Dimensional accuracy and surface finish of investment casting parts by indirect additive manufacturing from fused filament fabrication

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Abstract. This article discussed the utilization of open-source 3D printer to manufacture master pattern for investment casting in term of geometry accuracy and surface finish. Two sets of 3DP parts comprising of one set with post-processing and another set without post-processing were used to make RTV silicone moulds. The wax patterns produced from RTV silicone moulds are used as patterns for making investment casting in Plaster of Paris mould. The results show that the post processing does not affect or improve the casted part as the final casted parts will undergo post-processing. This indirect approach investment casting using open-source 3D printer can be seen as new cost effective solution for small batch production of part which does not required allowable tolerance below ±1.14mm.

1. Introduction
Additive manufacturing (AM) or 3D printing is a process where virtual model created from computer aided design (CAD) software can be built into physical 3D part by adding materials in a layer-by-layer manner. This process can make model making or prototyping processes to become rapid. Fused filament fabrication (FFF) or also known as fused deposition modelling (FDM) is a material extrusion method in one of the seven methods in AM. FFF deposited materials onto a build platform layer by layer until the physical is built up and solidified. FFF can improved investment casting process by printing the 3D part as master-pattern to replace the wax pattern which is produced by injection moulding in die casting for investment casting. Study on lead time and cost comparison of fabricated sacrificial pattern used in investment casting showed that the AM technology could significantly reduce the lead time and cost as compared to conventional method for pattern production[1-2]. However, the study [1-2] used commercial 3D printer to build up the 3D printed patterns for investment casting. Thus the cost is relatively high for cottage industries implementation. Hence, low cost open-source 3D printer such as RepRap and Fab@Home is seen as a viable 3D printer to be used in investment casting for cottage industry or as a hobbyist tool in a person’s home [3-4].

In indirect method, the master pattern of the desired casting is used to make the soft tooling such as room temperature vulcanized (RTV) silicone rubber moulding, epoxy mass casting and polyurethane face casting. For indirect AM method, the mould can used to generate multiple wax patterns to produce a low number of casting. However, the indirect method is not suitable when the geometry of the casting is complex and having internal cavities, because it would not be possible to remove the pattern without damaging the mould [5].
This paper discussed the geometrical accuracy and surface finish of investment casting parts produced by indirect additive manufacturing approach using post-process and without post-process 3D printed part from RepRap 3D printer.

2. Methodology
A CAD model is designed using CATIA software. The design model is shown in Figure 1 and the benchmarking parameter is shown in Figure 2 and Table 1. This work is focused on the deviation and shrinkage rate between the CAD model and the cast part. The CAD model file was converted into STL file and uploaded into Slic3r software to generate G-code. The calibration in Slic3r improves the quality of 3D printed part [6] and the setting is shown in Table 2. Proterface software acts as the 3D printer interface controller.

Table 1. Parameter of Design

| Features Parameter | Line 1 (T1) Height | Curve 1 (C1) Radius | Curve 2 (C2) Radius | Curve 3 (C3) Radius | Curve 4 (C4) Radius | Curve 5 (C5) Radius | Curve 6 (C6) Radius | Fillet 1 (F1) Radius | Fillet 2 (F2) Radius |
|--------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Value (mm)         | 10                | 19                | 25                | 87                | 2.4               | 54                | 8                 | 2                 | 2                 |

Table 2. Slic3r Print Setting

| Setting parameter | Layer height | First layer height | Horizontal shells solid layers (top) | Horizontal shells solid layers (bottom) | Fill density | Fill pattern | Speed for print moves | Speed for non-print moves | Extruder temperature | Bed temperature |
|-------------------|--------------|--------------------|-------------------------------------|----------------------------------------|--------------|-------------|-----------------------|--------------------------|----------------------|------------------|
| Value (mm)        | 0.4 mm       | 0.35 mm            | 5 layers                            | 5 layers                               | 40%          | Rectilinear | 30 mm/s               | 130 mm/s                 | 190 °C               | 60 °C            |
The printing filament material is Poly-lactic Acid (PLA). The recommended temperature range for printing using PLA filament is 185°C to 220°C. Two set of master-pattern was printed using PLA filament. One set of master-pattern is without post processing condition and the other set is with post-processing. Post-processing method used vapour smoothing process which is applied to improve the surface finish. In this process, acetone solution (C3H6O) is used and is poured into a beaker and heated with 80°C. The beaker is sealed completed and wait the acetone vapourized completely. The part printed is put into the beaker. The process is carried out for 3 to 5 minutes so that the heated acid can be fully vapourized on the part.

2.1. Specimens preparation Soft tooling and investment casting
Room Temperature Vulcanizing (RTV) silicone is chosen to produce wax pattern for investment casting. Two piece mould method is selected so that it can be assembled and disassembled. Parting line was drawn onto the master-pattern such that modelling clay be placed to create the first part of the mould. The second part of the mould was created the same way as the first part but with sprue and air vents added in to make a gating system.

RTV silicone mould was created using a mixing ratio of curing agent and silicone rubber at 1.5:98.5 by weight. The mixture was stirred evenly and de-gas before pouring into the mould box to avoid air bubbles. The mixture was allowed to be cured overnight at room temperature.

Paraffin wax was used for investment casting and was heated in an oven at 90°C to melt it. The melted wax was poured into the RTV silicone mould. The wax solidified after 30 minutes and was removed from the mould.

