EFFECTIVENESS OF PRIMECAST® AND PMMA ADDITIVE MANUFACTURING PROCESSES TO PRODUCE PATTERNS FOR INVESTMENT CASTING

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ABSTRACT

Investment casting produces parts that need little or no secondary machining operations. Wax patterns used for investment casting are typically produced through an injection moulding process with the accompanying tooling. However, cost and lead time to produce tooling can be high and complexity is limited by conventional machining ability. Additive manufacturing provides an alternative method for producing investment casting patterns that can provide dramatic time and cost savings. This paper reports on a study to determine the advantages and limitations of using PrimeCast® and PMMA patterns produced for investment casting by two different additive manufacturing technologies.

1. INTRODUCTION

Producing a near-net shape product by pouring metal into a mould is a manufacturing process that can be traced back thousands of years [1]. The process was refined when more complex designs were required by producing, through injection moulding, complex wax patterns that could be burned out before the metal was poured into the mould; the process is known as investment casting or lost wax casting [2]. It is known for its ability to produce components of excellent surface finish, dimensional accuracy and complex shapes. Investment casting is especially useful for making castings of complex and near-net shape geometry, where machining may not be possible or too wasteful. Small, thin walled castings with the highest level of detail and quality can be produce using the investment casting process [3]. However, the cost associated with investment casting rose and the lead times increased as the designs became even more complex. Also, when used in short runs, the production of the required wax patterns can be disproportionately expensive and time consuming. On the other hand, additive manufacturing (AM) offers a faster, less expensive alternative to creating investment casting patterns, particularly at the product development stage [4].

Worldwide, additive layer manufacturing, now formally known as AM and popularly called three-dimensional (3D) printing, is a technology that is rapidly growing in usefulness and capability, and South Africa is no exception. This technology was originally known as rapid prototyping, a process by which components are produced directly from computer models by selectively curing, depositing or joining materials in successive layers. These technologies have traditionally been limited to the manufacture of models suitable for product conception but, over the past decade, have quickly developed into a new production standard called AM. More accurately described, AM has become a professional production technique which is clearly distinguished from conventional methods requiring material removal. Although extensive research and development continue to be done and need to be done, the technology is today being used for commercial manufacturing purposes, although still only in certain niches. We are now beginning to see AM used for the construction of a range of functional end use components [5]. AM is internationally recognised as “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” as defined by ASTM [6].

The term investment casting has been derived from the typical use of a mobile ceramic slurry to form a mould with a highly smooth surface. The conventional investment casting process is a complex, multi-step process and starts with choosing a pattern material. Although conventional investment casting is still popular, it suffers from high tooling investments for producing wax patterns; therefore investment casting is excessively expensive for low-volume production typical in prototyping, pre-series, customised or specialised component productions [7]. A comparison of the basic steps in the production of a conventional investment cast component with investment casting using an AM pattern with a ceramic shell mould is shown in Figure 1 below.

In this study a comparison was done of patterns built by PrimeCast® and PolyMethyl Methyl Acrylate (PMMA) respectively, which were produced using AM technology. The investment casting patterns in PrimeCast® were built at Central University of Technology (CUT), while those in PMMA were built at Vaal University of Technology (VUT). The patterns were built from a design which had features such as thin walls, cavities, surface finish and angles that pose challenges to conventional investment casting, but which could be easily produced by AM technologies.

The focus of this study is a field in which little research has been done. Initial work done by Truscott et al. [9] on rapid prototyping techniques in the medical sector was found. It was also found that there has been significant work done on PMMA [10] [11] [12] and PrimeCast® [13] [14] [15] trying to show that they can replace the lost wax process in investment casting. However, no research was found on comparing the benefits and limitations of PrimeCast® and PMMA patterns for investment casting. This comparison of the two types of AM patterns is expected to assist the foundry industry in achieving the most beneficial investment casting results by selecting the most appropriate AM technology for a particular application.

