific model.

SLS: Unfortunately, or the SLS, the software package used is unable to determine the manufacturing time. A formula used by the Rapid Prototyping and Manufacturing Centre based on experience is 6mm/h (the 6mm/h will include the warm-up time for the machine), which means that the model height divided by six gives the hours involved.

Sanders: The software gives time estimates on how long the machine takes to build the specific model.

Product costs

Laser cutter: Running costs multiplied by building time. (Cutting time/h x R140.40) according to the Rapid Prototyping and Manufacturing Centre.

SLA: Running costs multiplied by building time. (Manufacturing time/h x R149.50) according to the Rapid Prototyping and Manufacturing Centre.

SLS: Running costs multiplied by building time. (Manufacturing time/h x R149.50) according to the Rapid Prototyping and Manufacturing Centre.

Sanders: Running costs multiplied by building time. (Manufacturing time/h x R71.50) according to the Rapid Prototyping and Manufacturing Centre.

Material costs

Laser cutter: Model fully shown in appendix A

SLA: The mass obtained was equal to the volume multiplied by the density. The CAD software which gives the volume and density of the material used, is known to work out the mass. The mass multiplied by the R/kg gives the material costs with the resin density of 995 kg/m^3 and a price of R1400.00/kg.

SLS: The same as the SLA, with the SLS Duraform density of $887kg/m^3$ and a price of R605.00/kg

Sanders: The same as the SLA and SLS, with the Sanders wax density of 590,6kg/m^3 and a price of R505.12/kg

Maximum scale.

It is important to realise that not all the machines used, were able to build the model on the scale 1:1 (as shown on the dimensions drawings at the top of each table). The models scale table shows what the maximum scale of that specific prototype can be without any pieces grown separately and pasted together. All the engineering prototypes were calculated on the same scale, namely 1:1.

Furthermore, for all the architectural models, calculations were made on a scale 1:10, except for the models built with the laser cutter their calculations were made on prototypes ten times larger. It is important to consider the results of the buildings in that context.

Laser cutter: The maximum size that the apparatus is able to cut is 1000mm x 540mm x any height (depending on the number of layers used).

SLA: 250mm x 250mm x 250mm [33].

SLS: Diameter of 300mm and height of 360mm [8].

Sanders: 304,8mm x 152,4mm x 228,6mm [24].

Layer accuracy.

The layer accuracy is the step size in millimetres. This is the size the machines use to build a prototype in the Z direction. The lower the value of the step size, the better the detail. The size is given in the tables.

Laser cutter: The layers used in the laser cutter are usually the thickness of the material. To improve the detail in such a model, smaller step sizes (thinner materials) must be use.

SLA: Layer thickness of 0,1mm, 0,15mm and 0,2mm can be used [33].

SLS: Layer thickness of 0,07mm to 0,14mm is normally used [8].

Sanders: Layer thickness of 0,013mm to 0,13mm can be used [24].

Summary

The summary shows the total values of the engineering and the architectural models. The row "Ave. (max allowable scale)" indicates the average scale of the group, engineering or architectural, in relation to the others.

The actual calculations on the laser-cutter are shown in appendix A

7.3.1.Chess piece (Material: 3mm Acroglass)

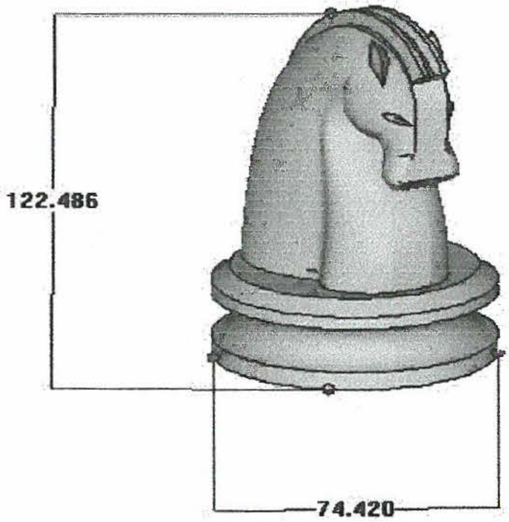


Fig. 7.22 Scale drawing (1:1)

Fig. 7.23 Prototype on laser cutter (scale 1:1)

Table 7.19. Summary on chess piece

Layout	SLA	SLS	Sanders	Laser cutter
Computer time	60min	30min	5min	64 min
Manufacturing time	1617min	1100min	2634min	82 min
Total time	***1677min***	***1130min***	***2639min***	***146 min***
Production costs	R4029.03	R2740.83	R3138.85	R126.36
Material costs	R235.73	R90.82	R50.48	R20.83
Total Cost	***R4264.76***	***R2831.65***	***R3189.33***	***R147.19***
Max. size (scale)	2:1	2,9:1	2,1:1	7,3:1
Layer Accuracy	0,15mm	0,10mm	0,10mm	3,00mm

7.3.2. **Fly-wheel cover** (Material: 3mm Acroglass)

