Research of Reverse Engineering on Dimensional Accuracy of Parts in Digital Casting Process

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Abstract. Dimensional accuracy has been recognized as the main challenges for castings that we have to overcome as manufacturing industry is proceeding at an astounding rate. The advent of rapid casting has already changed the casting patterns, which means that foundry of metal part is no longer restricted by difficulties of tooling processing especially in the case of complex design castings. It is true that this new technology which is time-saving and high-precision relatively may create new types of quality problems. The overall effort of the present article is to evaluate the dimensional accuracy of sand mold and metal part throughout the digital casting process so that a more accurate dimensional compensation could be applied to the next time. The dimensional accuracy of sand mold manufactured by 3D Printer and the final aluminum-based tire mold casted by the sand mold have been discussed quantitatively by using three-dimensional laser scanner. The effect of different directions on dimensional deviation of important surface is also discussed in this paper. It is found that the difference of sand mold mainly depends on the deviation in printing direction and a downward trend of the patterned surface would appear after the post curing. For the metal casting, appropriate dimensional compensation 1mm/m upon the pattern surface in Z direction is a good choice for further designing. This reverse engineering approach is applicable to not only the tire mold forming but also other industrially relevant parts manufacturing.

1. Introduction

New tire development is a highly complex process consisting of many engineering activities such as tire pattern design, material selection, tribological analysis, prototyping, testing, tire mold manufacture, and mass production[1]. The tire mold is a vulcanized molding equipment on the tire production line, whose quality directly influences the dimensional accuracy and working life of the tire and whose shape accordingly reflects the pattern, font and other appearance characteristics of the tire. The tire pattern that determines the wear resistance, heat dissipation and handling stability also changes with the higher and stricter requirement about the power performance, comfortability and safety of cars. The multi-axis computerized numerical control machining method commonly used in tire mold field requires planning precisely tool paths when processing complex and diverse pattern surface that inevitably cost plenty of time.

However, the recent breakthroughs in the development of additive manufacturing (AM) technologies have given a new impetus to the capabilities of construction processes[2]. Additive manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining[3].
Their overwhelming as regard the complexity of the assembled designs is no longer restricted to rapid prototyping, and they have already been a terrifically good technology across multiple industrial environments, including the aerospace, biomaterial and automotive industries. It is also noted that an increasing number of industries tend to focus on the combination of additive manufacturing technology and traditional technology such as joining, casting and injection molding.

In precoated sand-based additive manufacturing, a direct energy source, such as laser, is applied to melt the resin coated on sand powders so that the grains could be bound together. Hawaldar and Zhang simply compared the two mold casting processes, conventional sand casting process and rapid sand casting process, on the issue of part weight and time costing. The study affirmed the significant advantages in employing additive manufacturing technology in the production of mold of pump bowl. So the use of additive manufacturing process has been proved to be a cost effective and time efficient approach for producing pattern, core boxes and gating system for sand casting. Kang and Shangguan used an additive manufacturing-driven flexible sand mold to cast the single structure to improve production efficiency as well as reduce deformation and residual stress. This metallurgical approach is applicable to the industrially relevant parts manufacturing due to design freedom and manufacturing flexibility of AM, that accelerates board adoption of additive process. Nevertheless, concern about distortion issues caused by Selective Laser Sintering (SLS) has been heightened in recent years. Zakaria and Dalgarno used a precision balance to assess the downwards distortion of the beam overhang. This suggests the availability of liquid resin during the infiltration acts to enhance sintering and offset any effect that the additional weight has in causing distortion. Salmi and Paloheimo attached the measuring balls designed for measurements to each 3D model and determined the midpoints of the balls using a coordinate measuring machine so that the distances between these points were calculated and compared with the 3D model. Actually, the accuracy of these models varies between different materials, AM technologies and machine operations. Some methods can be used to solve dimensional accuracy problems such as laser power adjustment and layer printing delay. The main goal of the present article is to propose a generally applicable measurement of dimensional accuracy and explore the law of dimensional compensation of parts in digital casting process.