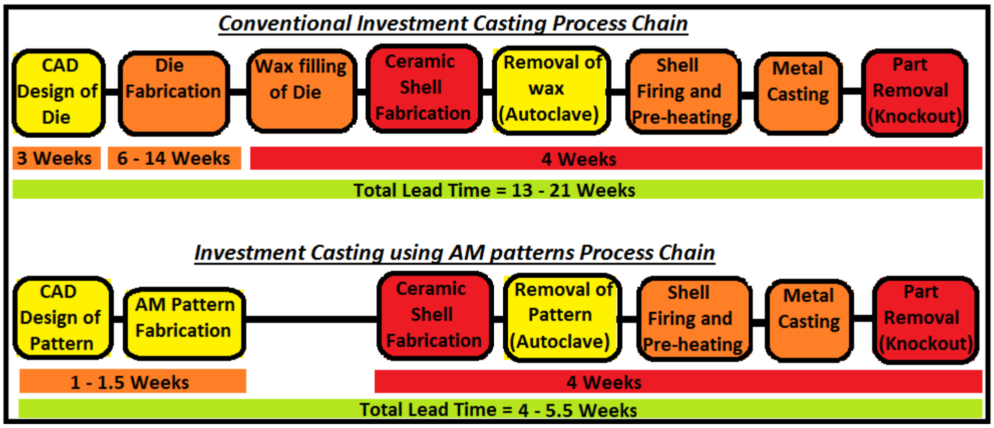

Figure 1. Comparison of conventional Investment casting with investment casting using AM patterns processes [8]

2. EXPERIMENTAL PROCEDURE

Investment casting patterns based on a standard test part were built from PrimeCast® and PMMA at CUT and VUT, respectively, at the same time. Metrology was performed on one pattern of each type using micro Computed Tomography (micro-CT) scannning because the complex geometry of this pattern could not be fully and accurately detected by other metrology techniques. Usually, the micro-CT scanners are used for industrial, non- destructive testing due to the superior resolution possible and for quantitative dimensional analysis. Micro-CT scan data of different features of the patterns were compared with the CAD design. This geometrical comparison shows the benefits and limitations of the two AM pattern making technologies under investigation.

2.1 Standard test part

A standard investment casting test part was used to compare patterns produced by the two types of AM processes. Figure 2 shows the test part as originally designed in the tooling projects of the FP6 Framework of the European Commission (EC) [8]. Every feature on this standard part has a specific purpose as described in Table 1.