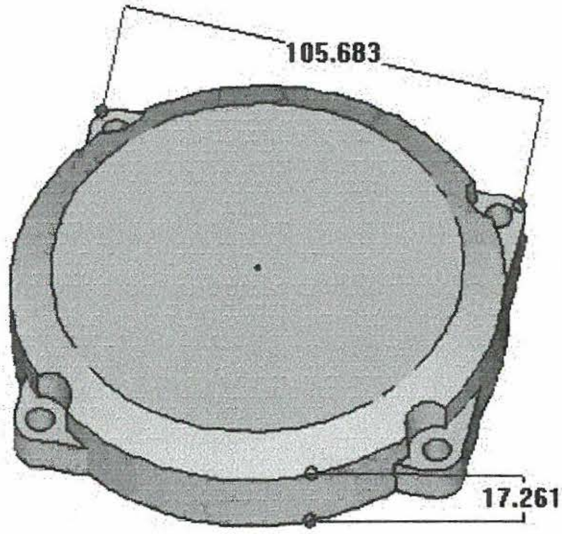


Fig. 7.24 Scale drawing (1:1)

Fig. 7.25 Prototype on laser cutter (scale 1:1)

Table 7.20. Summary on Fly-wheel cover

Layout	**SLA**	**SLS**	**Sanders**	**Laser cutter**
Computer time	60min	30min	7min	19 min
Manufacturing time	1021min	230min	1169,4min	37min 45sec
Total time	***1081min***	***260min***	***1176,4min***	***56min 45sec***
Production costs	R2544.00	R573.08	R1393.54	R76.05
Material costs	R110.68	R42.64	R23.70	R15.55
Total Cost	***R2654.68***	***R615.72***	***R1417.24***	***R91.60***
Max. size (scale)	2,1:1	3:1	1,9:1	4,5:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	3,00mm

7.3.3.Impeller (Material: 2mm and 3mm Acroglass)

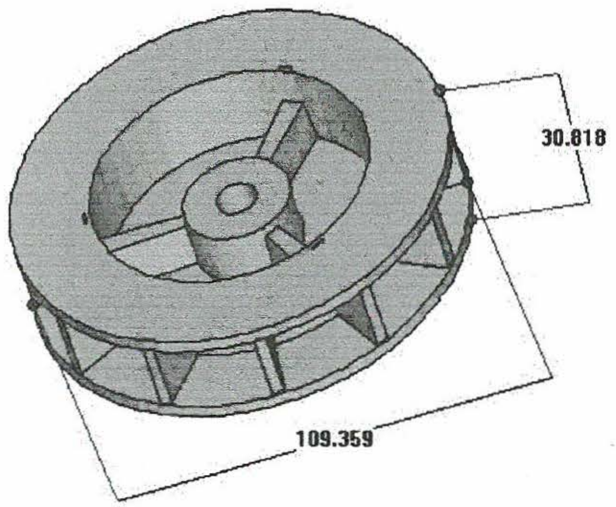


Fig. 7.26 Scale drawing (1:1)

Fig. 7.27 Prototype on laser cutter (scale 1:1)

Table 7.21. Summary of the impeller

Layout	SLA	SLS	Sanders	Laser cutter
Computer time	60min	30min	7min	25 min
Manufacturing time	1170min	310min	1336,2min	45 min
Total time	***1230min***	***340min***	***1343,2min***	***70 min***
Production costs	R2915.25	R772.42	R1592.31	R88.92
Material costs	R153.22	R59.02	R32.81	R19.96
Total Cost	***R3068.47***	***R831.44***	***R1625.12***	***R108.88***
Max. size (scale)	2,3:1	3,3:1	2,1:1	4,9:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	2mm and 3mm

7.3.4. House (Material: 1mm Acroglass)

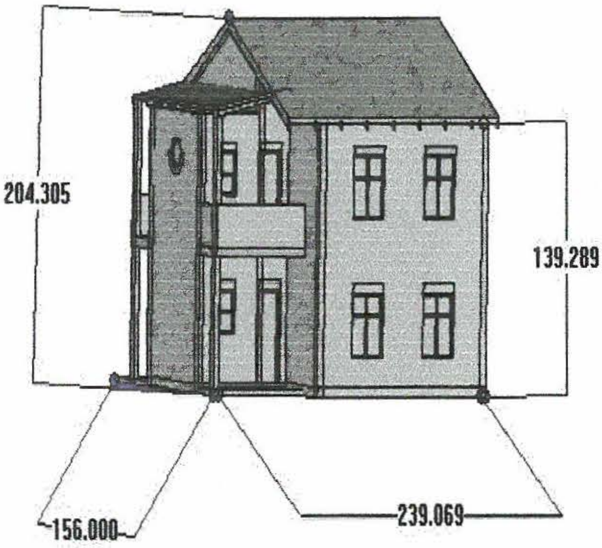


Fig. 7.28 Dimension drawing of prototype (1:1)

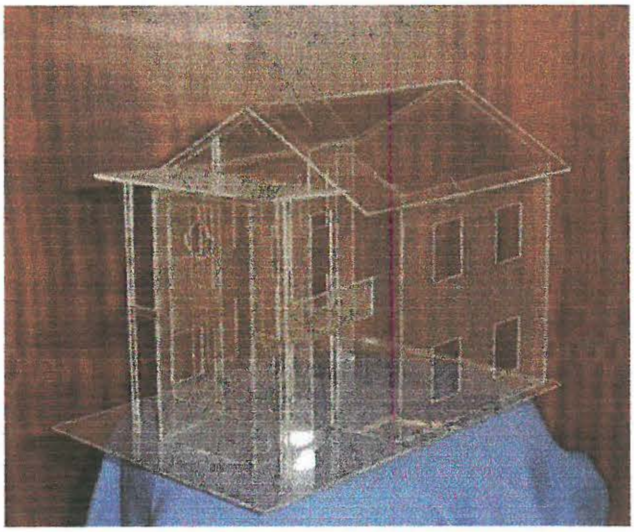


Fig. 7.29 Prototype on laser cutter (scale 1:1)