2. Material and Methods

2.1. Model preparation
The 3D model of the tire mold block (240mm×230mm×130mm) with complex pattern (Figure 1a) is designed by SolidWorks2018 CAD software (Dassault Systemes S.A, USA). Use AC4C aluminum alloy as the foundry material for the parts, then set the bottom pouring system and the open riser for the casting (Figure 1b). Considering a series of issues including the processing capacity of the equipment, the location fit between different sand molds, the transport, the cleaning of floating sand and the deposition of coating, the sand mold (340mm×430mm×300mm) is divided into three pieces (Figure 1c). One parting surface is located in the maximum cross-sectional area and the riser is placed in the upper sand mold. Another parting surface is set up in the lower sand mold for cleaning and coating. Reference line and location pin for accurately assembling are also designed in sand molds. In contrast with conventional mold manufacturing, additive manufacturing is flexible, there by making it possible for people to overcome barriers to complex design of parting surface. The more complicated the parting surface design is, the more obvious the advantages of the additive manufacturing technology are.

2.2. 3D printing and post curing
Prior to printing, the powder needs to be prepped. The material used in the experiment is coated ceramsite whose base material is the spherical electrolytic ceramics with high thermal conductivity and coated material is thermoplastic phenolic resin with high strength (Table 1). The resin is about 2%
for weight of the coated ceramsite while the curing agent methenamine is about 15% for weight of the resin[14].

Figure 1. The CAD model of the tire mold block, (a) single block of tire mold, (b) design of pouring system and riser, (c) blocking and positioning of sand mold, (d) schematic diagram of pattern reference line of sand mold and casting.

Table 1. Material characteristics and mechanical properties.

| Powder material | Coated ceramsite |
|-----------------|------------------|
| Base formula    | Al₂O₃             |
| Resin formula   | (C₇H₆O₂)ₙ         |
| Melting temperature of resin | 90.5°C          |
| Curing temperature of resin    | 151.5°C          |
| Flexural strength     | 11.01 MPa        |
| Tensile strength      | 4.84 MPa         |

A self-constructed selective laser sintering SLS 3D printer (PIRP 1500) is employed to cure the commercial coated ceramsite and build various sand products for casting. Selective laser sintering (SLS) uses a fine powder, which is heated by a laser beam in such a way so as to allow the grains to fuse together[15-17]. The sand-based 3D printing for casting uses the coated sand as the powder material and directly builds parts from the CAD model, eliminating steps of mold manufacturing in the traditional foundry industry.
In the process of printing the sand mold, the instantaneous energy brought by the laser is conducted into the powder layer, and several adjustable parameters especially laser power, scanning speed, hatch spacing and layer thickness directly affect the curing degree of the coated resin. SLS is performed according to the preprogrammed settings that laser power 160w, scanning speed 3000 mm/s, hatch spacing 0.2mm and layer thickness 0.3mm are selected.

The strength of the printed blank is so low that another post curing procedures are required to make up defects once the build has been completed. The local flame hardening as the initial strengthening way is adopted to prevent damages during the movement. For the whole sand mold, a heating furnace is required to ensure complete curing. The heating temperature 180°C and the holding time 3h are selected for the three sand molds of tire mold.

2.3. Deviation measurement

The 3D point cloud data measured by the portable scanner HandySCAN700 (CREAFORM, Canada) is used to reconstructed the surface of sand molds and metal casting during the whole process. Comparable data is performed by Geomagic Qualify (GEOMAGIC, America).

3. Results and discussion

Comparison results of scanned data and the initial CAD model are shown in Figure 2a-b and the color scale which is adopted by these two images shows the dimensional deviation value (mm). The overall green appearance of two figures means that most of dimensional deviations are within ±0.25 mm, that is, the accuracy of the printed sand mold meets the demand for dimensional accuracy in general. The value of the visible deviations in the important surface is no more than ±1mm and the average dimensional deviation of both two conditions are within 1.3 mm/m (Figure 3).