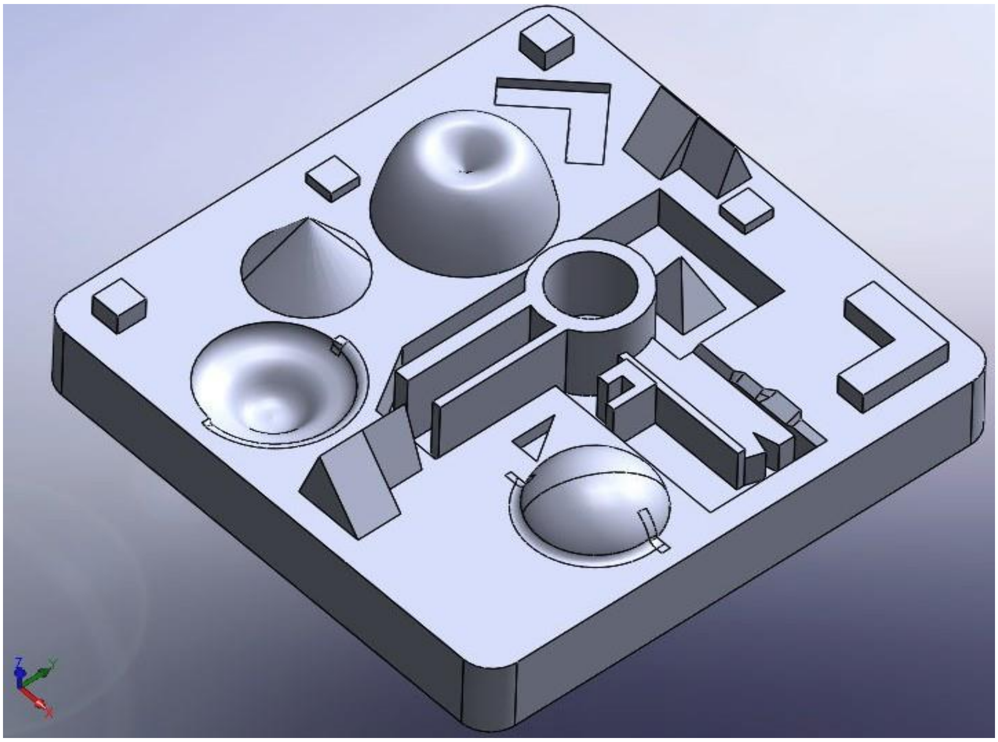

Figure 2. Standard FP6 Framework test part

Table 1: Feature and purpose of each geometry of the standard test part [8].

Feature	*Purpose*	*Quantity and Nominal size*
Cubes	Straightness, repeatability, linear accuracy	2 (8 x 8 x 8 mm) 2 (8 x 8 x 4 mm) (Half-cube)
Rectangular Protrusion	Perpendicularity, linear accuracy	1 (25 x 8 x 8 mm)
Pyramid	Angularity, accuracy	1 (12 x 17 x 20 mm)
Sphere (half)	Symmetry, repeatability of a constantly changing sloping profile, axial runout, radial runout	1 (ø35 mm)
Cone	Constant sloping profile, taper, axial runout, radial runout, symmetry	1 (ø30 x 26 mm)
Free-form (conical)	Non-constant sloping profile axial runout, radial runout, symmetry	1 (ø40 x 30 mm)
Free-form (sinkhole)	Non-constant sloping profile axial runout, radial runout, symmetry	1 (ø30 x 20 mm)
Wedges	Angularity	(X direction 20 x 20 mm) (Y direction 20 x 25 mm)
Rectangular Hole	Perpendicularity	1 (25 x 8 x 5 mm)
Cylindrical Hole/ Hollow Cylinder	Concentricity, circularity, accuracy	1 (ø30 x ø20 x 27 mm)
Triangular Hole	Angularity, perpendicularity	1 (10 x 8 x 4 mm)
Flat thin walls	Parallelism, thickness	1 (35 x 27 x 5 mm) 1 (35 x 27 x 3 mm)
Square base	Flatness, straightness, parallelism	1 (150 x 150 mm)
Mechanical features	Competence of machine to build particular features (visual inspection)	Free-form, chamfer, fillet
Yes/No Features	Machine's ability to build certain	Small triangular hole, small

	features (visual inspection)	cross-shaped hole, thin walls

2.2 Building of patterns

Eight patterns of each were built in PrimeCast® and PMMA, respectively, at the same time at CUT and VUT. An EOSINT P385 machine was used to manufacture PrimeCast® patterns at CUT. The machine uses a laser sintering (LS) process which is an AM process based on layer by layer powder spreading and successive laser sintering [13]. During LS, particles of powder are fused together by heat from a high-power laser to form a solid, three- dimensional object. The PMMA patterns built at VUT were manufactured using a Voxeljet VX 500 machine which uses a binder jetting process. In binder jetting two materials are used, namely a powder based material and a liquid binder. The binder acts as an adhesive between the powder particles and the layers. The binder is selectively deposited through fine nozzles (jetted) to join powder particles into layers and these layers of material are subsequently bonded onto each other to form a solid, three-dimensional object [14]. The patterns as-built are shown in Figure 3.

(a) **(b)**

Figure 3. (a) PrimeCast® and (b) PMMA test part patterns.

2.3 Metrology of patterns

The metrology on the patterns was performed using a General Electric Phoenix V|Tome|X L240/NF180 micro-CT scanner at Stellenbosch University (SU). A micro-CT scanner is an X- ray inspection machine that uses X-ray imaging and computed tomography to produce 3D images on a small scale at very high resolution, with voxel sizes down to 1μm or smaller. It allows 2D X-ray inspection of materials, as well as 3D CT scans of materials, to investigate and analyse the inside and outside of any object non-destructively. It makes use of differences in the X-ray attenuation properties of materials to reconstruct a 3D structure. It uses the same measurement principles as used in CT scanners in hospitals [16]. An object to be scanned is placed between the X-ray source and the detector. The object is exposed to a focused narrow X-ray beam and the absorbed radiation is measured with a sensor on the side opposite to the sample as shown in Figure 4. The procedure is repeated from different angles around the object to produce a full 3D reconstruction.