2.2. Plaster mould and casting
Plaster mould was fabricated by mixing plaster of Paris powder and water with a ratio of 1:1 by weight. The mixture was poured into the mould box containing the wax pattern and left for one day for drying before de-waxing. The plaster mould is heated in an oven at 75°C to melt out the wax before casting of a low melting point aluminium alloy, Zamak. Zamak is melted at 400°C using gas metal melting furnace (TEK - 160 Gas Metal Melting Furnace 110V). The molten Zamak is poured into the plaster mould. After the cast is solidified, the casted prototype is removed from the mould using a hammer. The sprue and vents are cut off and the surface of casted prototype is finishing using angle grinder.

2.3. Parameter measurement
The dimensional accuracy measurements on cast parts were measured using Mitutoyo Beyond Plus GR2008-09571 Coordinate-measuring machine (CMM) with accuracy of 1μm (Figure 3). Surface Roughness Tester Mitutoyo CS-3000 525-7800E-1 was used in surface roughness measurement of cast part (Figure 4). The results are given in term of Ra with μm unit. Table 3 shows the setting for the surface roughness tester.

| Feature   | Measuring Speed (mm/s) | Measuring Length (mm) | Sampling Length (mm) |
|-----------|------------------------|-----------------------|----------------------|
| Top / Bottom | 0.05                   | 7.5                   | 5.0                  |
| Side      | 0.05                   | 1.8                   | 1.0                  |

Figure 3. Coordinate Measuring Machine (CMM)

Figure 4. Surface Roughness Tester
3. Results and discussion
The analyses include comparison of parameter measurement between the master pattern and the cast part. The difference in parameters is calculated in length deviation and percentages.

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\text{Parameter difference} = \frac{\text{New parameter} - \text{Original parameter}}{\text{Original parameter}} \times 100\%
\]

The 3D printed part and the wax pattern is shown in Figure 5 and Figure 6. The Fillet 2 (F2) radius are not measured and recorded because the break-away support structure is built on that fillet. The fillets are not in proper shape after the supporting structure is removed. However the problem can be solved if dissolvable support material is used.

In Figure 7, from the visual inspection; the casted part have smooth surface area, however, there are minor defects on the bottom surface. This could be due to incomplete wax burn out or trapped air during casting.

![Figure 5. 3D Printed Part (Top View) (Side View)](image1)
![Figure 6. Wax Pattern (Top View) Wax Pattern (Side View)](image2)
![Figure 7. Casted Part (Top View) Casted Part (Side View) Casted Part (Bottom View)](image3)

3.1. Geometrical accuracy and surface rough analysis
The comparison of deviation between CAD model and cast part is shown in Figure 8. From the result, it show that the deviation between casted prototype which the FFF prototype with and without post processing are similar. This is because the difference between with and without post processing FFF prototype is negligible. The maximum deviation between CAD model and casted prototype is \(+1.14\)mm which is the Fillet 1 feature.

The surface roughness for casted part which the FFF Model with and without post processing is shown in Figure 9. It shows that the post processing process does not affect the surface finish of casted part because the surface roughnesses for both casted parts are similar. Besides that, the casted parts have better surface finish compared to FFF model after they undergoes the post-processing such as part removal and finishing.
4. Conclusion

The experiment shows that the post-processing process on the FDM model does not affect or improve the dimension accuracy and surface finish of casted part in investment casting. The maximum deviation of casted metal built by 3DP model which does not undergoes the post processing process is +1.132mm while the maximum deviation of casted metal built by 3DP model which undergoes the post processing process is +1.140mm.

On the other hand, the highest surface roughness for casted metal built by 3DP model which does not undergoes the post processing process is 2.004 μm while the highest surface roughness for casted metal built by 3DP model which undergoes the post processing process is 1.972 μm. Therefore, post processing process on the FDM model is unnecessary in investment casting.

The result shows that the dimensional accuracy in indirect investment casting using RepRap 3D printer is low. The maximum deviation of casted metal is +1.14mm. However, the surface finish of casted part is good. The surface roughness is ranged from 1.186 to 2.004μm. The shape of 3DP printed part is also limited as the printed part will damaged during the support material removing process.
However, this problem can be solved by using other open source 3D printer which the supporting material is different material with building material. This indirect approach investment casting using RepRap 3D printer can be used to manufacture the simple part which the allowance tolerance is ±1.14mm. This method is suitable for high batch production of metal artificial stature or souvenir in cottage industry because the manufacturing cost is low.

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6. References

[1] Chua C K, Feng C, Lee C W and Ang G Q 2005 The International Journal of Advanced Manufacturing Technology, Vol. 25, No. 1-2, pp. 26-32.
[2] Khan S F, Dalgarno K W and Siregar R A 2015 Applied Mechanics and Materials, Vols. 786, pp. 354-360.
[3] Pearce J M 2010 Journal of Sustainable Development, vol 3, no. 4, pp 17-29
[4] Pramod V, Baiju A, Babuji A, Plathanam R, and Abraham A K 2015 International Journal of Emerging Technology and Advanced Engineering, Volume 5, 199-202.,
[5] Chua, C.K., Chew, T.H. and Eu, K.H 1998The International Journal of Advanced Manufacturing Technology, Vol. 14, No. 9, pp.617-623,
[6] Lanzotti A, Martorelli M, and Staiano G 2015 Journal of Manufacturing Science and Engineering, Vol. 137.