

ASSESSMENT OF SURFACE FINISH AND DIMENSIONAL ACCURACY OF TOOLS MANUFACTURED BY METAL CASTING IN RAPID PROTOTYPING SAND MOULDS#

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ABSTRACT

In this paper, an initial assessment of the quality parameters of the surface finish and dimensional accuracy of tools made by metal casting in rapid prototyping (RP) sand moulds is undertaken. A case study from a local tool room, dealing with the manufacturing of an aluminium die for the lost wax process, is employed. Modern techniques, including surface roughness analysis and three dimensional scanning, are used to determine and understand how each manufacturing step influences the final quality of the cast tool. The best surface finish obtained for the cast die had arithmetic average roughness (Ra) and mean average roughness (Rz) respectively equal to 3.23 μ m and 11.38 μ m. In terms of dimensional accuracy, 82% of cast-die points coincided with the Computer Aided Design (CAD) data, which is within the typical tolerances of sand cast products. The investigation shows that mould coating contributes slightly to the improvement of the cast tool surface finish. The study also found that the additive manufacturing of the sand mould was the chief factor responsible for the loss of dimensional accuracy. These findings indicate that machining will always be required to improve the surface finish and the dimensional accuracy of cast tools in RP sand moulds.

OPSOMMING

In dié artikel word 'n aanvanklike beoordeling van kwaliteitsparameters in terme van oppervlak-afwerking en dimensionele akkuraatheid van gietstukke vervaardig deur metaal gieting in snel-prototipering sand gietvorms gedoen. 'n Gevallestudie aangaande die vervaardiging van 'n aluminium gietstuk vir die verlore wasproses word gebruik. Moderne tegnieke, soos oppervlak-grofheidsanalise en drie-dimensionele skandering, word gebruik om te bepaal hoe elke vervaardigingstap die finale kwaliteit van die gietstuk beïnvloed. Die beste oppervlak afwerking verkry vir die gietstuk het Ra en Rz waardes van 3.23 μ m en 11.38 μ m onderskeidelik gehad. In terme van dimensionele akkuraatheid, het 82% van die gietvormpunte ooreengestem met die rekenaarnumeriesbeheerde data wat binne tipiese toleransies is vir sandgegote produkte. Die ondersoek wys dat gietvorm oppervakbedekking effens bydra tot die verbetering van die gietstukafwerking. Ook is gevind dat die snel-prototiperingvervaardigingsproses van die sandgietvorm die hooforsaak is vir die verlies aan dimensionele akkuraatheid. Dié bevindings dui aan dat masjinerie altyd nodig sal wees om die oppervlak-afwerking en dimensionele akkuraatheid te verbeter.

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1. INTRODUCTION

Rapid prototyping (RP) or additive manufacturing processes for the fabrication of sand moulds include laser sintering (LS) and three dimensional printing (3DP) [1]. In LS, resin-coated sand grains are sintered together by the heat generated by a laser beam. 3DP technology, on the other hand, makes use of selective deposition of foundry resin on sand grains to achieve their agglomeration into solid parts. In both systems, post-treatment of the mould is required to obtain optimal strength of the parts. This is achieved by curing the mould in a furnace. The two RP systems locally available in South Africa are the Direct Croning Casting Process (DCCP) based on LS, and the Z-Cast process based on 3DP [2].

RP processes for sand moulds do not require time consuming and costly pattern making. They are therefore extensively employed, especially in the automotive foundry industry, to produce casting prototypes used for design and metallurgical evaluation prior to mass production. RP processes decrease the lead casting design time and accelerate the introduction of new components.

Recent technological developments of these RP processes include quick manufacturing time with the advent on the market of large machines capable of producing several moulds in a few hours. The S Max machine from ExOne Company is an example of such equipment based on 3DP [3]. Another modern trend is the use of RP sand moulds to manufacture aerospace components. This is already happening locally with the production of the Adept light craft engine block from laser sintered moulds [4]. Internationally, Prometal-RCT recently signed an agreement with Fonderie Messier, a French aluminium and magnesium foundry, to produce casting parts for aerospace applications in RP sand moulds [5].

Considering the above applications, some researchers have gone one step further and proposed the manufacturing of metallic tooling by casting in RP sand moulds. This alternative tool-making process is referred to as rapid casting for tooling (RCT) [6]. It is a contribution to the ongoing search for improved and innovative tool manufacturing processes to meet the stringent customer requirements of quality and economics [7, 8]. RCT is an addition to the plethora of indirect rapid tooling methods that have continued to be developed and diversified since their emergence in the last 15 to 20 years [9].