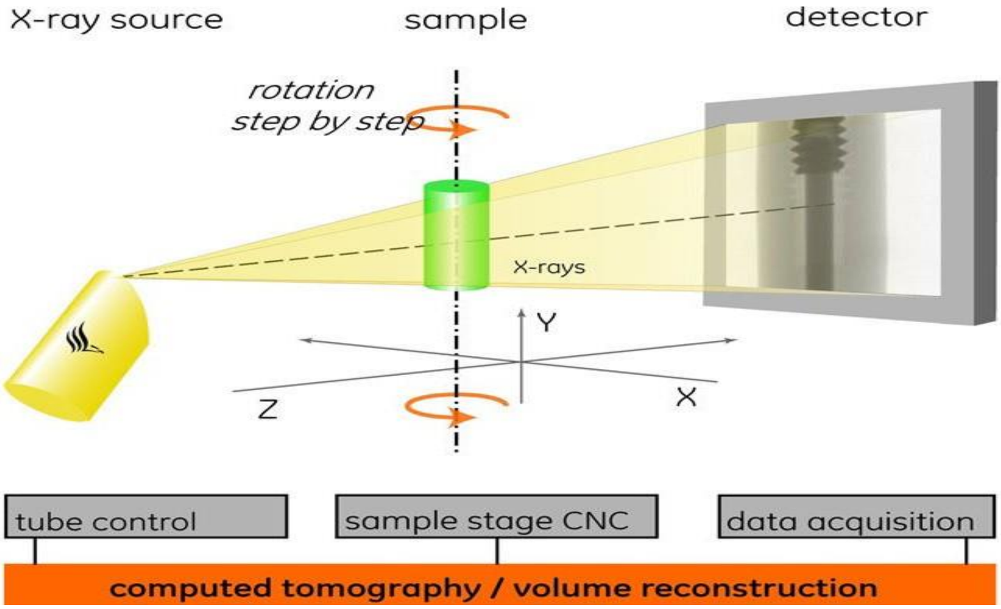

Figure 4. Schematic illustration of the measurement principle of a micro-CT scanner [17].

Two patterns, one each in PrimeCast® and PMMA, were scanned using the SU micro-CT scanner. The X-ray settings used were 200 kV and 100 µA. The machine acquires 3000 images in a full rotation with an image acquisition time of 600 ms per image, with no averaging and no skipping of images [17]. Detector shift was activated to minimize ring artefacts. The sample was positioned on the scanner's rotating stand at an angle so that no feature was parallel to the X-ray beam as it rotated, also ensuring that the object would not move during scanning. During rotation any feature that is parallel to the X-ray beam cannot be detected by the detector. Background calibration was performed and the scan time was approximately 30 minutes per scan. Reconstruction of the sample was done with system-supplied Datos reconstruction software. Analysis was performed with Volume Graphics VGStudio Max 3 voxel data analysis and visualization.

3. RESULTS AND DISCUSSION

The micro-CT scan data was compared with the CAD data of the patterns. The data set was colour-coded according to deviations between the AM patterns and the CAD design. Deviation values ranged between -0.30 mm and +0.30 mm. Green indicates the best fit, while yellow denotes areas where the pattern dimensions are larger than the original CAD dimensions. On the other hand, blue indicates areas where the pattern dimensions are smaller than the CAD dimensions.

3.1 Custom CT images of PrimeCast® and PMMA patterns

The custom images of the patterns displayed different colours depending on the deviation in mm for both PrimeCast® and PMMA as indicated in Figures 5 and 6. From Figure 5 it is clear that the results of the PrimeCast® pattern display more green on almost every feature. Blue can be seen towards the edges of the square base, edges of cubes and edges of rectangular protrusions. The results of the PMMA pattern shown in Figure 6 indicate more blue on the features that have repeatability of constantly changing sloping profiles such as half spheres and cones. Similarly, features that have both axial and radial runout such as cones and free-form features (sinkhole and conical) display blue, as well as some points on the square base and top edges of almost every feature.

