Application of 3D printing in casting

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ABSTRACT

The article presents the applicability of 3D printing in casting. Even complex models produced by 3D printing can be effectively applied in the field of lost pattern casting. The process was realized using Polycast and Pioneer investment powder (gypsum). Based on the measurement it is clear that the size differences come from the printing technology. The minimum wall thickness cannot be less than 0.8 mm, but there is inaccuracy under 2.1 mm when there is no infill section in the rib. More contour lines can reduce the deformation and the inaccuracy.

Keywords: *Lost pattern casting, Tin casting, 3D printed models*

1. Introduction

Whether in the automotive or mechanical engineering industries, the development or small-scale production of complex components such as gearboxes and other parts of the driveline must be fast and efficient [1]. Precision casting using the conventional wax pattern used in the past has several weaknesses in this regard. Because metal printing is still relatively immature today, most companies still use wax-patterned [2] or plastic printed pattern for casting [3, 4]. In previous wax-patterned precision casting, in many cases, the immediate production of the desired wax models was a problem because it required expensive injection molding tools and wax presses.

These tools can be almost prohibitively expensive and time consuming when needed for small series or upgrades, resulting in very high unit prices [5]. Today, wax pattern are being replaced widely by pattern, which made by 3D-printing. Manufacturing plastic pattern with 3D printing is very simple, accurate and fast. No tools are required as the printing process is based on the CAD data of the part. The 3D printer produces the pattern by layer-by-layer construction method with excellent repeatability and performance, no matter how complex the part itself. Constructions designs can go beyond current manufacturing processes, and changes are extremely simple by resubmitting CAD data [6, 7]. The casting method used in this research belongs to the lost pattern casting, within that the casting was realized with gypsum mold.

Traditionally, a precision metal pattern is used for gypsum mold casting. Gypsum mold material is poured, then after removing the pattern, the cavity of the product is formed. After the gypsum mold has hardened, it is advisable to remove the residual moisture content from the mold by a heat treatment. The resulting mold usually consists of two parts, because the undercut of the parts requires the use of dividing planes [8]. The whole process is illustrated in Fig. 1.
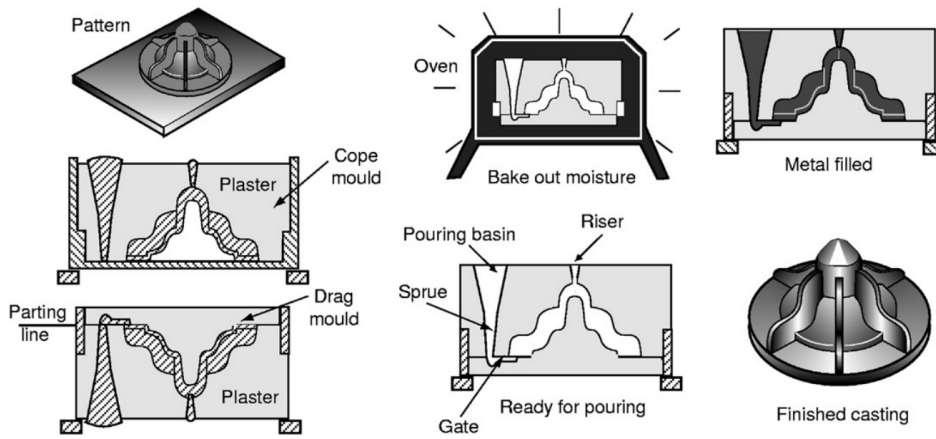
Figure 1. Plaster mould casting [8]

To avoid the parting line the accuracy can improve. Evaporative-pattern casting (lost-foam casting) one of the solution to eliminate the parting line. This case the mold is produced by pouring the mold material around the pattern. Then, the pattern evaporates by burning out and thus the mold cavity is formed [9]. Fig. 2 illustrates lost pattern casting [8]. Moreover with lost pattern casting, it is possible to cast more detailed and complex geometries, as it is much simpler and more cost-effective to produce the pattern, and unlike casting into plain sand, there are no restrictions on the parting line [10]. In this article, lost pattern casting was implemented using 3D printing, which combines the benefits of additive manufacturing technology with casting.

