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Analysis of fused filament fabrication/fused deposiotion modelling applications for production of casting patterns used in sand casting

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ABSTRACT

This paper presents an analysis of FFF/FDM (fused filament fabrication / fused deposiotion modeling) applications for production of casting patterns used in sand casting, with particular emphasis on short-run and prototype production. For this purpose, casting patterns of different shape and height of incremental layer (0.29 mm, 0.19 mm, 0.14 mm and 0.09 mm) were made of Z-ABS filament produced by Zortrax. Geometrical and dimensional analysis of the patterns was carried out, surface roughness parameters were measured, and a visual analysis of the surface was performed. In order to evaluate the conclusions observed based on the analysis of casting patterns, 130 × 102.5 × 37.5 mm sized shaped castings were designed and manufactured from aluminum and grey cast iron, which were also subjected to analysis. The last element of the research was a visual analysis of the reproduction of markings on the castings.

Keywords: 3D printing, FFF/FDM technology, rapid prototyping, surface roughness, casting models dimension.

INTRODUCTION

Foundry, as one of the oldest manufacturing processes, has evolved significantly over the centuries, but many unchanging regularities can still be observed today. One such example is the production of castings in expendable molds based on foundry sand. Foundry sand, due to its natural specificity, exists and existed thousands of years before our era without any significant changes. Of course, in the meantime, various unnatural ingredients have appeared, such as synthetic binders such as phenol-maldehyde resin or other molding materials such as Carborundum, but the specificity of the process has remained unchanged [1, 2].

The basis of the process is the need to make a casting pattern, which will create a mold cavity during the production of the casting mold. In the past, these patterns were made by hand in specially designated sections of the foundry, called pattern shops - mainly from wood and wood composites [3, 4]. Nowadays, the production of those elements is much faster thanks to the use of multi-axis CNC machines and CAD/CAM environment, while plastics, metals and modern wood composites are mostly used. The use of multi-axis CNC machine tools and CAD software is clearly associated with high costs and the need for large-scale production, which very often results in the inability or unprofitability of making prototypes or short production series of castings. Therefore, reducing the costs and time of manufacturing foundry equipment (e.g. casting patterns) is of great importance in the case of short production runs [5].

These goals can be achieved, among others, by using additive technology such as 3D printing techniques [6, 7]. Due to the expiration of patent rights and the constant decline in the prices of materials and 3D printers themselves, purchasing equipment that meets the requirements of casting process should not be an obstacle for any foundry. One of the most accessible and cheapest 3D printing methods is FFF/FDM technology. This method allows for the production of patterns used in classic foundry techniques based on foundry sand [8–10] and can also be used in precision casting by making disposable foundry patterns from e.g. HIPS (high impact polystyrene) or PLA (polylactic acid) in investment casting method [11–14]. This technology involves plasticizing a thermoplastic material in the printer head (so-called extruder) and applying it layer by layer to the work table (platform). Regarding the most popular printers on the market, after making one full layer of the cross-section of the model previously designed in the CAD environment, the work table is shifted in the Z axis by the value specified in the printer software (it is called incremental layer) and the next layer is made. The process ends when all the specified layers are completed. The construction diagram of described FFF/FDM 3D printer along with the details of the process is shown in Figure 1. An alternative existing architecture for FFF/FDM 3D printers is the delta configuration, where the print head is responsible for motion in both the XY plane and the Z-axis.

The 3D printing technology, like any technology, has certain advantages but also certain limitations. One of the most noticeable disadvantage of using FFF/FDM 3D printers is the minimal size of incremental layer which, depending on the printer model, is 0.08–0.09 mm. The value of this parameter affects the quality of the surface, especially its roughness, which may affect the visual assessment of the products and consequently disqualify them for further use [8, 15]. In addition, the quality and strength of the 3D printed models may be influenced by, among others: the type of material and its shrinkage, the amount of support material, filling type of the interior of the model, orientation and location on the platform and also the temperature of the print head, platform and chamber [16–18]. Application of 3D printed technology to manufacture the casting patterns in foundries is still a niche topic and requires further investigation.