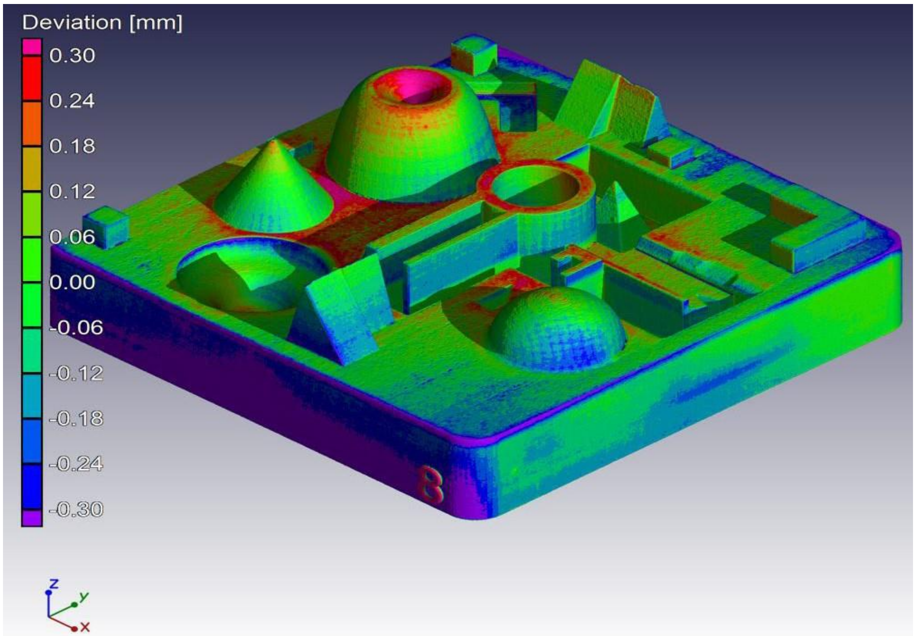

Figure 5. Comparison between the CAD design and the PrimeCast® pattern

Each specific feature of each of the PrimeCast® and PMMA patterns was analysed and the results were tabulated in Table 2 below. On the PrimeCast® pattern, features such as the cone and triangular hole have a very small deviation range, while features such as cubes and the square base have a wider range. The PMMA pattern provides small ranges on the triangular hole only, while features such as cubes, rectangular protrusions and the square base have a much wider deviation range than the PrimeCast® pattern.

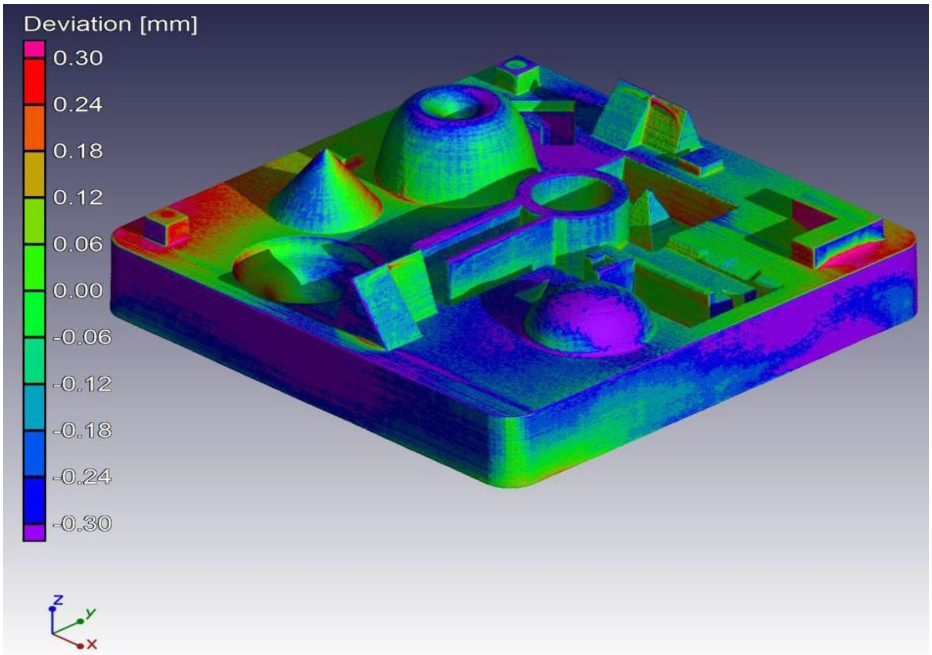

Figure 6. Comparison between the CAD design and the PMMA pattern

Table 2: Deviation results for each geometric feature of the standard test part.