2. Materials and methods

For the study, a FDM printer and "Polycast" brand filament were used. This material soften at 73 °C for casting and burn without residue at temperatures above 600 °C. The main properties and the suggested printing parameters of Polycast are in Table 1.
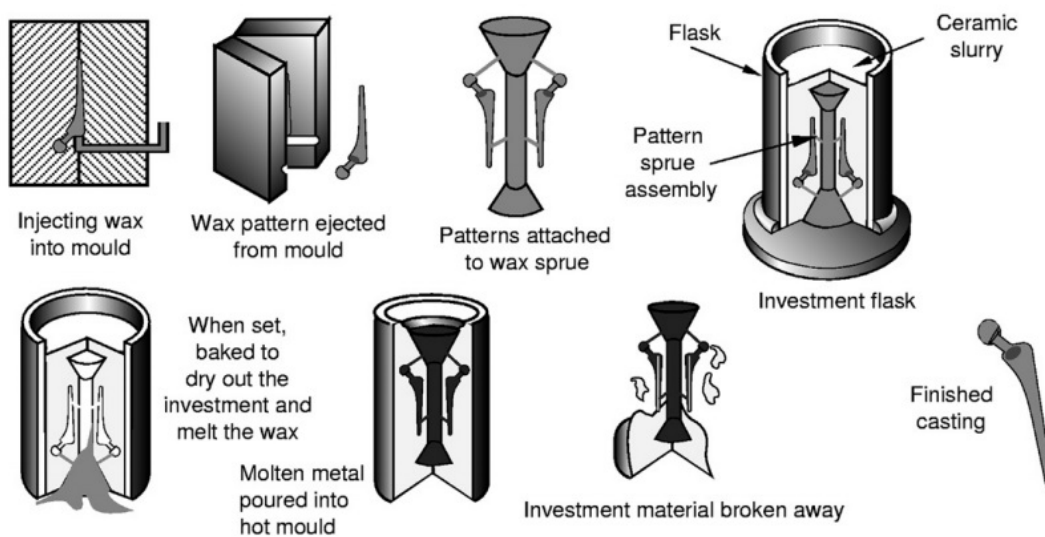

Figure 2. Wax-based – lost pattern casting [8]

Table 1. Polycast filament properties [11]

Property	Typical Value
Density (ρ), [g/cm^3]	1.1
Glass transition temperature (T_g), [°C]	70
Vicat softening temperature (T_v), [°C]	67
Young's modulus (E), [MPa]	1 745
Tensile strength (R_m), [MPa]	35.7
Elongation at break (ε), [%]	6.9
Nozzle temperature (T_n), [°C]	220
Build plate temperature (T_p), [°C]	60
Printing speed (v), [m/s]	50

For printing a Prusa I3 MK3 MMU2S printer was used and 0.2 mm layer thickness has been set. For printing temperatures and speed, the recommended values were used from the table (Table 1). The infill percentage was the minimal 20%. In the present case, the mechanical properties were not the key question, but minimal amount of material should be preferred. Thanks for this, the next technology step is become much easier.

Pioneer investment powder (gypsum), Crystalline Silica CAS 14808-60-7 composition 70-80%, has been used to create the mold [12]. The mouldable material was formed by mixing the powdered material with water in a ratio of 2.5:1. The mold material can be molded for 10 minutes and then solidified. After solidification, it is advisable to wait 24 hours for the already solidified material to reach the desired strength.

SN99 (Table 2) was used to the raw-material of the casted parts, which contained 0.04% silver and 0.06% copper as impurities.

3. The developed casting process

The goal was to make parts with complex surfaces by casting. The selected sub-type casting was the lost pattern method. The parts do not require support when printing because of the selected casting technology. With this solution small burrs can avoid because there is no support removing process. Not only just the mold can be created easier, but the accuracy and the surface quality are also greater.