The complexity of the foundry industry necessitates the application of various standards, which often focus on discrete stages, including the production of casting patterns, the dimensional precision of the final castings, and the chemical analysis of the metal alloys. It is, however, imperative to bear in mind that the end result is a metal casting that must conform to customer demands. As such, it is not unusual for signed contracts to incorporate supplementary standards, for instance, DIN ISO 286.

According to PN-EN 12890:2002 – "Founding – Patterns, pattern equipment and coreboxes for the production of sand moulds and sand cores", wooden models of H2 and H3 class can be used for short production series, pilot series or prototypes, and, as is the case in most foundries, models made of plastic with the K2 class. For overall dimensions of approx. 130 mm (the analyzed case), the dimensional tolerance of models for the H3 class is ± 0.8 mm, and for the H2 and K2 classes is ± 0.5 mm. In the case of a significant parameter that affects the ease of removing the model from the mold, i.e. surface roughness, for models of classes H2 and H3, the standard provides only for grinding the surface with 80 grade paper, while for models in the K2 class, the recommended value of Ra surface roughness parameter equals 12.5 µm.

It should be emphasized here that casting in sand molds is characterized by one of the worst roughness levels that can be achieved in the foundry industry. Of course, the final quality assessment is made by the customer based on the signed contract, however castings made in this way are characterized by 20÷100 µm roughness for Ra parameter, while for comparison, castings made in pressure molds are characterized by the value 0.32÷2.5 µm. This is due to the use of bulk materials that are characterized by different

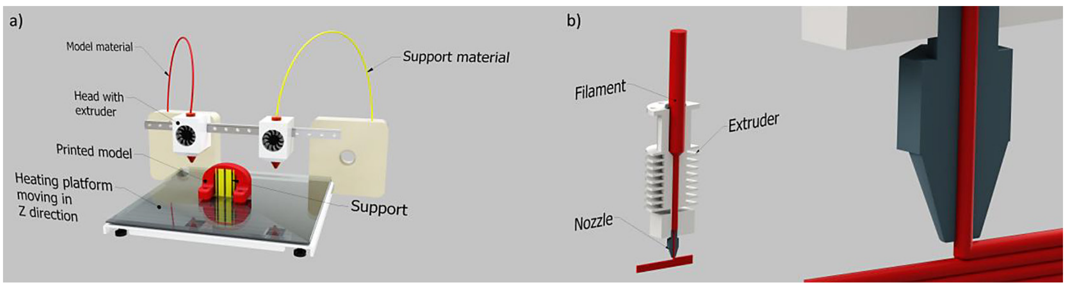

Figure 1. The FFF/FDM process: (a) general scheme, (b) application of plasticized material

grain sizes, while in the case of pressure casting, it is necessary to mention that molds are made in metal alloys using a subtractive techniques (e.g. milling, electro-discharge etc.).

As can be seen, making castings in traditional molds is associated with many factors that should be taken into account when making castings. The behaviour of individual alloys in combination with the mold materials has an impact on the shape and quality of the final product. The conventional fabrication of foundry patterns for small-scale production typically involves the use of high-quality wood or plywood, which extends their manufacturing duration. In contrast, mass production of castings often utilizes resin models, requiring the creation of a master pattern and subsequently the final pattern [19]. The principal limitations of these described methodologies are their time intensiveness, high individual costs, and challenges in realizing complex geometric shapes. Additionally, these manufacturing routes are not economically feasible for one-off production, especially when design changes are implemented. Another challenge addressed by 3D printing is the minimization of human-induced errors during manual fabrication, as well as the avoidance of hazardous waste associated with resin materials. The significance of 3D printing technology lies in its ability to enable the rapid, precise, and cost-effective creation of models, irrespective of their complexity [20]. Notably, it also permits facile design adjustments, decreased material consumption, and a substantial reduction in the time required for product development – from the initial design concept to the final physical realization. As a result, 3D printing is increasingly recognized as a practical substitute for conventional manufacturing techniques, particularly in the realms of prototype development and small-scale production.

In this paper, it was decided to design and produce several casting patterns using 3D printing technology. Dimensional and geometric analysis of the patterns was carried out, and surface roughness was measured. Based on the analyzes, it was decided to produce test castings, which were also analyzed. Particular attention was paid to the surface quality of the 3D printed models and castings. The last element was the evaluation of the visual reproduction of markings on the model and castings made of aluminum alloy and cast iron.