Feature	***Purpose***	***Overall deviation range (mm)***	
		PrimeCast®	***PMMA***
Cubes	Straightness, repeatability, linear accuracy	-0.24 to +0.24	<-0.3 to >+0.3
Rectangular Protrusion	Perpendicularity, linear accuracy	-0.18 to +0.18	-0.3 to +0.3
Pyramid	Angularity, accuracy	-0.06 to +0.06	-0.12 to +0.12
Sphere (half)	Symmetry, repeatability of a constantly changing sloping profile, axial runout, radial runout	-0.24 to +0.12	<-0.3 to 0
Cone	Constant sloping profile, taper, axial runout, radial runout, symmetry	-0.06 to 0.06	-0.24 to +0.24
Free-form (conical)	Non-constant sloping profile axial runout, radial runout, symmetry	-0.06 to >+0.3	<-0.3 to +0.06
Free-form (sinkhole)	Non-constant sloping profile axial runout, radial runout, symmetry	-0.18 to +0.18	-0.3 to +0.3
Wedges	Angularity	-0.24 to +0.06	-0.3 to +0.18
Rectangular Hole	Perpendicularity	-0.24 to +0.06	-0.3 to +0.06
Cylindrical Hole/ Hollow Cylinder	Concentricity, circularity, accuracy	-0.18 to +0.18	<-0.3 to +0.06
Triangular Hole	Angularity, perpendicularity	-0.06 to +0.06	-0.06 to +0.06
Flat thin walls	Parallelism, thickness	<-0.3 to +0.06	<-0.3 to +0.12
Square base	Flatness, straightness, parallelism	-0.3 to +0.18	<-0.3 to >+0.3

The PrimeCast® and PMMA patterns showed good accuracy on geometrical features that indicate orientation such as angularity, perpendicularity and parallelism. Both patterns were however not very accurate in terms of features showing position such as axial runout, radial runout and concentricity. The PrimeCast® pattern results indicated good accuracy on features with form checks (straightness, circularity, cylindricity, and flatness).

3.2 Relative surface deviation graphs for the PrimeCast® and PMMA patterns

Deviation graphs provide fast graphic summaries of the data acquired from the patterns. Figures 7 and 8 show the relative surface deviation graphs obtained from the two types of patterns. For both patterns an asymmetric distribution of deviation from the CAD geometry is observed. The deviation from an ideal Gaussian distribution to the left (larger positive deviation) is more pronounced for the PMMA pattern than for the PrimeCast® pattern. At zero deviation, the PrimeCast® pattern has a relative surface of 12.3% while that of PMMA is 9.7%. This confirms the impression gained from the colour images in Figures 5 and 6 that the PrimeCast® pattern generally correlates closer with the CAD model.