In principle, PLA plastic is also suitable for printing the form. However, it is advisable to use a vacuum chamber during firing, as inappropriate conditions the PLA will not evaporate but will char and burn on the mold cavity wall. This making the molded product inaccurate and contaminated [14]. So the pattern has been made from Polycast filament material (Step #1). Polycast filament material has the advantage of completely evaporating at $T > 600$ °C. This way the product will not be contaminated and free of inclusions. The mold is made of Pioneer Investment Powder gypsum

Table 2. Tin properties [13]

Property	Typical Value
Density (ρ), [g/cm^3]	7.4
Tensile strength (R_m), [MPa]	22
Elongation at break (ε), [%]	41
Melting point (T_m), [°C]	227

Figure 3. Casting error because of the rapid solidification

(Step #2), which has a high heat shock resistance. Due to its fine grain size, can be used to produce accurate products. When preparing the mold, it is important to adhere to the mixing ratio (2.5:1), otherwise a mixture of acceptable hardness will not be obtained and the mold may crack during firing. The gypsum mold must be allowed to stand for 24 hours until it reaches the required strength. The printed pattern was completely covered by casting gypsum.

It is advisable to place the crucible upside down in the oven so that the plastic that has become liquid at the beginning can flow out from the mold (Step #3). As the furnace only heated up to 600 °C. Although the plastic completely evaporates at high temperatures, it initially becomes only liquid. Based on our experience, to remove the liqiud plastic from the mold can gives better quality. In this case, it takes less time to burn out the polymer. If we do not wait long enough for firing, it will not evaporate completely and remains at the bottom of the mold.

The tin (SN99) has a good shape-filling ability and has a low shrinkage even after casting [15]. Particular care should be taken when casting liquid metal into a mold because the load of the flowing metal can damage the fired surface of the mold. This can be eliminated primarily by proper design and construction of the gating system and the right casting speed. Our case, the pouring cup is
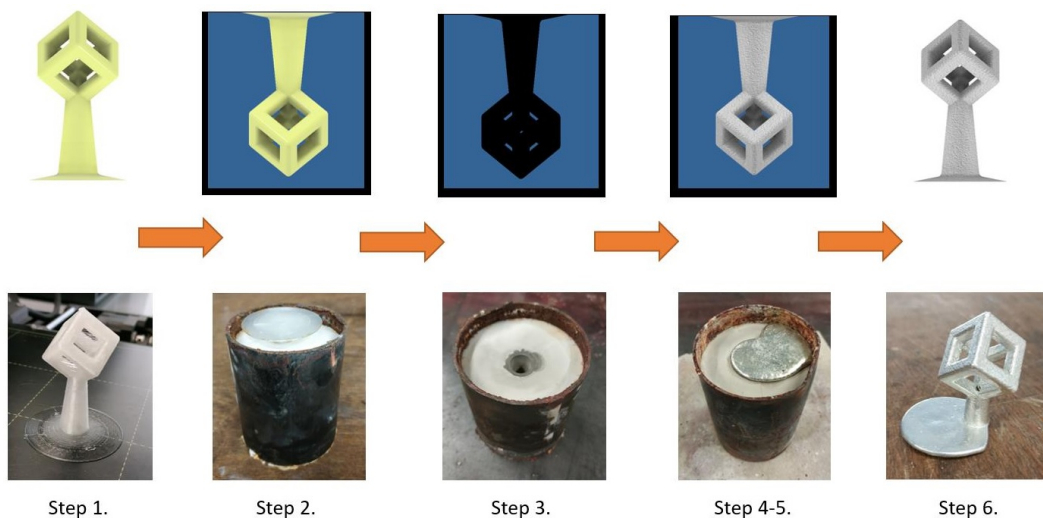