MATERIALS AND METHODS

The first stage of research was to design the geometry of the 3D models responsible for reproducing the external and internal shapes of the castings, manufacture the models using FFF/FDM 3D printing technology and dimensional analysis of the physical samples. The designed models corresponding to the external cubic and cylindrical dimensions are shown in Figure 2a and 2b (correspondingly), while the models corresponding to the internal dimensions are shown in Figure 2c.

The height of the designed models was 50 mm, the length of side or internal/external diameter (on the upper surface of the models) have been divided for two groups: first ranged from 1÷10 mm (ranged every 1 mm) and second ranged from 12÷30 mm (ranged every 2 mm). The draft angle of all models was 1.5°. Measurements were taken on the top and bottom edges (for external dimensions) and on the top edge for internal dimensions of the 3D printed models.

The height of the 3D printed incremental layer is one of most important parameters used in every additive technique. It determines the quality of surfaces depending on the angle between

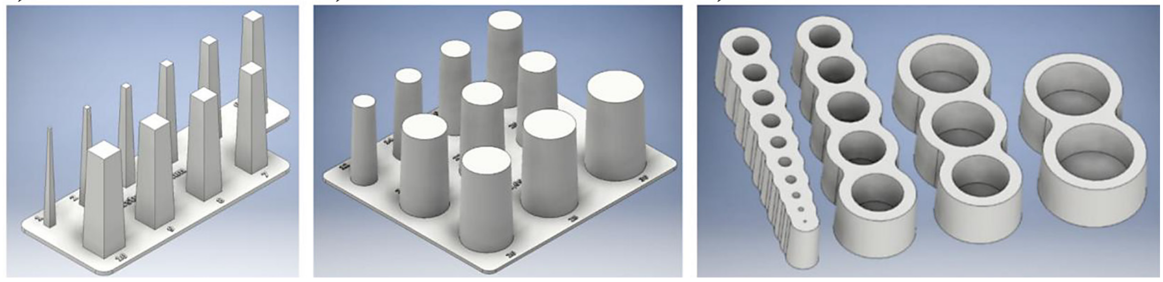

Figure 2. Examples of geometries reproducing an external shapes: (a) cubic models, (b) cylindrical models, (c) hole models

the platform base (working table) and the 3D printed surface. Due to limitations related to the measurement equipment, a 3 mm high geometry was designed to analyze the effect of the incremental layer on the height of 3D printed models (Figure 3a). An example showing comparison of theoretical 45 degree surface (red) with real surface (black) for 1 mm height 3D printed model with 0.09 mm value of incremental layer is shown in Figure 3b.

All 3D printed models for dimensional analysis were made using FFF/FDM technology on the Zortrax M200 printer with the following parameters: the height of a single incremental layer were: 0.28 mm, 0.19 mm, 0.14 mm and 0.09 mm, the material used for the models was ABS (Acrylonitrile Butadiene Styrene) produced by Zortrax Company (trade name: Z-ABS), the nozzle used was a 0.4 mm nozzle, surface layer: top =10, bottom = 6, infill density = 30%, extrusion temperature was 275 °C, platform temperature was 80 °C.

All measurements were made using an Mitutoyo Digimatic Micrometer MDC-25SX with an accuracy of 0.002 mm. Each dimension was measured 10 times. The arithmetic means and measurement uncertainties type A with confidence interval equal 0.95 was calculated.

Additionally, the surface roughness of 3D printed models (Figure 2a) was measured on flat surfaces on steps with a side width of 4, 8, 16 and 28 mm length. The surface roughness parameters Ra, Rz and Rt were measured. Measurements were made using a MarSurf PS 10 roughness gauge. Five measurements were made in each measurement area.

The second stage of the research included designing and 3D printing a model for geometric analysis. The 3D printed model was made of Z-ABS with the best available print quality (0.09 mm for incremental layer). Geometric analysis consisted in comparing the 3D scanned geometry of the 3D printed model with designed CAD model. For this purpose, the ATOS TRIPLE SCAN 3D scanner was used and the obtained geometries were compared in the GOM software. The model of the designed geometry is shown in Figure 4.