The details of the dimensional deviation distribution after printing (yellow) and post curing (purple) are shown in Figure 2c, corresponding Figure 2a and b. The horizontal coordinates correspond to the dimensional deviation values shown in the color scale of Figure 2b while the vertical coordinates represent that the percentage of the number of points whose deviation value is in the specific ranges and all point cloud data. The bar chart intuitively displays points of deviation value at the range from -0.60 mm to +0.60 mm steady represent most point cloud data and proportions of deviation value in the range of ±0.25mm hold a safe lead. Specifically, the dimensional deviation within ±0.25 of sand mold that after curing is produced at more than 60%, a bit higher than that of sand mold that after printing. Although the figures for the intervals of -0.60 to -0.25 and 0.25 to 0.60 are much higher than those for other intervals, they are about 45% lower respectively than the highest ones. Besides, negative dimensional deviation like the interval of -0.95 to -0.60 is relatively acceptable since it means there are more machining allowance in the following process. Still some defects exist on the relatively unimportant position like the red area of lifting structure. However, they do not affect the subsequent casting process.
Figure 2. Dimensional deviation comparison of sand mold, (a) comparison of 3D point cloud data after printing and the initial CAD model, (b) comparison of 3D point cloud data after post curing and the initial CAD model, (c) dimensional deviation distribution after printing and post curing.

Figure 3. Average dimensional deviation comparison of sand mold and metal casting.
To quantify the dimensional changes further, fifty random feature points are extracted from the patterned surface and these data are arranged in ascending order of 3D deviation. As shown in Figure 4, there was a remarkable relation between the 3D deviation and its component in Z direction in the entire process in comparison with component in X, Y direction. Especially in the Y direction, the standard dimensional deviation is only 0.10mm/m and 0.08mm/m after printing and post curing respectively.

![Figure 4. Dimensional deviation comparison of sand mold, (a) scatter plot of the 3D deviation and its components in X, Y and Z directions after printing, (b) scatter plot of the 3D deviation and its components in X, Y and Z directions after post curing.](image)

Then another fifty feature points are extracted along the line with consistent coordinate value in the Y direction to find out the changing law of deviation in Z direction as the coordinate value in the X direction changes (Figure 5). Due to the dimensional deviation caused by shrinkage deformation of metal, the model size of the designed sand mold is enlarged to neutralise the influence of shrinkage in solidification. So the reference line a represented the required sand mold model contour and the reference line b represented the required rough casting contour are not the same line (Figure 1d).

The patterned contour of sand mold after printing and post curing are restructured by enough discrete points (Figure 5a). From the restructured surface, the gap between measured value and reference value in X direction is narrow whether post curing or not. For the Z direction, the coordinate values of the printed surface have a fluctuation within a range of ±0.25mm of the reference value. During the process of coated ceramsite sand manufactured by laser source, the resin coating on the surface of the particles melts and flows into the contact points to form a resin neck[18] (Figure 6b). The resin rapidly flows to the contact points under the surface tension during the heating process, which results in a minimum resin surface area. Meanwhile, the particles are pulled together under the action of surface tension[18-20]. This leads to a slight macroscopic deviation of the sand mold in Z direction after initial printing.
Figure 5. Plots of patterned surface along the line with consistent coordinate value in Y direction.
After absorbing the laser energy, the temperature of surface of coated sand is higher than the inner. The temperature becomes lower as it gets further away from the surface. Therefore, there is a temperature gradient in the Z direction so that three phenomena appear from top to bottom[21]. First, the sand is firmly bonded together under the action of the solidified resin when the heating temperature is higher than the curing temperature of the resin (Table 1). Second, the sand adheres to each other with the melted or semi-melted resin while the heating temperature is between the melting temperature and the curing temperature of resin (Table 1), that is the reason the initial printed sand mold usually has a low strength. So when the sand mold is taken out from the printing platform, the small sharp corner of it would be broken off. Reasonable selection of process parameters could improve the curing degree and dimensional accuracy of the sand mold, thus the positive deviation in Z direction generated in the early stage of additive manufacturing development is no longer a problem that hinders the technology. Then, there are still some loose sand inside or outside the sand mold whose resin are not heated by the laser source in the printing process and would be completely harden in the post curing process. Therefore, loose sand that does not form a sand mold must be cleaned before curing, especially on important surfaces. Post curing is to heat the coated resin to the curing temperature so as to improve the strength of the overall sand mold. It is also necessary that heat preservation to eliminate the thermal stress.