Figure 4. The casting process

made integral with the component. When preparing the sample, it is advisable to achieve the correct orientation of the model. This was extremely important in the casting (Step #4), because after the melting of the casting material, the surface of the bulk material solidified relatively quickly at room temperature. Thus, during molding, the already frozen material leads to surface defects and uneven filling. Fig. 3 shows the effect of the rapid solidification and the presence of impurities affect the quality of the casting. After casting, the metal must be allowed to cool down (Step #5). Then the gypsum mold can be completely washed out form the parts with high-pressure water (Step #6), so that the molded sample is not damaged. Fig. 4 shows the implementation (Step #1 to Step #6), from the design of the plastic model to the finished molded model.

4. Casting accuracy, technological limits

It can be seen in Fig. 4 that the construction of the relatively complex lattice structure was not an obstacle either. One of the advantages of the method to be emphasized is that such a mold could be difficult to implement when casting with a sand mold due to the undercuts. Next to the complex shape there are two parameters which determine the casting possibility: one is the difference between the pattern and the final product, the other is the minimum wall thickness.

To do evaluate these properties, a special specimen was designed. The pattern contains ribs of different wall thicknesses, they were placed evenly distributed around the inlet opening. Thus ensuring that the ribs of different wall thicknesses had an equal chance of filling and that the metal could cool evenly in the mold cavity. The Fig. 5 illustrates the model and the finished casting.

It can be seen the finished piece that air bubbles trapped on the mold, which creates spikes (marking with red in Fig. 5) of the casted part. The casted piece shows a larger burr at the bottom (top in Fig. 5) of the ribs, the reason of this the printing technology. The adhesion has to increase with the printing tray with the fitted skirt. If the skirt could not be completely removed the burrs appear of the casted part also. Take account, if the skirt not removed completely, the metal parts
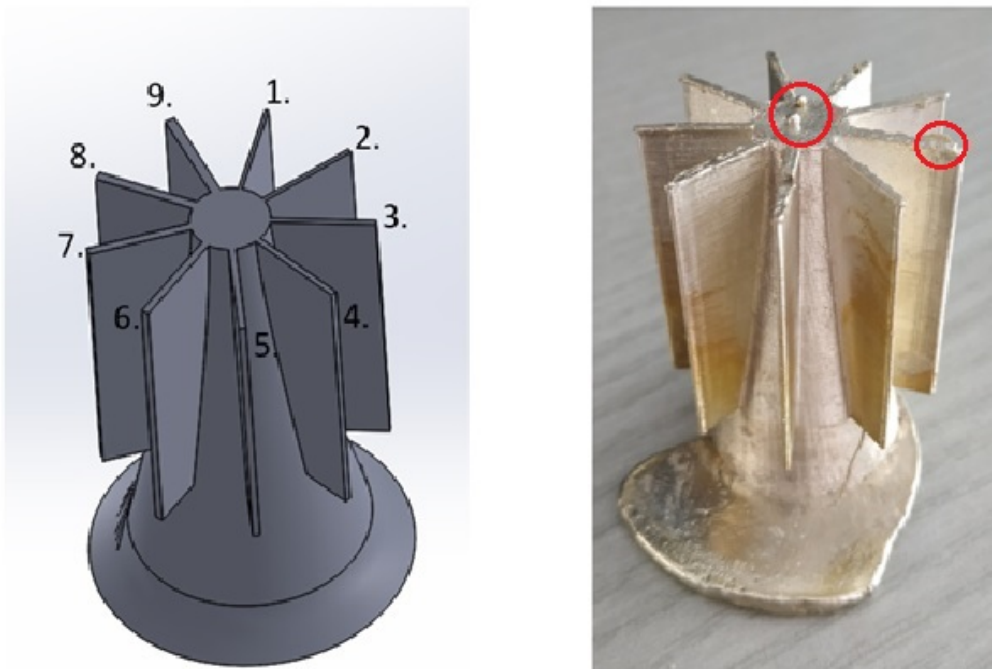

Figure 5. Specimen with ribs and the casted metal part

become bigger. Most of the case, the metal can deburr much easier so with material removing the casted part become in the tolerance zone. Apart from these, the sample is perfectly suitable for carrying out the measurement, as neither inclusion nor other deformities were formed. After the first sample, another sample has been manufactured with bigger rib thicknesses.