The ATOS Compact Scan is a mobile and versatile 3D scanner designed for a wide range of measurement and inspection tasks across various industries with scanning speed approximately 1 second. Typically ranges of working distance are from 450 mm to 1200 mm, minimal area of scan is 45 x 35 mm while maximal is 1200 × 1000 mm. The maximum permissible error is 0.05 mm.

The third stage of the research was surface quality inspection of the castings. This stage was divided into several parts: preparation and production of 3D models, making the castings, visual assessment of the castings and surface roughness analysis. For this purpose, the same techniques

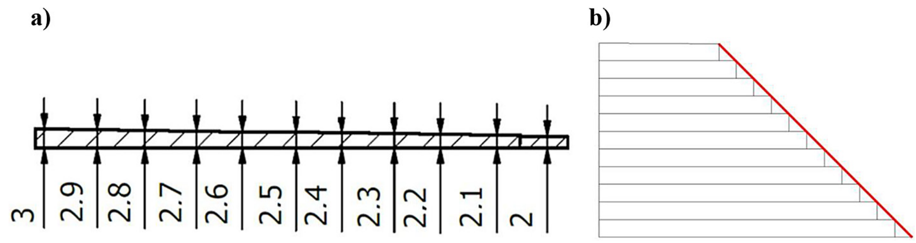

Figure 3. Incremental layer effect: (a) analyzed geometry, (b) influence of the incremental layer on the surface quality

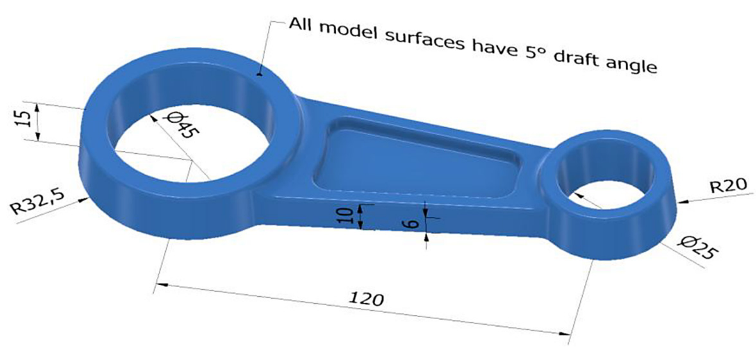

Figure 4. Designed model used for geometric analysis

were used as in the previous stages, i.e. FFF/FDM 3D printing and gravity casting of aluminum alloy made in green sand mold.

Due to the specificity of the casting and 3D printing processes, it was decided to design two models. The geometry shown in Figure 5 was used to analyze the angular surface quality representation. For this purpose, 4 casting patterns were made using FFF/FDM 3D printing technology with the following parameters: the height of a single incremental layer were: 0.28 mm, 0.19 mm, 0.14 mm and 0.09 mm, the nozzle used was a 0.4 mm diameter. In the presented geometry, the angles between platform (base) and the side surface change every 2 degrees and range from 2 to 88 degrees. Dimension of model was shown on Figure 5.

The second designed geometry shown in Figure 6a represents a half pattern of a typical casting (valve body) made in the foundry industry. In contrast to the earlier model, the valve body is a predominantly oval model with pattern inscriptions. Due to the geometry of the model, it was decided to make castings from aluminum and cast iron. As before, the castings were made by gravity in a green sand mold consisting of: 93% quartz sand and 7% bentonite clay. The humidity of green sand was 3%. The surfaces marked in the Figure 6a were used to measure the roughness of the Ra parameter of the model and castings. The last element was the evaluation of the visual reproduction of markings on the casting pattern and castings. Dimension of pattern inscriptions are shown in Figure 6b.