RCT essentially has five steps: computer assisted design (CAD), casting simulation, RP, casting, and finishing operations (Figure 1). The authors have claimed that, compared with traditional tool-making processes such as machining and existing rapid tooling, it offers potential advantages: near net shape, quick manufacturing time, and low production cost.

In a theoretical study comparing locally-available RP processes using the analytical hierarchy process (AHP) technique, it was found that DCCP is more suitable than the Z-Cast process when applied to RCT [10]. According to this study, tools obtained from DCCP moulds would have the best surface finish and dimensional accuracy. On the other hand, tools produced from the Z-Cast process would be cost-efficient and quick to produce. The study was based on the results of several benchmarking studies [11,12,13,14] in which parts from various RP processes were compared using characteristics such as surface finish, dimensional accuracy, manufacturing time, and cost.

However, at present it is not known how RCT tools will score in practice, based on these tool characteristics. It is also important to investigate the effects of the various RCT steps on these characteristics. In this paper, only the surface finish and dimensional accuracy of RCT tools are examined, using a case study. These tool characteristics are among the most crucial regarding tool usability.

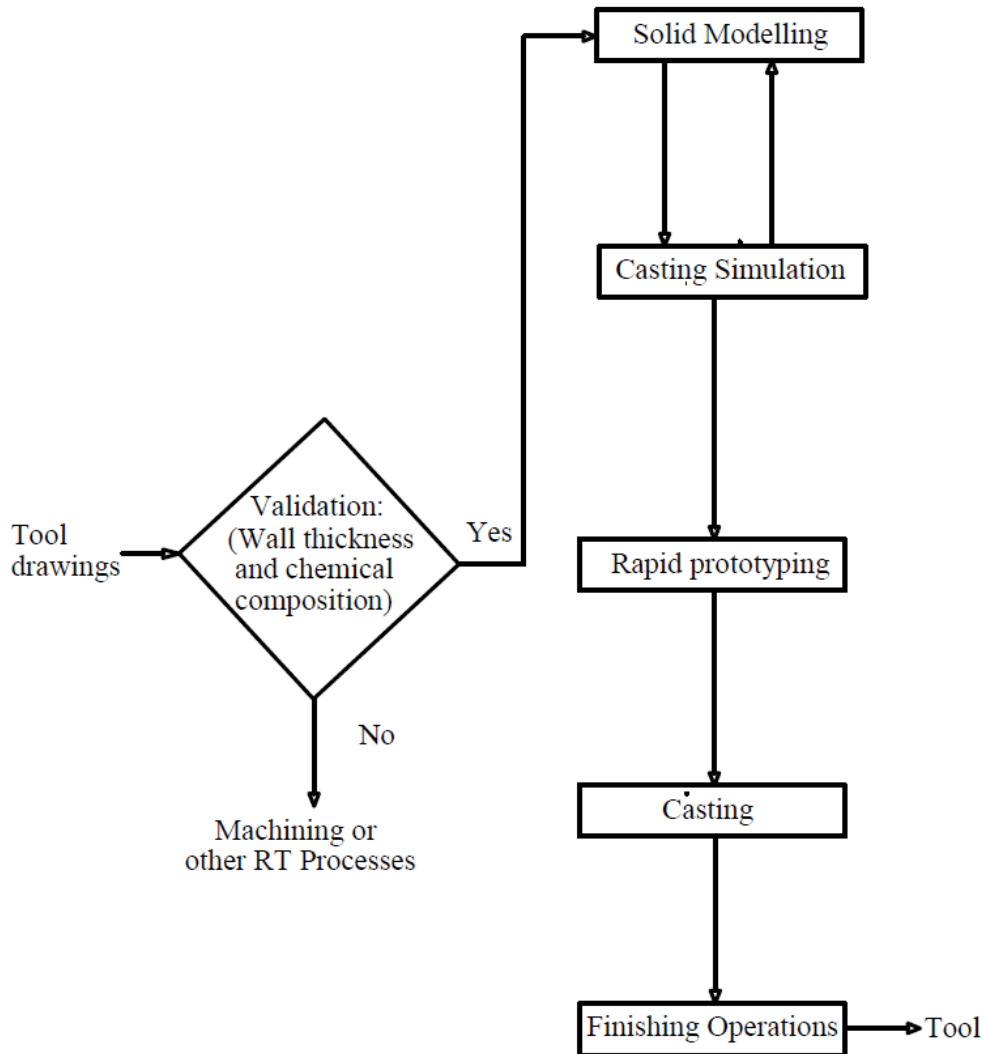


Figure 1: RCT process chain [3]