Each rib was measured on the 3D printed sample and on the casted piece as well. A digital caliper was used at several points along the length of the rib. The wall thickness of the 1st rib is 0.5 mm, then that of the subsequent ribs always increases by 0.1 mm. By measuring the individual ribs along their length in several places, it was found that the shrinkage or casting direction during casting did not adversely affect the dimensions, and the thicknesses have an acceptable tolerance within the entire surface. By plotting the measured values graphically, the differences are striking and the conclusions can be drawn more easily. The upper part of Fig. 6 shows the measured data. Based on the diagram, it can be said that the difference between the dimensions of the printed sample and the dimensions of the CAD model is larger than between the dimensions of the printed sample and the casted part.
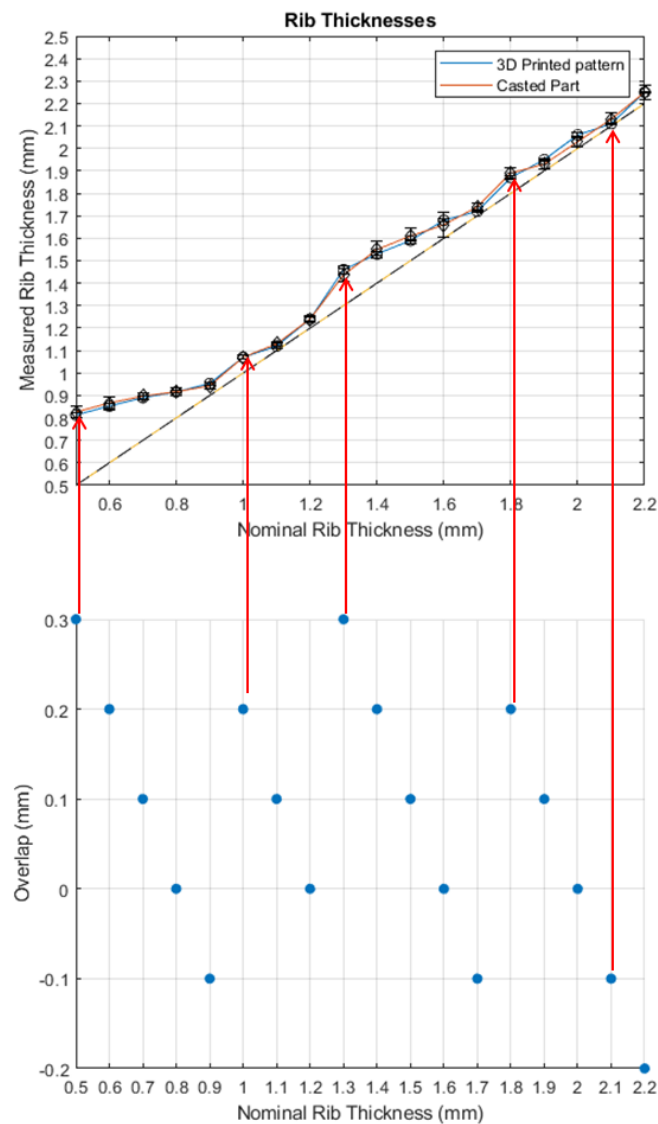

Figure 6. Measured data

There is almost no difference between the printed sample and the cast part, only 10-20 μm differences was recorded. This was the same as the range of the inaccuracy of the caliper. Thus, it can be said that the lost pattern casting can be realized from a 3D printed pattern is functional and can be carried out with high accuracy. Possible size problems are only comes from the inaccuracy of the printing process. The lower part of Fig. 6 shows the overlap value for each rib, which is a manufacturing feature, which involved in the next chapter.