Table 7.22. Summary on the house

Layout	SLA	SLS	Sanders	Laser cutter
Computer time	60min	30min	5min	71 min
Manufacturing time	125min	204,3min	163,2min	71,16 min
Total time	***185min***	***234,3min***	***168,2min***	***142 ,16 min***
Production costs	R311.45	R509.05	R194.48	R133.85
Material costs	R1.72	R0.66	R0.36	R39.09
Total Cost	***R313.17***	***R509.71***	***R194.84***	***R172.94***
Scale build	1:10	1:10	1:10	1:1
Max. size (scale)	1,04:1	1,2:1	0,98:1	3,46:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	1,50mm

7.3.5.Hostel (Material: 1.5mm Acroglass)

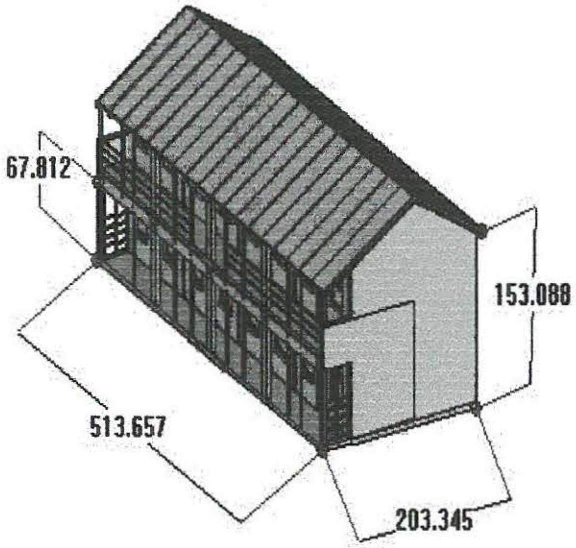


Fig. 7.30 Dimension drawing of prototype (1:1)

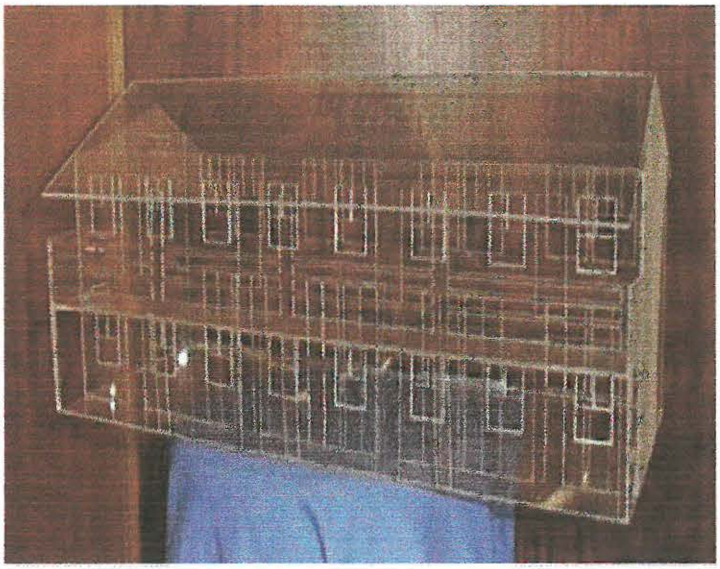


Fig. 7.31 Prototype on laser cutter (scale 1:1)

Table 7.23. Summary on the hostel

Layout	SLA	SLS	Sanders	Laser cutter
Computer time	60min	30min	6min	74 min
Manufacturing time	146min	200,1min	289,8min	105 min
Total time	***206min***	***230,1min***	***295,8min***	***179 min***
Production costs	R363,78	R498,59	R345.35	R200.77
Material costs	R4,16	R1,60	R0.88	R71.93
Total Cost	***R367,94***	***R500,19***	***R346.23***	***R272.70***
Scale build	1:10	1:10	1:10	1:1
Max. size (scale)	0,48:1	0,7:1	0,6:1	1,95:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	1,50 mm

7.3.6. **Beach house** (Material: 3mm Masonite)

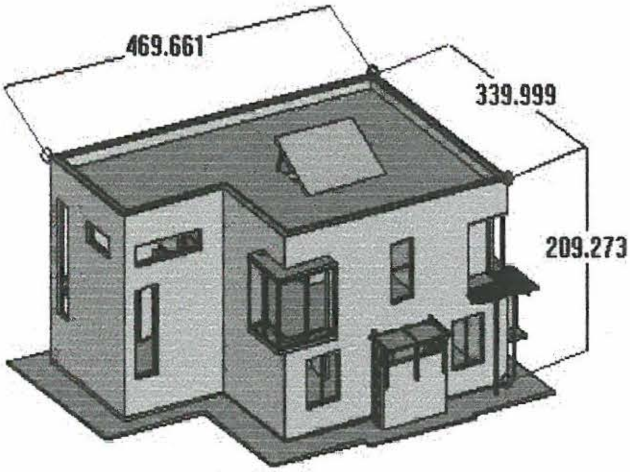


Fig. 7.32 Dimension drawing of prototype (1:1)