2. METHODOLOGY

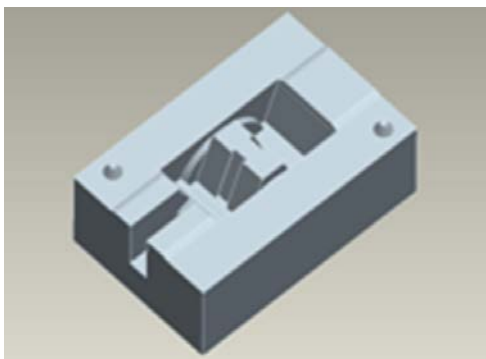
The study methodology consists of three elements:

- The manufacturing of tools by casting in RP sand moulds
- The measurement of the mould and tool surface finish
- The assessment of the mould and tool dimensional accuracy

2.1 Manufacturing of tools by casting in rapid prototyping sand moulds

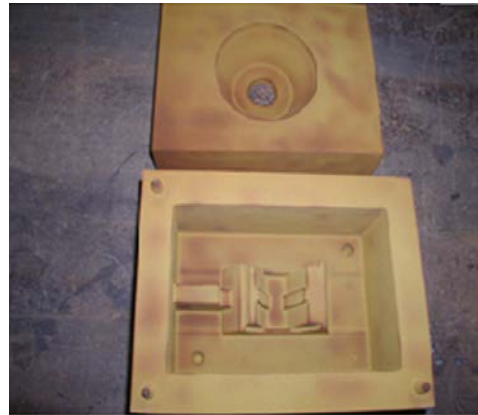
The tool manufactured in this investigation was an aluminium die for the production of wax patterns used in the investment casting of a steel bracket. The 2D drawings of this steel component are shown in Appendix 1. The die parts were produced following the RCT process chain, shown in Figure 1. The casting modelling of sand moulds was done using Pro-Engineering software. A snapshot of the 3D model of the bottom part of the die is

shown in Figure 2(a). Casting simulation using Magmasoft software was conducted, ensuring that the mould would be filled without turbulence and the die would solidify without detrimental shrinkage porosity. A top gating system through a Foseco Kalpur device was used. An EOSINT S 700 RP machine was used to grow the sand mould for cast dies shown in Figure 2(b). This machine is based on LS of foundry sand. One of the sand moulds produced was brush coated with Foseco's ISOMOL 185. ISOMOL coatings are flammable, solvent-based mold and core coatings. The principle refractory medium contained in these coatings is a high-purity zircon. ISOMOL coatings are recommended for use in the casting of iron, steel, and non-ferrous alloys - including aluminium alloys. These coatings can be used through a wide range of metal casting sections. ISOMOL coatings provide excellent casting surface quality [15]. Gravity casting was used to produce the final tool. Aluminium silicon alloy (LM4) was melted in an electric furnace at 750^o C and the liquid metal degassed prior to casting. The final cast die components are shown in Figure 2(c).



(a)

(b)



(c)



Figure 2: (a) CAD of the lower part of the die; (b) DCP mould; (c) RCT die - cast before finishing operations

2.2 Measurement of the mould and tool surface roughness

The surface finish or surface roughness was determined using a portable surface roughness tester (TIME model TR 110). This instrument provides two roughness parameters, the arithmetic average roughness (R_a) and the mean average roughness (R_z), that characterise the surface profile of the mould and casting. R_a reflects the average height of roughness component irregularities from a mean line. R_z , on the other hand, is the average distance between the highest peak and the deepest valley in five sampling lengths or cutoffs. R_z is generally more sensitive than R_a to changes in surface finish, because maximum profile heights, and not the averages, are examined. Schematic representations of R_a and R_z are shown in Figure 3. The mould surface roughness was obtained as the average of the surface roughness of 18 points, shown in Figure 4. Corresponding points on the cast die were considered to determine its overall surface finish.

Surface roughness was measured for the following objects:

- Uncoated RP mould
- Coated RP mould
- Casting produced from uncoated mould
- Casting produced from coated mould