5. Inaccuracy of FDM printing

Bigger difference only occurs for thinner walls (under 0.9 mm), which can be traced back to the FDM printing technology. The 3D printer use a nozzle with 0.4 mm diameter hole which it extrudes the plastic filament. Consequently, if the setting parameters are optimal, both the extruded and the deposited fiber should be at least 0.4 mm thick (Fig. 7/a). Sometimes, because of the thin layer thickness, the print head may deform the deposited fiber (Fig. 7/b) due to the narrow gap thickness, so its width may increase. Also the overlapping fibers cannot be mixed together in this way either, as they suffer from plastic deformation. Fig. 7/c shows the simplify real cross section with deformation in case thin layer and overlapping of the extruded lines.

The material leaving the extruder will undergo a plastic deformation due to the pressure change, so the diameter of the extruded material will not be the same as the diameter of the extruder, but will be slightly wider [16]. The software tries to maintain the nominal size by printing adjacent contour lines closer together, but this results a theoretical overlap within a layer and then smears
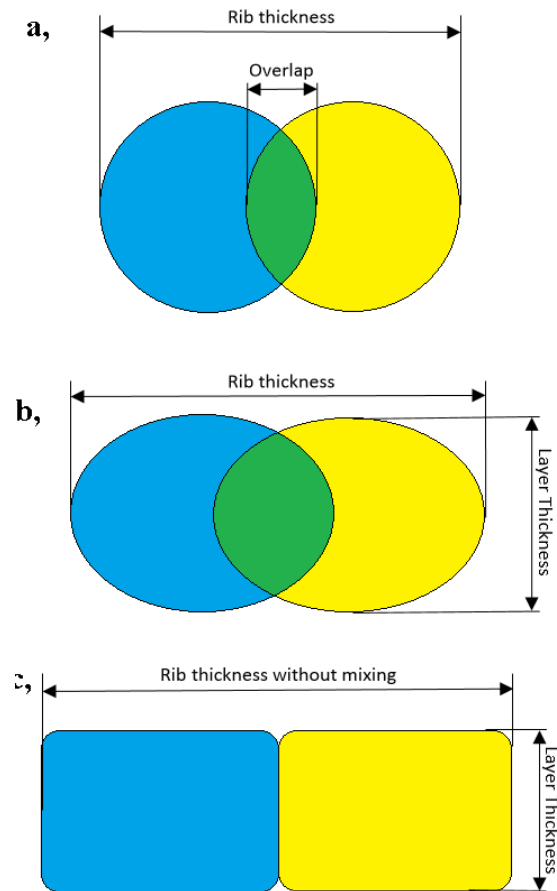

Figure 7. Cross section of the extruded lines a) nominal b) compressed c) deformed
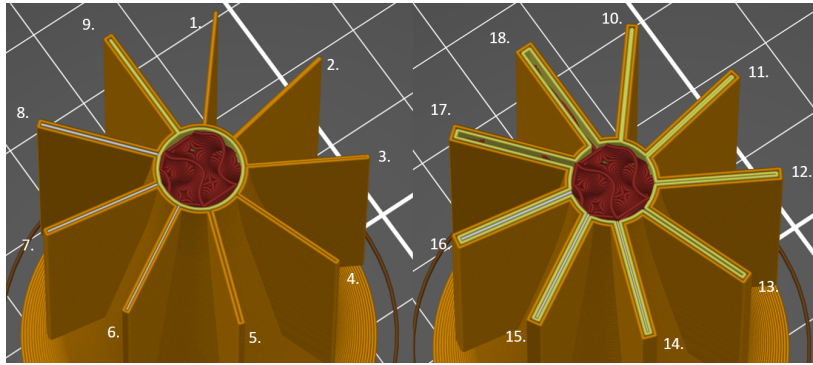
Figure 8. The generated toolpath

it in the plane of the printer head when the next layer is formed. Based on these phenomenon, the given thickness of printed part can be only bigger than 0.4 mm.