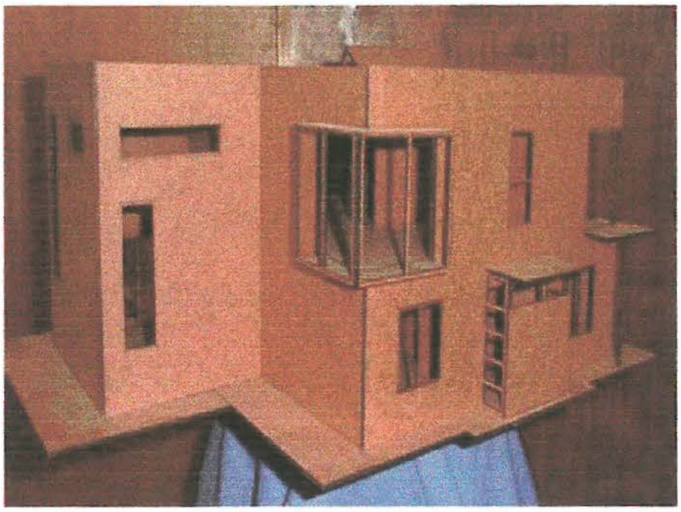


Fig. 7.33 Prototype on laser cutter (scale 1:1)

Table 7.24. Summary on the beach house

Layout	**SLA**	**SLS**	**Sanders**	**Laser cutter**
Computer time	60min	30min	5min	124 min
Manufacturing time	235min	209,27min	400,8min	230 min
Total time	***295min***	***239,27min***	***405,8min***	***354 min***
Production costs	R585.55	R521.43	R477.62	R218.02
Material costs	R11.51	R4.43	R2.46	R12.34
Total Cost	***R597.06***	***R525.86***	***R480.08***	***R230.36***
Scale build	1:10	1:10	1:10	1:1
Max. size (scale)	0,53:1	0,7:1	0,45:1	1,59:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	3,00 mm

7.3.7.Summary

Table 7.25. Summary of all the engineering prototypes

Engineering prototypes:	***SLA***	***SLS***	***Sanders***	***Laser cutter***
Total computer time	180min	90min	19min	108min
Total Manufacturing time	3808min	1640min	5139,6min	164,75min
Total time	***3988min***	***1730min***	***5158,6min***	***272,75min***
Total Production costs	R9488.27	R4086.33	R6124.69	R291.33
Total material costs	R499.63	R192.48	R106.99	R56.33
Total Cost	***R9987.90***	***R4278.81***	***R6231.68***	***R347.66***
Ave. (max. allowable scale)	2,1:1	3,1:1	2:1	5,6:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	1,50 mm(min.)

Table 7.26. Summary of all the architectural prototypes

Architectural prototypes:	***SLA***	***SLS***	***Sanders***	***Laser cutter***
Total computer time	180min	90min	16min	269min
Total Manufacturing time	506min	613,67min	853,8min	406,16min
Total time	***686min***	***703,67min***	***869,8min***	***675,16min***
Total Production costs	R1260.78	R1529.07	R1017.45	R552.64
Total material costs	R17.38	R6.67	R3.71	R123.36
Total Cost	***R1278.16***	***R1535.74***	***R1021.16***	***R676.00***
Scale build	***1:10***	***1:10***	***1:10***	***1:1***
Ave. (max. allowable scale)	0,68:1	0,86:1	0,67:1	2,3:1
Accuracy (deviation)	0,15mm	0,10mm	0,10mm	1,50mm(min.)

CHAPTER 8

Conclusions and recommendations

In the search for a cheaper, bigger and quicker prototyping technology, the following were recorded:

- **Software**

In this new era where the drawing board is replaced by computer-aided solid modelling and tool making with laser-powered rapid prototyping processes, it is important to note that the software used made this whole project possible. First of all software had to be found that would be able to do the slicing of a model drawn on a CAD package. It is important to distinguish between a 3D drawing, which is the prescription for most RP processes, and 2D drawings. For 3D drawings, the models are normally in .stl format, which means that it is a solid model constructed of small triangles to produce a positive volume. There were three processes identified, discussed in chapter 2, to do the slicing of a solid model. Both the Magics and MicroStation Section method are able to do the slicing of a solid model that is in .stl format. The Boolean method is useful when a model is not in a .stl file format.

Surface modelling can best be sliced when turned into a solid model using the method discussed in paragraph 2.1.1.2. When turned into a solid model, any of the three methods can be used.

With two-dimensional drawings not much can be done. It can be printed out as is or a 2D architecture drawing, etc. can be redrawn from all four the sides and cut and pasted together.

Two programs, EngraveLab and Nu-tel, are then used to convert the data in a format acceptable for the plotter. It is important to note what type of files is importable into these programs. The most commonly type used was the *.plt* file type.

- **Materials**

To study all the materials available is nearly impossible and the doors are opened for further research. First of all, the thickest material the 30W laser could cut was 3mm thick Perspex. This can only be achieved when the laser beam is perfectly focussed ± 38mm from the lens (Fig. 5.2). The materials examined were UHI, Acrylic Glass and Masonite. The UHI and Acrylic Glass are commonly available in 1,5mm, 2mm and 3mm thickness with the Masonite available in 3mm thickness. UHI as prototyping material is not prescribed, as it releases strong fumes when cut and, because of its flexibility, it stays sticky on the edges long after the cutting. Black burn marks sometimes occur. When a see-through material is necessary, Acroglass will be the ideal material to use. No burned or sticky edges occur and it is readily available.