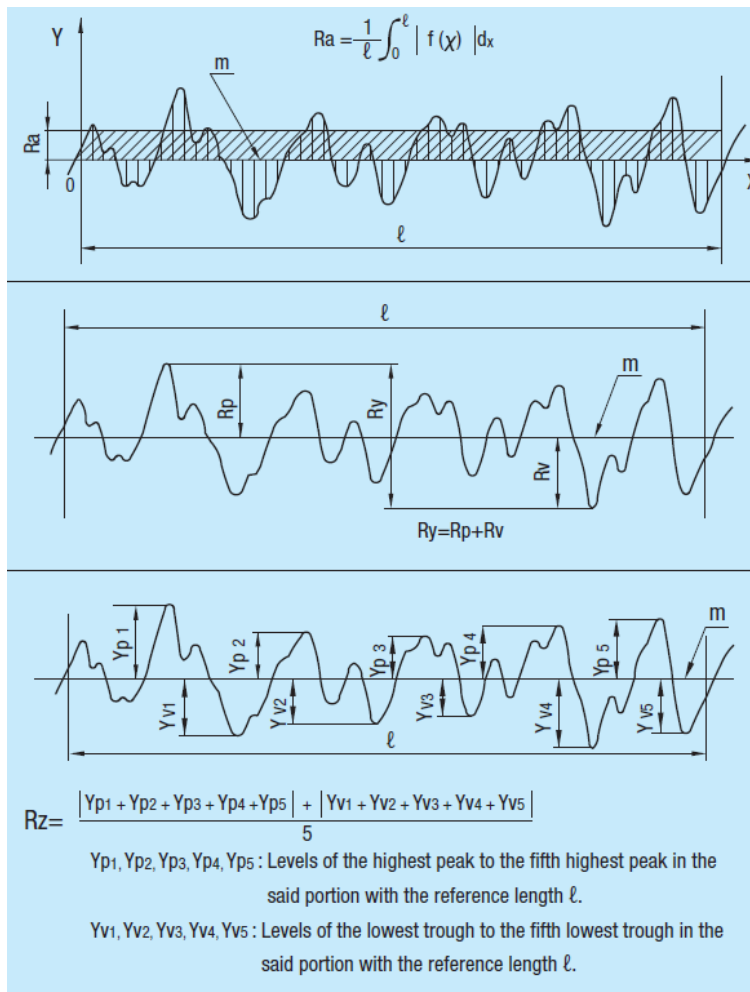


Figure 3: Variety of surface roughness indicators and typical calculations [16]

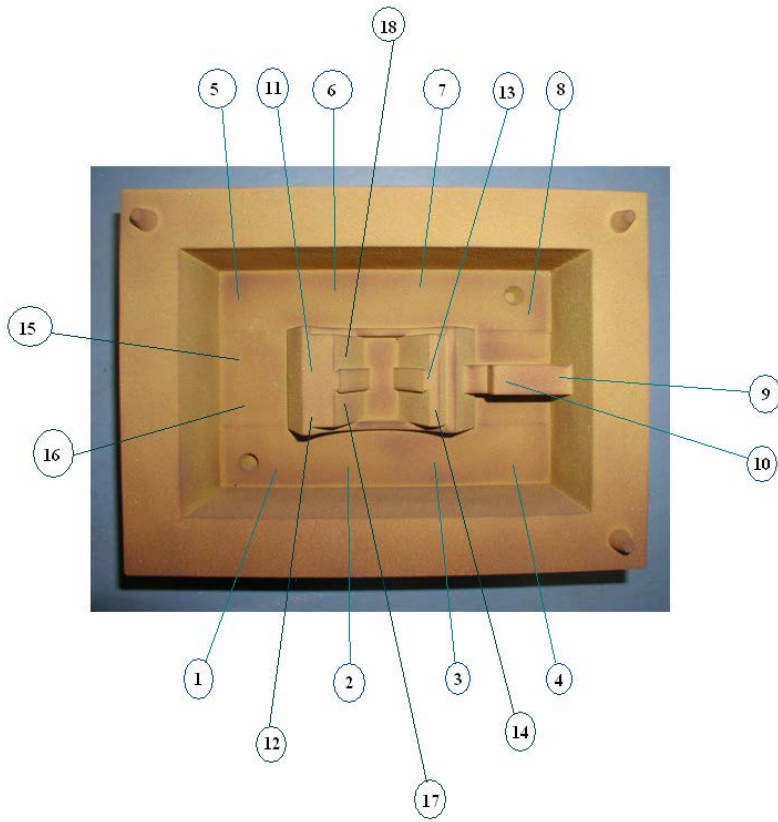


Figure 4: Points used to determine average surface roughness of the mould

2.3 Assessment of the mould and tool dimensional accuracy

A two-step process, shown in Figure 5, was followed to measure and assess the dimensional accuracy of moulds and cast tools. A VIVID 910 3D non-contact digitizer from Konica Minolta was used to produce the 3D scanned data from the parts. The 3D scanned data were then compared to the original CAD data during the merging step using Geomagic Qualify software. Dimensional accuracy results consist of 3D comparison and deviation distribution of dimensions. Table 1 shows the dimensional tolerances used for the merging of sand moulds and castings. These tolerances have been informed by the literature that reports on the dimensional accuracy of LS and shell casting processes [11,17].