RESULTS AND DISCUSSION

Dimensional analysis of 3D printed models

The main observed problem with Z-ABS 3D printed models and their application in foundry industry was the flattened surface on the upper edges (Figure 7a). If the process engineer will not control the 3D printing parameters or at the final moment doesn't round the 3D printed model this error will result in the tearing of the green sand during model

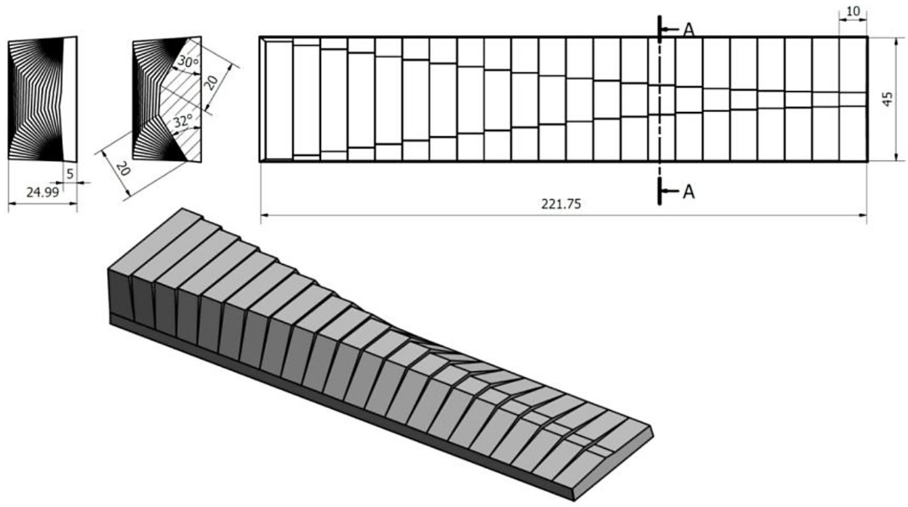

Figure 5. Geometry used to examine the representation of angles on the casting

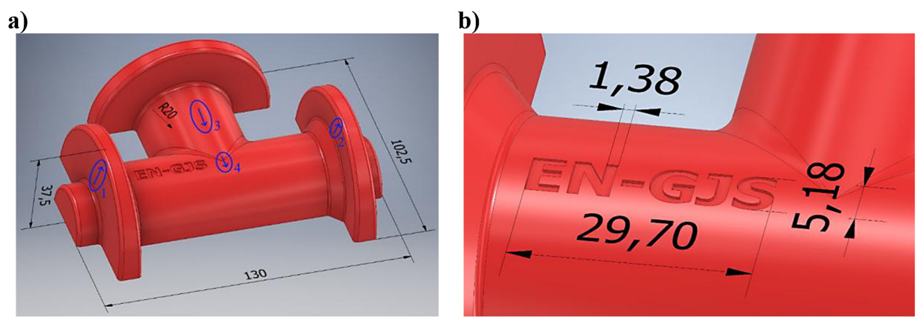

Figure 6. The casting pattern: (a) external dimensions and directions of surface roughness measurement, (b) dimensions of the letters

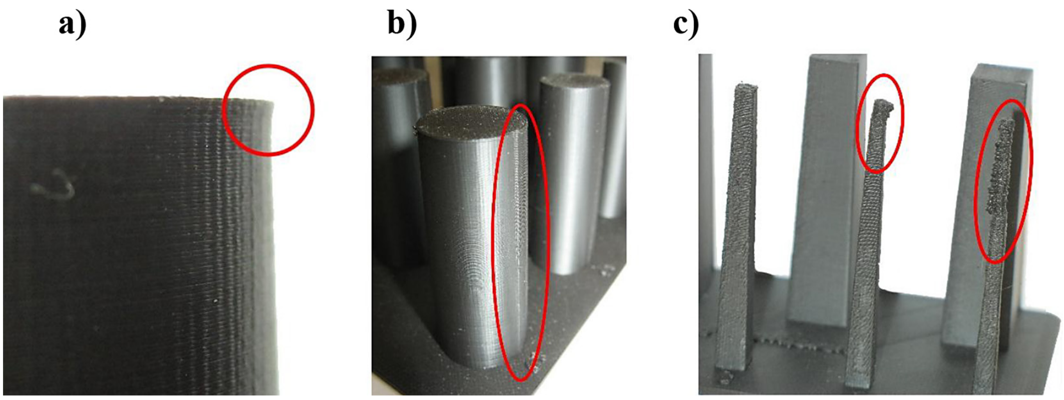

Figure 7. 3D printed models defects: (a) flattened upper edge, (b) seam, (c) no printout

removal from the mold and thus a defect in the surface and dimensions of the casting.