The speed at which a material can be cut (Fig. 5.3, 5.4 and 5.5.) has a significant influence on the product cost. When a large amount of material is necessary, e.g. large sheets for architectural models, then Masonite is the most cost-effective. Masonite will also present the finest detail (Table 5.12.). It is the easiest material to cut and provides a good finish. The only problem is black burn marks on the edges that have been cut.

- **Slicing choice**

According to the two types of models built, architectural or engineering, the direction of the slicing has a huge impact on the product cost.

In Table 7.7, results on an architectural model, a townhouse, can be seen. The cutting time of a model sliced in the X-Y direction is on average 10,5 times less then the same model sliced in the Z direction. The area of material required is also on average 5,8 times less than when building in the X-Y direction. The computer time or slicing time is 3,6 times less than the Z-sliced direction. As these results show, architectural models should be sliced in the X-Y direction. The Z-direction should only be considered when one or more walls are twisted into an S or Circular shape.

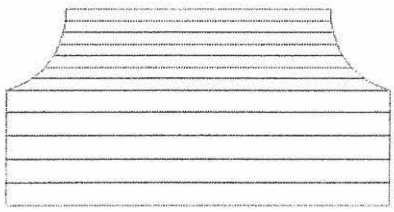
The results obtained by slicing an engineering model, the impeller, show that there is not such a big difference in the slice direction as mentioned in the architectural model. The summary in Table 7.14. shows that the cutting time of the impeller sliced in the X-Y direction is on average 1,9 times less then the same model sliced in the Z direction, while the architectural model was 10,5 times longer for the Z-direction. The area of material required is also only 1,6 times less when building in the X-Y direction. The computer time is interesting: the X-Y direction takes about 2 times longer than the impeller sliced in the Z direction. As these results show, there is not such a big difference in the computer time, cutting time and area of material required as discovered for architectural models.

Another engineering model, the chess piece (Fig. 7.15.), was sliced in the X, Y and Z directions. Table 7.18. confirmed that there is very little difference in the computer time, cutting time and area of material required. As shown by means of engineering prototypes, the product costs will not differ much in accordance with the slicing choice. The importance of these models was to determine at which sliced direction the best-looking model could be achieved. To make a rule for the best direction of slice is difficult. However, the best engineering results were achieved when the slicing direction was perpendicular to the longest extension. For circularly shaped models, like the fly-wheel cover (Fig.7.24.) and the impeller (Fig.7.26.), it is best to slice the model in the direction in which the circle is cut as a whole. Thus it means that a model which is symmetrical on both the X and Y axes (like the cone Fig.2.1.), the slicing should be parallel to the circle.

- **Material thickness**

In both the engineering and architectural prototypes, the material thickness is important. For architectural models the material thickness mostly determines the model strength. But when scale is important, like in the case of the townhouse (Fig.7.1), a wall thickness of 6mm will be served best by cutting two 3mm Masonite pieces instead of three 2mm or four 1,5mm pieces.

The same is applicable to the engineering prototypes. When a square block of 12mm x 12mm has to be built, it will be more cost-effective and better-looking if four 3mm pieces



are used. But in the case of the cone (Fig.2.1.), the model will look the best when built with the thinnest sliced pieces to produce a smooth curve.

Fig. 8.1 Model sliced in 3mm as well as 1.5mm pieces

The figure above is a good example of using 3mm pieces for the square part and the 1,5mm pieces where the curve commences (take into consideration that the slicing on computer must be set on 1,5mm for the curve as well). A conclusion can be made that one should always try to use the thickest material available if the model allows it.

- **Lamination**

Reference holes are cut to align a model in order to ensure a good finish. The size of the reference holes can vary according to the size of the model. The best results were obtained when reference pins were cut of the same material as that used to build the model, as this made it less visible. Pin sizes of 2mm by 3mm were used. If big models are cut, the reference pin size can be increased (Fig.6.2 and Fig.6.3.) The pin direction is always perpendicular to the slice direction and placed so that all, or the maximum amount of slices, are caught. It is important to note that when a model is hollow, reference pins are not prescribed. The referencing is mainly used in engineering models. It is only possible in architectural models if the slicing is in the Z direction.

The numbering of the sliced parts (or encoding) is only helpful when one has a lot of small loose parts. This ensures the correct sequence of the parts, but introduces an extra cutting sequence. Figure 6.7. and Figure 6.8. are clear examples of the above mentioned. The types of adhesives are fully discussed in Chapter 6. For Masonite models, White glues were used (Alcolin and Ponal) and in the Perspex models, Super glues (Bostic Superglue). This field is still open for further research.