But the thickness not only affected of extruded filament size but also the printing path. The created surface model is opened in the printer's slicing program and sliced with the usual parameters to show the created toolpath. The generated toolpath is shown in Fig. 8. The FDM printing technology always start to print the contour of the layer. In our case it was only one contour line (which is the minimum), but in case of ribs that is means two printed filament next to each other (clearly seen in Fig. 8 the rib 3-7). In reality, however, it first draw a given layer of parts with a contour line and then infill the surface bounded by the contour line according to the infill pattern and density percentage.

Since the infill pattern is not parallel to the contour lines, it does not apply that its size. So the size can only be a multiple of the thickness of the contour line for thin walls. The part is at least as thick or thicker than the contour lines, the part will be finished close to the nominal size. In the present case, however, ribs numbered 1-3. have smaller thickness than the two contour lines together, they cannot be thinner than 0.8 mm.

To understand more the size effect, the printed path was examined in more detailed. In the present case, the contour line embodies the right and left sides of the ribs. When drawing the middle cylindrical part, it begins to extrude one side by layer, then reaching the end of the rib, extruding the outer surface of the rib by a perpendicular displacement and then extruding the other side of the rib moving backwards. Even perpendicular displacement is small, at constant speed the volume also constant, so the rib cannot be smaller (Fig. 7/c). The perpendicular displacement gives the overlap. Overlap of 0 mm (the perpendicular displacement is 0.4 mm) means the two contour lines are right next to each other, while an overlap with a negative value is a gap between the two contour lines.

This explains why there is such a difference between the curves at the beginning in Fig. 6. Interestingly, rib 1. apparently consists of a single contour line, which would be logical, as its nominal size is only 0.1 mm larger than the thickness of the contour line, but in order for the layer to print continuously, the print head reaching the tip of the rib does not interrupt the extrusion with a high-speed motion, but also extrudes the material backwards, barely moving in the perpendicular direction. So in this case also two outer contour lines have been created.

From the measurement results, it can be seen that when printing the ribs, the duplex line results in a thickness of at least 0.8 mm. In fact, when the tracks are printed so close together that the material extends sideways. It can be observed that 1-5. for ribs, the software draws only the outer contour lines with the extruder and starts extruding the inner contour lines only at rib 6, as it can been seen .As the nozzle moves more and more between the two outer tracks, the thickness also increases slightly. It can be seen in Fig. 8 that rib 5 (0.9 mm thick) develops a state where the

printed contour fills the space so that it is nearly identical to the CAD model. Since the value of the overlap is negative for this rib, no deformation per layer will occur, which explains the accuracy.

For ribs thicker than 0.9 mm but 1.2 mm thinner, outer contour lines and the inner contour lines are also present. Three lines, two outer contours and one inner contour line, are drawn next to each other. However, because the extruder can print a line at least 0.4 mm thick, it prints the inner contour line on the outer contour line for a fill space of less than 0.4 mm. For this reason, the same consequence occurs as for the previously mentioned thin ribs (up to a rib thickness of less than 0.9 mm). There is a further difference between the 1.2 and 1.7 mm thick ribs. But the 1.7 mm thicker ribs are already approaching the nominal size and are made with the same inaccuracy. In the case of ribs with a thickness of 1.7 mm, the effect of the adjacent lines extruded on each other is still significant. However, for thicker wall thickness (1.8–2.0 mm ribs), this effect is less significant.