The dimensional accuracy was determined for the following objects:

- Uncoated RP mould
- Coated RP mould
- Casting produced from uncoated mould

Table 1: Tolerances used in the merging process

Tolerances [mm]	Sand mould	Cast tool
Max. critical	2.0	2.0
Max. nominal	0.2	0.5
Min. nominal	-0.2	-0.5
Min. critical	-2.0	-2.0

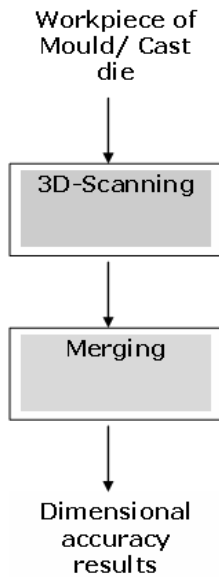


Figure 5: Process flow diagram for the assessment of dimensional accuracy

3. RESULTS

3.1 Surface roughness

Figure 6 shows the average values of surface roughness for the various parts. The coated mould has a better surface finish than the uncoated mould. The difference in roughness is important, as the Ra and Rz parameters of the uncoated mould are 2.5 and 1.8 times larger respectively than the same parameters for the coated mould. On the other hand, the RCT tool obtained from the coated mould has an overall smoother surface finish than the cast tool produced from the uncoated mould. The best surface finish obtained for the cast die had an Ra of $3.23\mu\text{m}$ and an Rz of $11.38\mu\text{m}$.

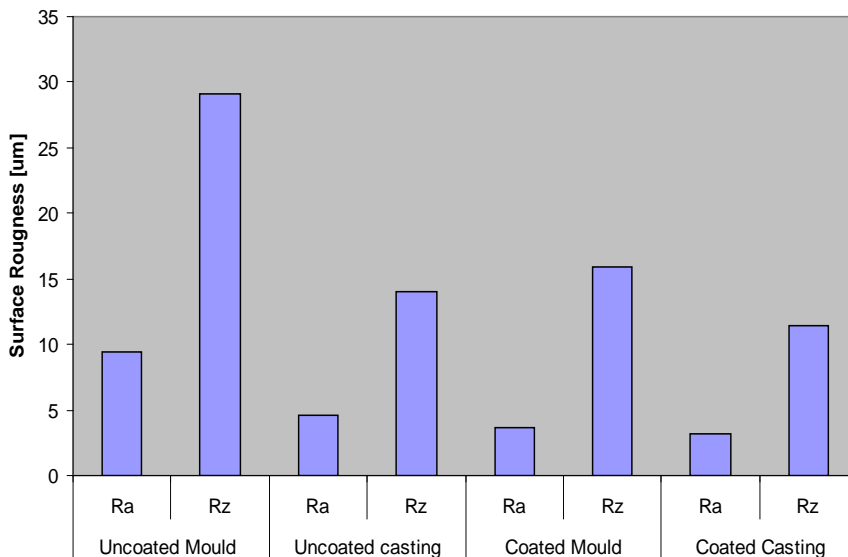


Figure 6: Average roughness for the RP moulds and the RCT tool

3.2 Dimensional accuracy

3.2.1 3D comparison

The 3D comparisons of the scanned data with the original reference CAD data are shown in Figure 7. The green areas represent points that have dimensions within the nominal tolerances defined in Table 2. The blue areas represent points that have dimensions below those of the reference part. The yellow and red areas represent points with dimensions above those of the reference part. It appears that the coated mould has a better overall accuracy than the uncoated mould, and than the cast die from the coated mould.

Figure 8 represents the quantified geometric and dimensional accuracy obtained after merging. An accuracy of 82% was achieved for the cast die within the nominal tolerances of $\pm 0.5\text{mm}$. The coated mould appears to exhibit a better accuracy than the uncoated mould, with 90% point clouds coinciding with the original CAD data within an error range of $\pm 0.2\text{mm}$ in the former case, compared with 82% in the latter case.

3.2.2 Deviation distribution of dimensions

The deviation distribution graphs from the comparison of scanned data with the reference CAD data are shown in Figures 9(a), 9(b), and 9(c). On the other hand, Figure 10(a) and 10(b) reveal the comparison of the coated mould scanned data with the cast die, and with the uncoated mould. The following general observations can be made from these graphs:

- Data are missing in the central part of the graphs;
- 70% to 80% of the points lie on the right hand side of the graphs; and
- a pattern emerges as one progresses from Figure 9(a) to Figure 9(c). The left-hand side bars are continuously truncated, while the right-hand bars increase in height.