- **Products**

The models built are again categorised into the two main groups, namely engineering and architectural prototypes. These models are compared to the other available rapid prototyping methods and summarised as follows:

Table 8.1. Summary of engineering prototypes

Engineering prototypes:	***SLA***	***SLS***	***Sanders***	***Laser cutter***
Total time	3988min	1730min	5158,6min	272,75min
Total Price	R9987.90	R4278.81	R6231.68	R347.66
Ave. (max. allowable scale)	2,1:1	3,1:1	2:1	5,6:1

Table 8.2. Summary of architectural prototypes

Architecture prototypes:	***SLA***	***SLS***	***Sanders***	***Laser cutter***
Total time	686min	703,67min	869,8min	675,16min
Total Price	R1278.16	R1535.74	R1021.16	R676.00
Scale build	1:10	1:10	1:10	1:1
Ave. (max allowable scale)	0,68:1	0,86:1	0,67:1	2,3:1

As shown in the tables above, larger, quicker and cheaper prototypes, compared to the other available methods, can be built. The greatest advantage of this method is first of all the size. The above-calculated models can on average be built 2,7 times bigger than by using the SLA, SLS and Sanders RP- methods. Secondly, the price: the production costs when using the laser cutter are 14,3 times less for the engineering models and 1,9 times less for the architectural models. The cost is huge in the case of architectural models. A scale of 1:10 was used for the calculation of the product costs and time taken with the SLA, SLS and Sanders machines. Thirdly, the time (computer time and manufacturing time) is 13,3 times less in the engineering prototypes and 1,1 times less in the architectural models when the laser-cutting method is used instead of the other machines mentioned.

The only disadvantage of this process is losing fine detail in the model. Where the laser cutting process uses steps of 1,5mm, 2mm and 3mm, most other processes use step sizes of 0,12mm.

This disadvantage leads to a new combination of rapid prototyping methods. The idea will be to produce a model where the low detail section is built with the laser cutting method and concurrently the high detailed section made up by SLA, SLS or Sanders etc. processes. The different sections will then be pasted together to form a prototype consisting of a combination of rapid prototyping methods, which even may include CNC machining. This will ensure a well-finished prototype that is ready for manufacturing and cheaper and quicker to build. A good example is the Fly-wheel cover (Fig. 7.24) where the base (17.261mm as shown) can be build with the laser cutting process and the more complex curved shape build on the SLS sinterstation etc. This idea opens a new field of

prototyping and further research is necessary (Fig. 8.2).

Fig. 8.2 Fly-wheel cover manufactured using concurrent engineering[2].

[2] The base was manufactured using the laser cutting method and the more complex curved shape built on the SLS sinterstation.

The laser-cutting method is ideal for models where little detail is necessary, for concept models and for concurrent product development, as explained in the diagrammatic layout below.

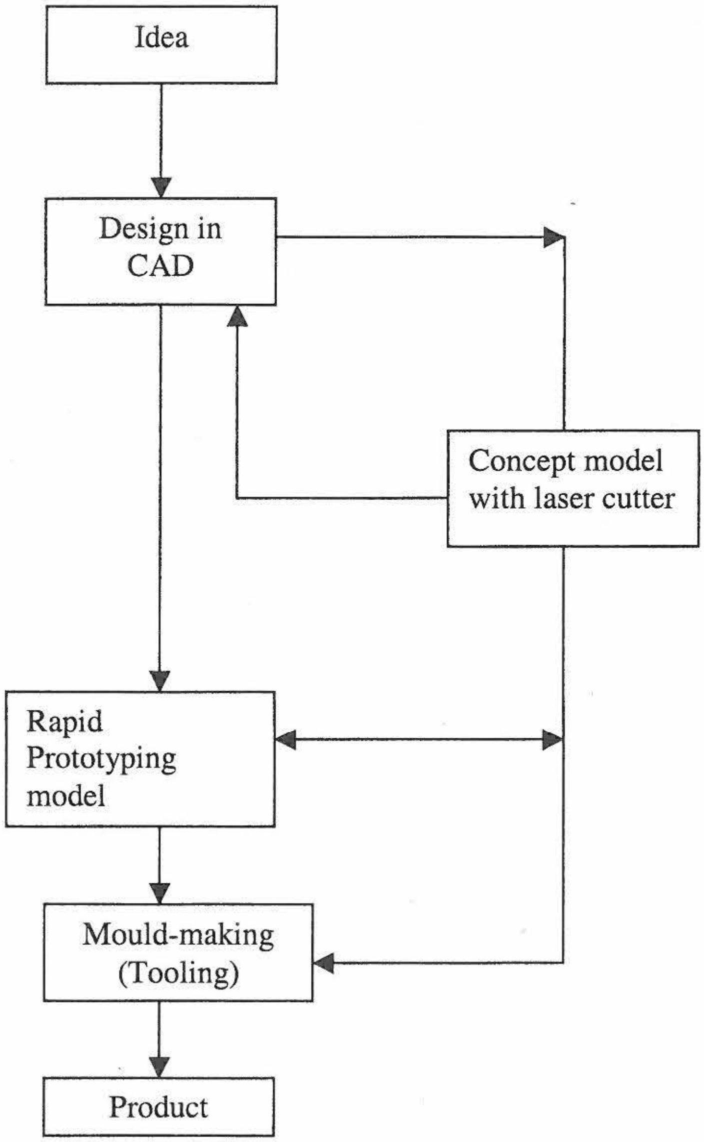


Fig. 8.3 Diagrammatic layout of product development

- **Recommended improvements**

Although this method works more effectively than anticipated, there is still room for improvement.

1.) **Stronger laser.** A more powerful laser will open the door to more cuttable materials with larger thicknesses and decreased cutting time.

2.) **Better controller.** A wide range of plotter controllers is available that will produce a smoother circular cut.

3.) **More compatible Software.** The plotter software can be upgraded to make it possible to import a wider range of file types.