Another common disadvantage in 3D printed model application in foundry is the so-called seam (Figure 7b). It is created as a result of the completion of a layer print when the table is lowered during the transition from one layer to another. This defect is exceptionally visible on oval or round shapes, changing the roundness profile on each layer of the printed model. This can be prevented by setting in the 3D printer software (if available) as random start of each new layer. In that case every surfaces need to be grinded, which will extend the time to produce the final model. In case of slender and thin shapes occur on model the 3D printer head will not be able to accurately apply plasticized filament. It is caused by its non-completely solidifying. This defect was shown on Figure 7c. Every separate or all descripted defects can cause problems in casting mold manufacturing.

Figure 8 shows the difference between nominal and actual dimensions measured on the top surface of models printed using different size of incremental layer. The presented data show that the maximum difference in the values of the linear dimensions of the 3D printed models, in relation to the nominal values, are ± 0.18 mm. According to the PN-EN 12890 standard for dimensions up to 30 mm, used in small-scale production, these are permissible values.

The lack of measurements no. 1 and 2 is caused by incomplete printing of the top part of the models (see Figure 7c). The more important analyzed dimension, which is not affected by external interference, is the diameter and length of the side at the base of the model. The differences between the nominal and actual dimensions for all cases are shown in Figure 9.

Regardless of the shape of the printed geometry and the size of the incremental layer, the actual dimensions were smaller than the nominal. The largest deviations occurred for models made with an incremental layer of 0.29 mm and amounted to max. -0.25 mm. For the other cases (different incremental layer) the dimensional differences were smaller form 0.05 mm to 0.2 mm and similarly to previous measurements were within the PN-EN 12890 standard.

In addition to information about the change of linear dimensions expressed in mm, an important aspect is an information about their change

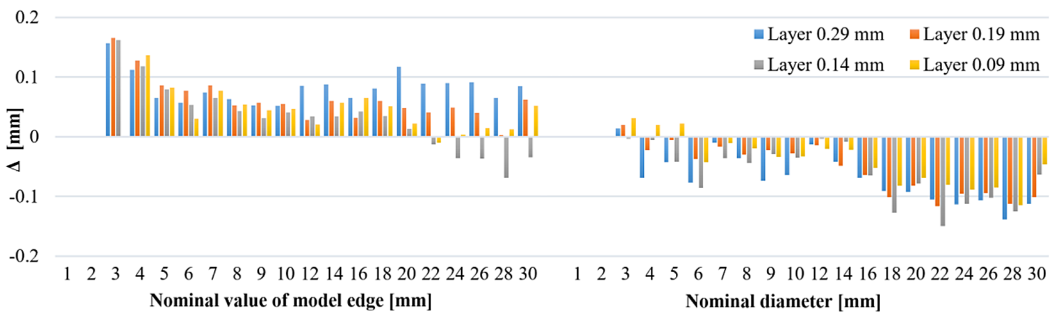

Figure 8. Difference in the length and diameter of the printed model depending on the size of the incremental layer

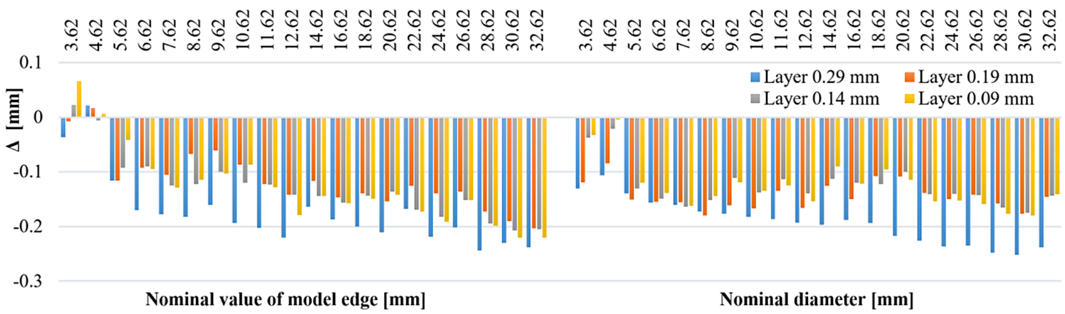

Figure 9. Difference in the length and diameter of the printed model depending on the size of the incremental layer

expressed as a percentage. Figure 10 shows the percentage difference of the actual from nominal dimensions of the 3D printed models for the two smallest values of the incremental layer, i.e. 0.12 mm and 0.09 mm.