4. DISCUSSION

4.1 Surface finish

The coated mould exhibits a better surface finish than the uncoated mould (Figure 6). This is due to the coating product that was applied before casting, filling the interstices of the uncoated mould's surface created by the granular structure of the sand grains, and the layer-by-layer manufacturing of the mould. This improvement in surface finish due to the coating is transferred to the cast tool. The RCT tool produced from the coated mould has an overall better surface finish than the one produced from an uncoated mould. However, the difference of tool surface roughness between the casting from the uncoated mould and the one from the coated mould is not very significant - the Ra and Rz parameters are close. Possible reasons include the particle size of the moulding sand, the pouring temperature of the cast alloy, and the wetting properties of the aluminium silicon alloy.

The LS process for the sand mould is similar to the Shell sand process, characterised by the use of very fine sand with an AFS number higher than 60 in order to improve the surface finish of a casting [18]. It appears that in this instance, the application of a coating has a reduced effect in improving the casting surface finish. The other possible reason is the relatively low pouring temperature (750°C) of the cast alloy in this investigation, compared with the sintering temperature of silica sand (1450°C) [19]. At this temperature, it is unlikely that any sand burn defect can occur, which explains the limited effect of the coating in improving the surface finish. Finally, if the alloy does not wet the mould surface sufficiently, its irregularities will not be transmitted to the casting.

The average Ra and Rz for the cast tool produced from the coated mould were 3.23 and $11.38\mu\text{m}$ respectively. These values are still much higher than a machined part, with values of Ra between 1.6 and $0.1\mu\text{m}$ [20]. This confirms the need to include additional machining in the final operational steps of the RCT diagram, so that the RCT tools meet the standard specification of tools for surface finish.

4.2 Dimensional accuracy

The application of a coating layer to the sand mould cavity seemed to have compensated for the errors of the uncoated mould, thus making the coated mould appear to have a better overall geometric and dimensional accuracy. Considering the RCT steps, the most probable source of the dimensional errors in the uncoated mould would be the AM step by laser sintering. This step involves the layer-by-layer growing of the mould, followed by its strengthening by curing in an oven at 220°C for 200 minutes. It is possible that mould expansion and deformation occur during curing. This phenomenon, evident with the larger RP mould, still has to be fully investigated.

On the other hand, the cast die seemed to have lost the dimensional accuracy of the coated sand mould, as shown in Figure 8. Figures 7(c) and 9(c) suggest that the cast die has expanded in terms of dimensions. This expansion could be attributed to mould wall movement during the casting step. The displacement of sand mould walls is generally caused by the metallo-static pressure on those walls by the molten metal entering the mould cavity. Factors such as the low strength of the mould, or the loose closing of the mould, accentuate the mould wall movements such that the expansion of the casting might possibly surpasses the contraction associated with the casting solidification, resulting in a loss of dimensional accuracy. Figures 7(e) and 10(b) corroborate the explanation of possible mould wall movement during casting.

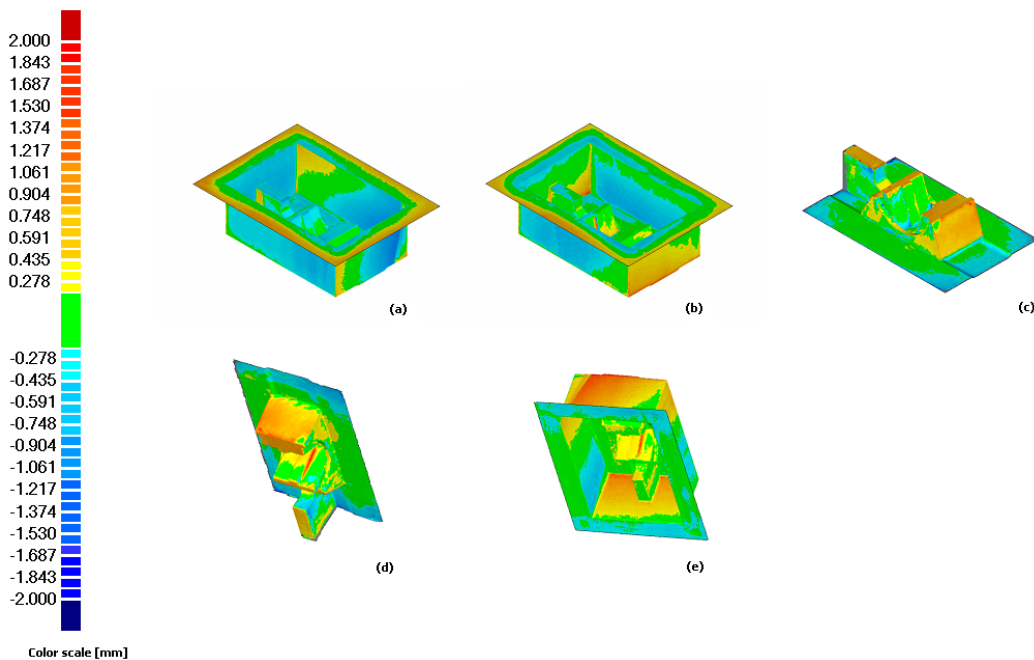


Figure 7: 3D comparison of scanned parts with original CAD data:
(a) uncoated mould (b) coated mould (c) coated casting
(d) coated casting vs coated mould (e) coated mould vs uncoated mould