4.) **X-Y gantry system.** A larger table or gantry can be used to further enlarge the size of the final product.

5.) **Air purifier.** The air purifier only purifies the air by filtering out all the solid waste from the air but the fumes still remain.

6.) **Vibrations on the gantry.** There are still vibrations on the table due to the rotating Z gantry, and the support table can be improved.

APPENDIX A

Calculations of the laser-cut prototypes

A) **Calculations on the chess piece** (Material: 3mm Acroglass)

1. **Computer time on laser cutter:**

Magics	11 min
MicroStation	46 min
Engravelab	4 min
NuTel	3 min
Total time	**64 min**

2. **Manufacturing time on laser cutter:**

Cutting time	54 min
Laminating time	28 min
Total time	**82 min**

3. **Accuracy on laser cutter:**

Step size used 3mm

4. **Material cost:**

Area required x R/m^2 = (0,4449 x 0,35683) x R131.20

= **R 20.83**

5. **Building costs:**

Cutting time x R/min = (54 x 2,34)

= **R 126.36**

6. **Max. scale:**

Max. size on model (scale 1:1) = diameter of 74,42mm

Max. possible size = diameter of 540mm

Max. scale (540/74.42) **7,3:1**

B) Calculations on the Fly-wheel cover (Material: 3mm Acroglass)

1. **Computer time on laser cutter:**

Magics	3 min
MicroStation	12 min
Engravelab	2 min
NuTel	2 min
Total time	**19 min**

2. **Manufacturing time on laser cutter:**

Cutting time	32 min 30sec
Laminating time	5 min 15sec
Total time	**37 min 45sec**

3. **Accuracy on laser cutter:**

Step size used	3 mm

4. **Material cost:**

Area required x R/m^2 = (0,49 x 0,244) x R130.06

= **R 15.55**

5. **Building costs:**

Cutting time x R/min = (32,5 x 2.34)

= **R 76.05**

6. **Max. scale:**

Max. size on model (scale 1:1) = diameter of 120mm

Max. possible size = diameter of 540mm

Max. scale (540/120) **4,5:1**

C) Calculations on the impeller (Material: 2mm and 3mm Acroglass)

1. Computer time on laser cutter:

Magics	4 min
MicroStation	18 min
Engravelab	2 min
NuTel	1 min
Total time	**25 min**

2. Manufacturing time on laser cutter:

Cutting time	38 min
Laminating time	7 min
Total time	**45 min**

3. Accuracy on laser cutter:

Step size used 3mm and 2mm

4. Material cost:

Area required x R/m^2 = (0,45673 x 0,33613) x R130.02

= R 19.96

5. Building costs:

Cutting time x R/min = (38 x 2,34)

= R 88.92

6. Max. scale:

Max. size on model (scale 1:1) = diameter of 110mm

Max. possible size = diameter of 540mm

Max. scale (540/110) **4,9:1**

D) Calculations on the house (Material: 1,5mm Acroglass)

1. Computer time on laser cutter:

Magics	5 min
MicroStation	51 min
Engravelab	6 min
NuTel	9 min
Total time	**71 min**

2. Manufacturing time on laser cutter:

Cutting time	57,16 min
Laminating time	14 min
Total time	**71,16 min**

3. Accuracy on laser cutter:

Max. deviation X and Y direction, 1mm (Wall thickness used)

4. Material cost:

Area required x R/m^2 = (0,300669) x R130.01

= **R 39,09**

5. Building costs:

Cutting time x R/min = (57,2 x 2,33)

= **R 133.5**

6. Max. scale:

Max. size on model (scale 1:1) = bottom of 239mm

Max. possible size = 540mm (with)

Max. scale (540/156) **3,46:1** (test length = 3,46 x 239 = 827.3mm)

E) Calculations on the hostel (Material: 1,5mm Acroglass)

1. Computer time on laser cutter:

Magics	4 min
MicroStation	56 min
Engravelab	9 min
NuTel	5 min
Total time	**74 min**

2. Manufacturing time on laser cutter:

Cutting time	85 min 50sec
Laminating time	19 min 10sec
Total time	**105 min**

3. Accuracy on laser cutter:

Max. deviation X and Y direction, 1,5mm (Wall thickness used)

4. Material cost:

Area required x R/m^2 = (0,5533) x R130.00

= **R 71.93**

5. Building costs:

Cutting time x R/min = (85,8 x 2,34)

= **R 200.77**

6. Max. scale:

Max. size on model (scale 1:1) = bottom of 513,7mm

Max. possible size = 1000mm (length)

Max. scale (1000/513,7) **1,95:1** (test with = 1,95 x 203,3 = 395,7mm)

F) Calculations on the beach house (Material: 3mm Masonite)

1. **Computer time on laser cutter:**

Magics	6 min
MicroStation	88 min
Engravelab	14 min
NuTel	16 min
Total time	**124 min**

2. **Manufacturing time on laser cutter:**

Cutting time	93 min 10 sec
Laminating time	137 min
Total time	**230 min 10 sec**

3. **Accuracy on laser cutter:**

Max. deviation X and Y direction, 3mm (Wall thickness used)

4. **Material cost:**

Area required x R/m^2 = (1,186) x R10.40

= **R 12.34**

5. **Building costs:**

Cutting time x R/min = (93,17 x 2,34)

= **R 218.02**

6. **Max. scale:**

Max. size on model (scale 1:1) = top of 340mm

Max. possible size = 540mm (with)

Max. scale (540/340) **1,59:1** (test length = 1,59 x 469,7 = 746mm)

REFERENCES

[1] **Beach, D.P. Shotwell, A. Essue, P.** Applications of laser and laser systems, 1st ed. New Jersey, PTR Prentice Hall, 1993

[2] **Bentley.** MicroStations95 User's guide, 5th ed. Belgium, Brics NV, 1996

[3] **Braham, J. Stephen, J. M.** Laser cutting technique builds big prototypes. Machine design, 8 February 1996, p. 22.