Thicker ribs create more contour lines, which reduces this error. This is because the outer contour is created first, i.e. there is no shortage of space and the contour lines start to solidify in the correct position. When the inner contour lines are printed, they squeeze the outer layer. When last contour line is inserted (which fill the rest), the stiffer outer part can change the size much smaller. Actual infilling (with pattern and density) can only be observed for the last two ribs. The size of these ribs is also close to the nominal size, so it can be assumed that thicker ribs also have such accuracy. The highest accuracy is achieved when the nominal size is a multiple of the extruded line or it is thicker than 2.0 mm. The last two ribs no longer affected by this phenomenon, because there is infill inside the rib. From this point, the accuracy of the printer will determine the actual size. The lower part of Figure 6 shows the overlaps depend from perpendicular displacements. It is clear that the size curves are broken when the printing strategy changes (marked with arrows). The slicing program always tries to have more overlap (rib thicknesses of 0.5, 1, 1.3, and 1.8 mm), however, the volume is still constant, so the wall thickness cannot actually decrease.

6. Conclusions

Metal printing is still extremely expensive these days, additive loss pattern casting is preferred in practice as an alternative, low-cost solution. In this article, the feasibility study of Additive Loss Pattern Metal Casting was presented. The Loss Pattern was made from Polycast filament sample material, and the mold was made with special plaster (Pioneer Investment Powder). The casting was formed by casting molten metal (SN99) into the mold cavity previously burn out the polymer pattern and then removing the gypsum mold.

After establish the new casting process, a special specimen was designed to evaluate the accuracy. The ribs of different wall thicknesses were printed from polymer and then the mold required to cast the tin was made. We found that the dimensions of the printed and cast parts show a negligible difference, while the dimensions of the CAD model already showed a more significant difference compared to the printed part.

While exploring the causes, we found that the print path plays a key role in the error. Based on these, the following was found when printing thin ribs:
- at least two contour lines are made in case of one rib, so the thickness of the rib must not be less than 0.8 mm,
- the slicing program tries to compensate for dimensional errors by overlapping (smaller perpendicular displacement), which is not a sufficiently efficient method,
- a rib consists of more contour lines, which lead smaller size error caused by printing,
- above 2.1 mm, where the infill already appear, the rib width error is depends on the accuracy of the printer.

7. Acknowledgement

8. References

[1] Gy. Falk, T. King, *Precíziós öntés 3D nyomtatással*, download date: 10. 10. 2020, url

[2] M. Horváth, *ANZDOC*, download date: 18. 9. 2020, url

[3] M.R. Nichols, *How does the automotive industry benefit from 3D metal printing?*, Metal Powder Report 74(5), 2019, pp. 257-258. CrossRef

[4] L. Gardner, C. Buchanan, *Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges*, Engineering Structures 180, 2019, pp. 332-348. CrossRef

[5] Á. Németh, Sasovits, *Öntészet*, download date: 5. 11. 2020, url

[6] B. Berman, *3-D printing: The new industrial revolution*, Business Horizons 55(2), 2012, pp. 155-162. CrossRef

[7] M. Attaran, *The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing*, Business Horizons 60(5), 2017, pp. 677-688. CrossRef

[8] K.G. Swift and J.D. Booker, *Manufacturing Process Selection Handbook*, Oxford: Butterworth-Heinemann, 2013. CrossRef

[9] J. Campbell, G.W. Kuhlman. J.R. Grassi, *Lost Pattern Mold Removal Casting Methods and Apparatus (patent)*, 2005, download date: 19. 11. 2020, url

[10] T.S. Piwonka, A comparison of lost pattern casting processes, Materials & Design 11(6), 1990, pp. 283-290. CrossRef

[11] Lulzbot, *Polymaker*, download date: 18. 11. 2020, url

[12] SRS, *SRS Setting The Standard*, download date: 18. 11. 2020, url

[13] M.B. Ouvres, *mbv*, download date: 18. 11. 2020, url

[14] J. Flynt, *Polylactic Acid (PLA): The Environment-friendly Plastic*, 3DINSIDER, download date: 9. 11. 2020, url

[15] TheMetalCasting, *Tin Alloy*, download date: 9. 11. 2020, url

[16] T. Czvikovszky, P. Nagy, J. Gaál, *A polimertechnika alapjai*, Budapest, Műegyetemi Kiadó, 2007.