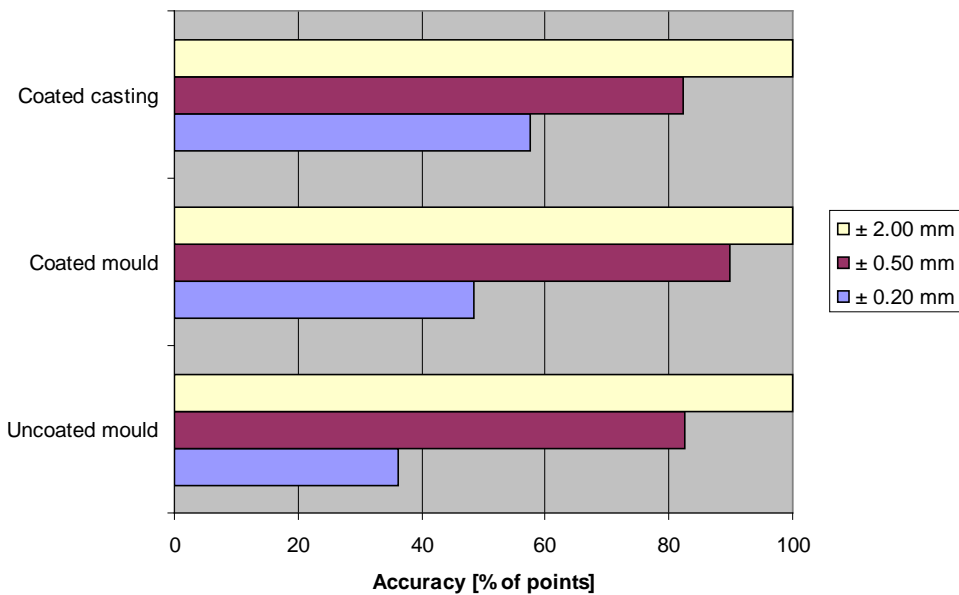


Figure 8: Geometric and dimensional accuracy of RP moulds and cast die

Two phenomena - sagging during mould curing, and mould wall movement during casting - could be determining the final dimensional accuracy of the RCT tools. It appears that the most important factor in the loss of dimensional accuracy was the RP step.

5. CONCLUSION

In this study, an initial assessment of the surface finish and dimensional accuracy of RCT tools was conducted. The investigation showed that mould coating contributes slightly to the improvement of the cast tool surface finish. With the dimensional accuracy of the cast tool, incremental contribution of the RP step and metal casting led to the final cast die being larger than that aimed for during the casting modelling. The biggest contributor to the loss of dimensional accuracy was the RP stage, possibly during the post treatment of the mould by curing in a furnace. Because of this, machining will always be required to improve the quality of RCT tools, particularly if they are to be used for mass production processes, for which there are stringent standards for the surface finish and the dimensional accuracy.