[4] **Chryssolouris, G.** Laser machining theory and practice, 1st ed. New York, Spinger-verslag, 1991

[5] **Dam, J.** LLCC (Laminated Laser Cut Cavities). Rapid tooling & Manufacturing, Scandinavian conference & exhibition, 1997, p. 1 – 6.

[6] **De Beer, D.J.** Design, Technology and entrepreneurship as factors of international competitiveness. Science Park and School for Design Technology and Visual Art, vol.1, 2000, p.4

[7] **De Beer, D.J.** Rapid Prototyping - Art to part. Lecture prepared for the Pro Engineer users group vol.1, 2000, p.1, 2

[8] **DTM** . The Sinterstation System 2000 user's guide, April 1998

[9] **D'Urso, P.S.** Stereolithographic (SL) Biomodelling. Rapid Product Development, 1995, p. 13.

[10] **Dvorak, P.**Modeling, drafting, and prototyping. Machine design, 6 April 1995, p. 83-99.

[11] **Engravelab**. Engravelab User's manual, 1st ed. CADlink Technology Corporation, 1995

[12] **Grimm, T.A.** SLS and SLA different technologies for different applications. Prototyping Technology: International '97, 1997, p. 130 – 136.

[13] **Hech, J.** The Laser Guidebook , 2end ed. New York, McGraw-Hill, 1992

[14] **Hugo, I.** Isel-Schrittmotor-Controller C116-4 Hardwarebeschreibung, 1st ed. Leibolzgraben, Isel-automation

[15] **Hussey, B Wilson, J Maritime, C.** Structural Adhesives directory and databook, 1st ed. London, Chapman & hall, 1996

[16] **Iannini, R.E.** Build your own working fibre-optic infrared and laser space-age projects, 1st ed. Blue Ridge, TAB Books, 1987

[17] **Jacobs, P.F.** Rapid Prototyping & Manufacturing Fundamentals of Stereolithography, 1st ed. U.S.A. , Society of Manufacturing Engineers, 1992.

[18] **Johnson, J.** A look inside Lasers, 1st ed. Oxford, Blackwell Raintree, 1981

[19] **Lees, W. A.** Adhesives and the engineer, 1st ed. London, Mechanical Engineering Publication Limited, 1989

[20] **Myers, Y. Norton, J.** Rapid manufacturing with rapid tooling. Prototyping Technology: International '98, 1998, p. 30 – 34.

[21] **Nederman.** Nederman products catalogue, June 1994

[22] **Prawel, D.** CAD & Computing. Rapid Prototyping & Tooling State of the Industry: 1999 Worldwide Progress Report, 1999, p. 130-144.

[23] **Raymond, M.K.** Unravelling rapid prototyping methods. American machinist, June1996, p. 24-31.

[24] **Sanders prototype.** Modelworks ™ User's Manual, May 1998

[25] **Silfvast, W.T.** Laser Fundamentals, 1st ed. New York, Cambridge University Press, 1996

[26] **Synrad.** Series 48 Lasers Operation and service manual, 2nd ed. Mukiltoe,Synrad Inc. , 1996

[27] **Techno.** Linear motion products catalogue H830, 1st ed. Canada, Techno Division of Designatronics, 1996

[28] **Weber, M.J.** Handbook of Laser Science and Technology, 1st ed. Florida, CRC Press, 1991

[29] **Wilson, J. Hawkes, J.F.B.** Lasers Principles and applications. 1st ed. New York, Prentice Hall, 1997.

[30] **Wohlers, T.** RP materials. Rapid Prototyping & Tooling State of the Industry: 1998 World-wide Progress Report, 1998, p. 76 – 78.

[31] **Wohlers, T.** Why rapid prototyping? Rapid Prototyping & Tooling State of the Industry: 1997 World-wide Progress Report, 1997, p. 11-14.

[32] **Young, T.** The crafter's guide to glues, 1st ed. Pennsylvania, Chilton Book Company, 1995, p.2 – 76.

[33] **3D systems.** SLA – 250 Build Station user's guide, June 1995

ABBREVIATIONS AND ACRONYMS USED

BRH	Bureau of Radiological Health
CAD	Computer-aided Design
CDRH	Centre for Devices and Radiological Health
CO_2	Carbon dioxide
CSP	Cross-section prototyping
DC	Direct current
FDM	Fused deposition modeling
Laser	Light amplification by stimulated emission of radiation
PVA	Polyvynal acetate
RP	Rapid prototyping
SLA	Stereolithography
SLS	Selective laser sintering
SMMEs	Small, Micro and Medium Enterprises
TEA	Transversely exited atmospheric (pressure)
TEM	Transverse electromagnetic mode
UHI	Ultra-high impact