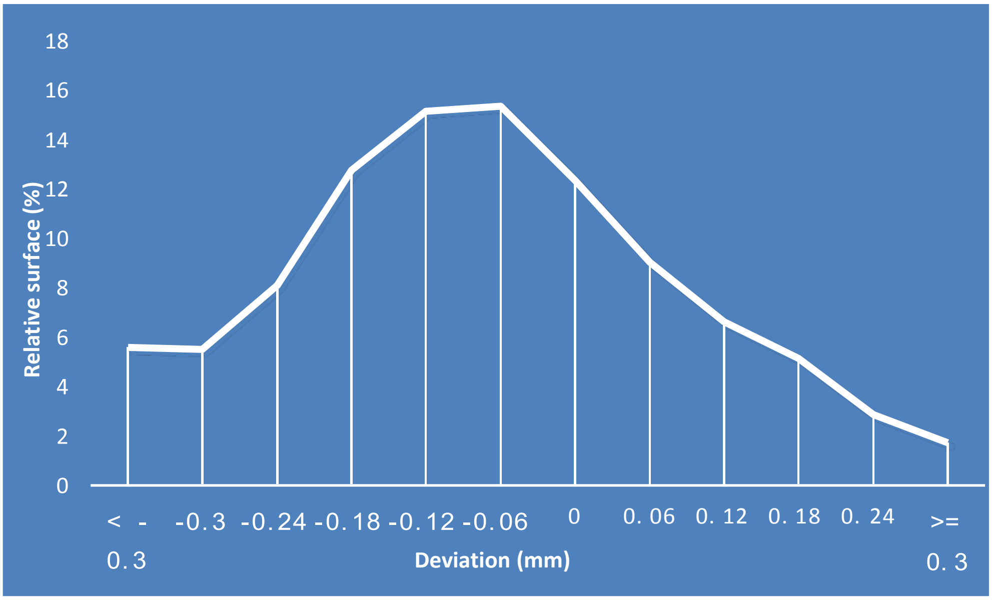

Figure 7. Relative surface deviation graphs of PrimeCast® pattern

The percentage of relative surface on the negative side of the graph on the PMMA pattern is around 40% compared to 30% of the PrimeCast® pattern. This means that there was more shrinkage on the PMMA pattern as compared to PrimeCast® pattern. The positive deviation was almost the same for both patterns.

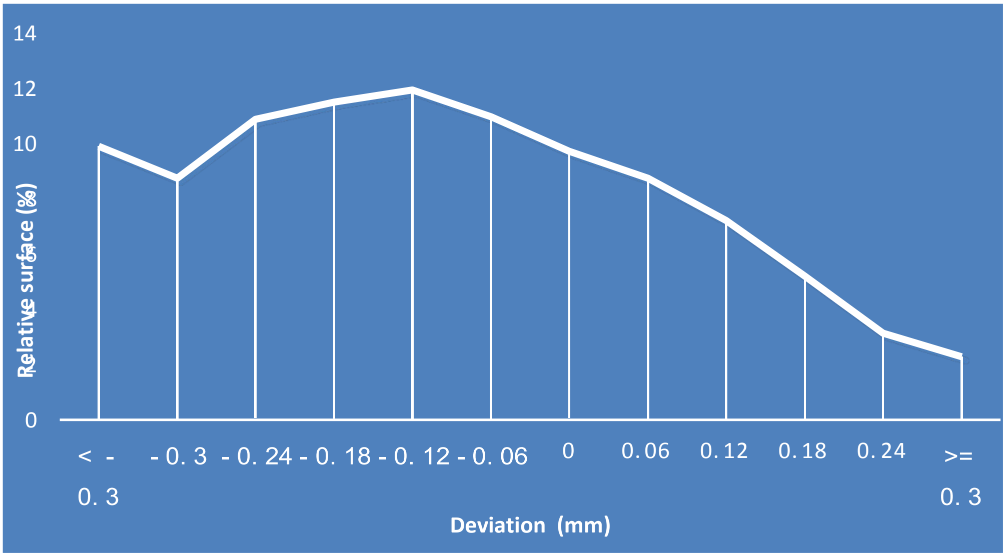

Figure 8. Relative surface deviation graphs of PMMA pattern

4. CONCLUSION

In this study comparisons were done between the CAD design and the patterns built from two different AM technologies. Both technologies were able to produce the required part within acceptable tolerances, but it is also clear that they do not show the same accuracy. In general the PrimeCast® pattern performed slightly better compared to the PMMA pattern in terms of accuracy. Future work in this research include producing investment casting moulds from the patterns presented here. Aluminium and titanium alloys will be cast into the moulds and metrology will again be performed on the produced parts.

5. ACKNOWLEDGEMENT

The financial support of the South African Department of Science and Technology through the Collaborative Program in Additive Manufacturing is gratefully acknowledged (Contract № CSIR-NLC-CPAM-15-MOA-CUT-01).

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