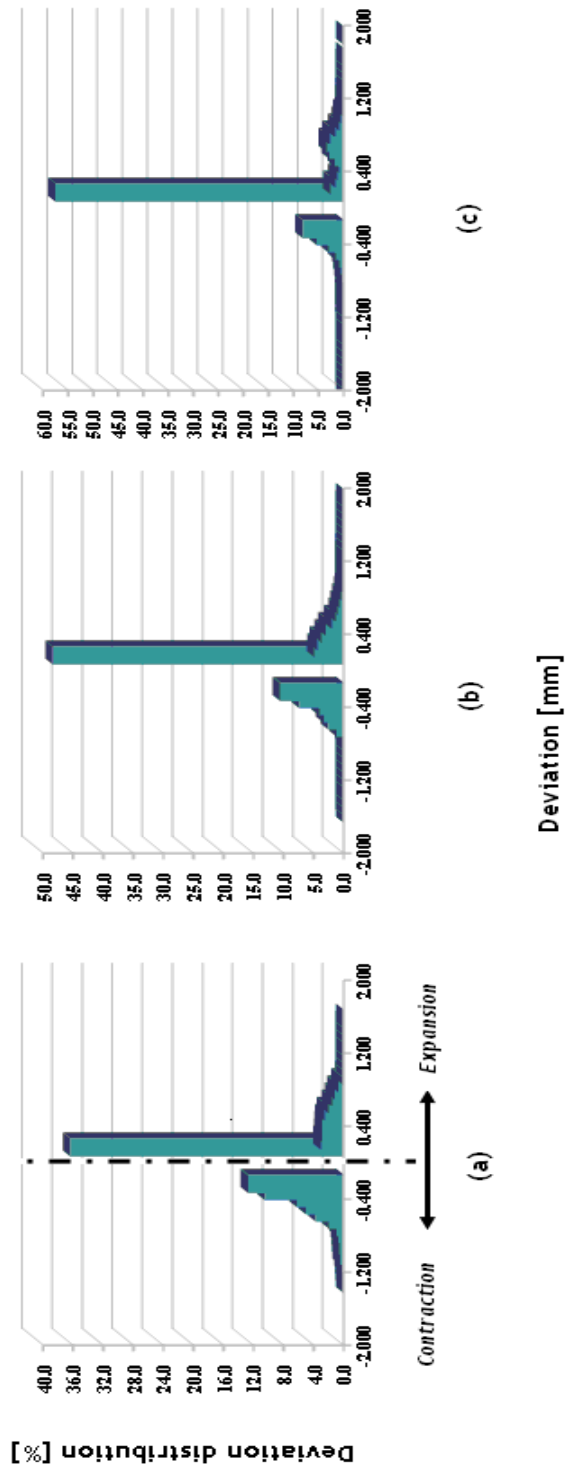


Figure 9: Deviation distributions: (a) uncoated mould, (b) coated mould, (c) coated casting

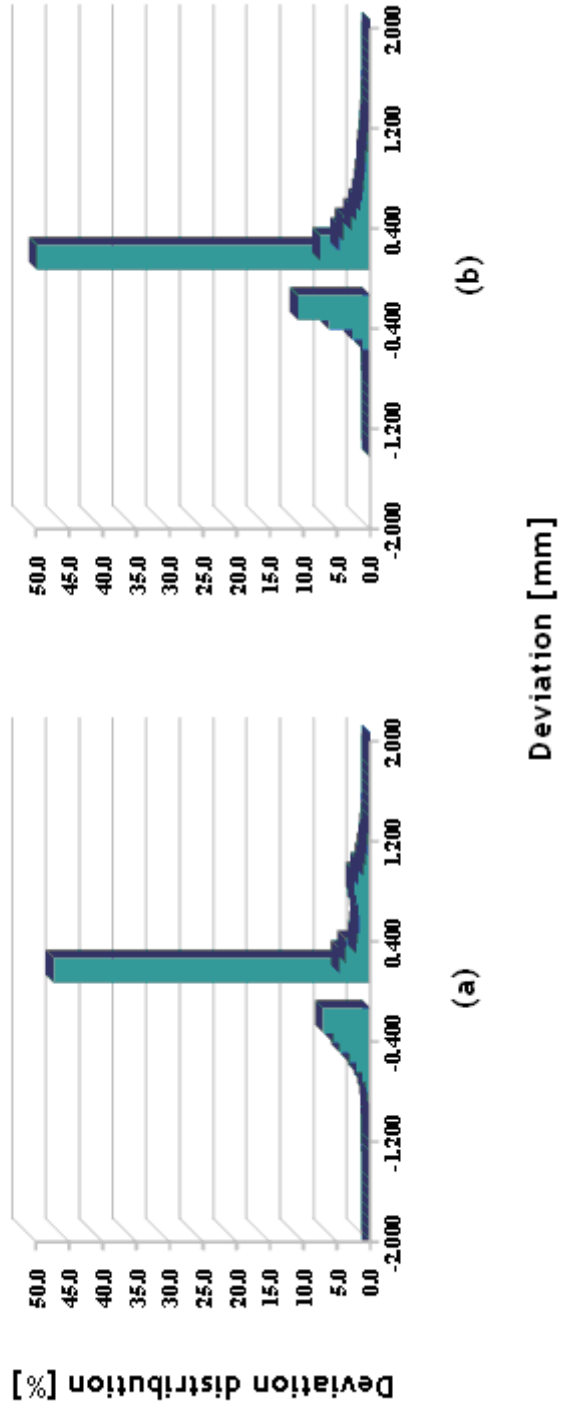


Figure 10: Deviation distributions: (a) coated casting vs coated mould, (b) coated mould vs uncoated mould

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Appendix 1: 2D drawings of steel bracket