The obtained data show that, regardless of the shape and size of the 3D printed models, the percentage change in linear dimensions stabilizes for model sizes larger than 15 mm and for ABS filament is 0.7%. The difference between nominal and actual diameter of the holes dimension depending on the size of the incremental layer where shown in Figure 11.

The largest differences between actual and nominal hole diameters occur for an incremental layer of 0.29 mm (Δ = -0.3 mm). Using a 3D printed model with an incremental layer of 0.09 and 0.14 mm reduces the Δ value to about -0.15 mm.

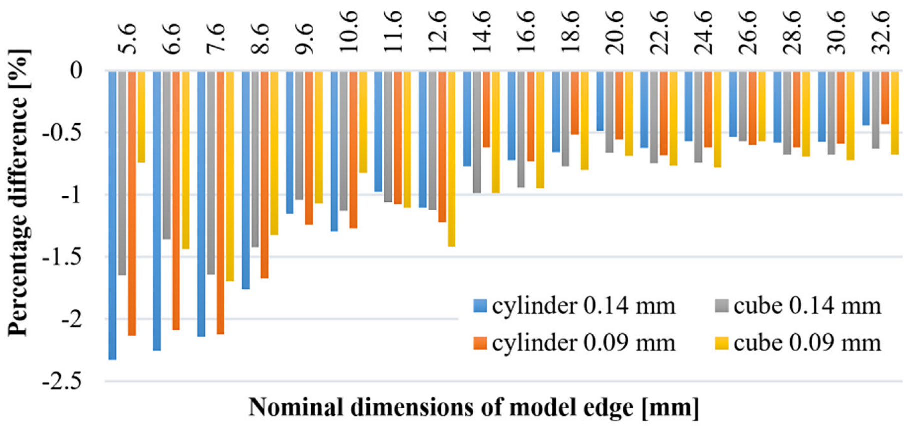

Figure 10. Percentage difference between the nominal and actual dimensions for different shape and incremental layer

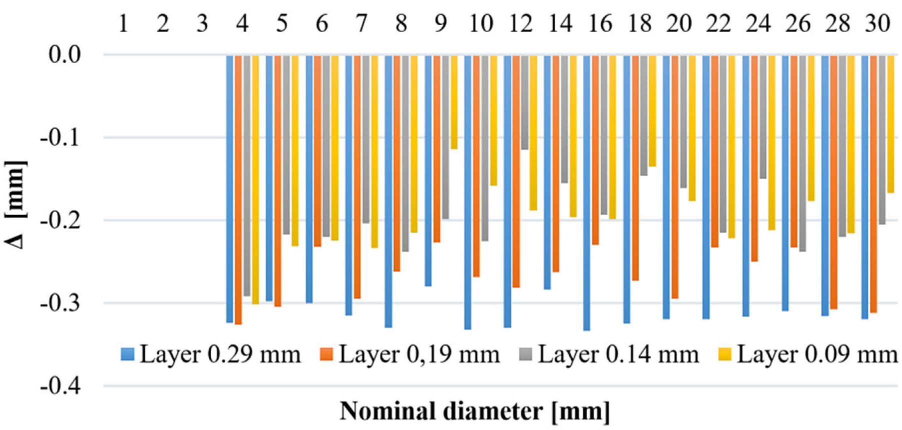

Figure 11. Hole diameter differences of the 3D printed model depending on the size of the incremental layer