![Figure 6. The block of sand mold 1# printed by SLS, (a) overall appearance of sand mold, (b) SEM photo of sand mold after initial printing.](image)

In the post curing process of printed mold of coated sand, the surface of the sand mold have a dent trend in the Z direction due to the continuous physical and chemical reactions of sand mold at the basis of printed deviation (Figure 5a). The packing structure changes caused by the resin flow promote the shrinkage and deformation of the sand mold. So it is different that the point cloud data obtained in the same position of the part after printing and post curing. If the small dimension deviation in the Z direction is positive, the dent of post curing will correct the deviation so the accuracy would be ensured. If the small dimension deviation is just good or negative, the post curing will amplify the negative deviation which would bring the unnecessary burden in later processing. Dimensional deviations of sand mold after printing and after post curing (Figure 5a) are calculated in Figure 7 and this difference about +0.2mm, that means the post curing process make the patterned surface go down 0.2mm, leads to the change of deviation distribution in Figure 2c. The noticeable growth of 2.49% in the intervals of -0.25 to 0.25 is due to the settlement in post curing.
Figure 7. The dimensional difference between sand mold after printing and sand mold after post curing.

The casting process is carried out to form the final metal part. The final casting forming from the printed sand molds are without obvious defects on the important patterned surface (Figure 8c). Similarly, the dimensional deviation of metal casting is proposed to show the deformation behaviour and measurement results are compared in Figure 8a-b. It should be noted that there are some differences on the patterned section between the sand mold used to cast and the metal part (Figure 5b). This is mainly due to the shrinkage deformation of the metal during the solidification process. To address this concern, dimension compensation has been adopted at the beginning of the sand mold design. Moreover, the final casting fits the initial CAD data of tire mold in size (Figure 5c) with the average dimensional deviation 2.33mm/m (Figure 3). From the Figure 5c, the main reason is the deviation in Z direction. It is detrimental to the later machining since if there is no machining allowance on the surface of the part. To ensure the dimensional accuracy of the final rough casting, dimensional compensation of 1mm/m upon the pattern surface in Z direction should be an admissible suggestion.
4. Conclusions

We have used the additively manufactured sand mold in casting to replace mold used in most common aluminum foundry, producing defect-free casting with high accuracy. Three-dimensional accuracy detection of parts is used throughout the whole digital casting process. There is no doubt that any measuring method, especially applied to the complicated parts, may have its limitations. In this study, the point cloud data of the parts are extracted as much as possible as the sample data for comparison to ensure the results are reliable. In the light of these discrete point cloud data, we can come to the conclusion that:

- The marginal deviation of sand mold printed by SLS has been derived from resin neck, and the deviation in printing direction would be enlarged after post curing, usually ending up about 0.2mm negatively deviated from the initial printing value;
- Although the final casting has a tolerate deviation only 2.33mm/m, it should be noted that appropriate dimensional compensation in Z direction still has important implications to dimensional accuracy.
- It is unquestionable that rapid tooling is a complex technique which covers multiple disciplines, as a series of physical and chemical reactions would take place throughout the manufacturing process and minor details of process design and real practice can also affect the dimensional accuracy of the final parts. Therefore, reconstructing the point cloud data of the complex surface of sand mold can
help us find defective molds and avoid the production of substandard products in dimension at the beginning of casting. Besides, it can verify the dimensional accuracy of final casting so that products delivered to clients are qualified.

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