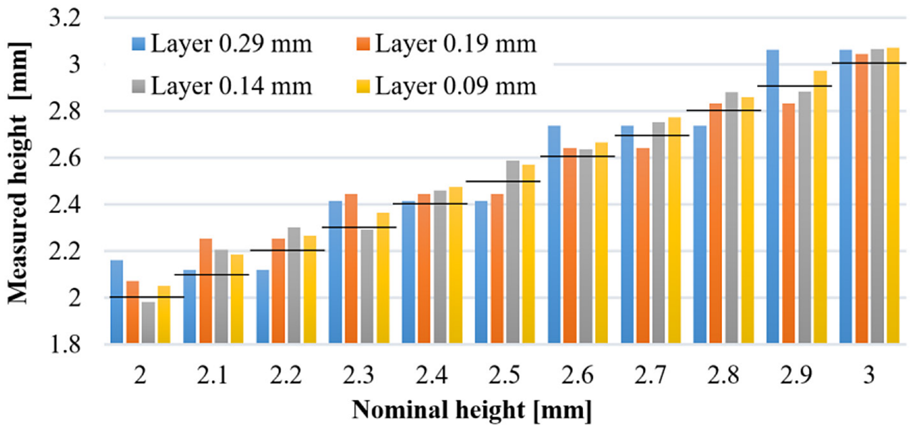

Figure 12. Actual of model heights as a function of value of the incremental layer

Manufacturers state that every FFF/FDM 3D printer enable positioning of the head with an accuracy of about 1.5 µm. However, the value accuracy of the height of printed element is determined only by the size of the incremental layer. Most of FFF/FDM printers could printing with the minimum incremental layer even approx. 0.08 mm. The results of measurements of the height of the 3D printed models as a function of the nominal size are shown in Figure 12. Black horizontal lines shows the nominal value of the height of CAD geometry.

In the analyzed variants, it can be seen that the greatest differences between the nominal and actual dimensions are characteristic of 3D printed models with a layer height of 0.29 mm and 0.19 mm (ranges from -0.1 to 0.18 mm).

Roughness of 3D printed models

Measured surface roughness profiles of individual 3D printed models are shown in Figure 13. Figure 14 presents summary of the measurement results.

The highest value of Ra parameter occurs for models printed with an incremental layer of 0.29 mm and amounts to approx. 22.5 µm. It is a value that hinders the removal of the model from the mold and will damage mold's cavity surface. Reducing the size of the incremental layer

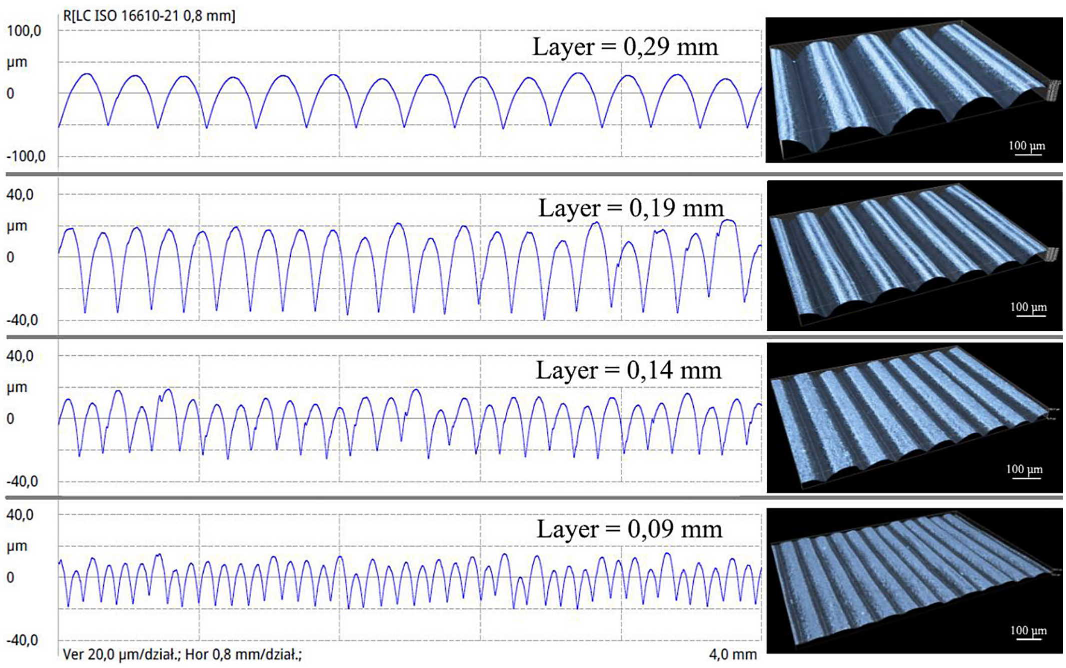

Figure 13. Profiles of the 3D printed models depending on the value of the incremental layer

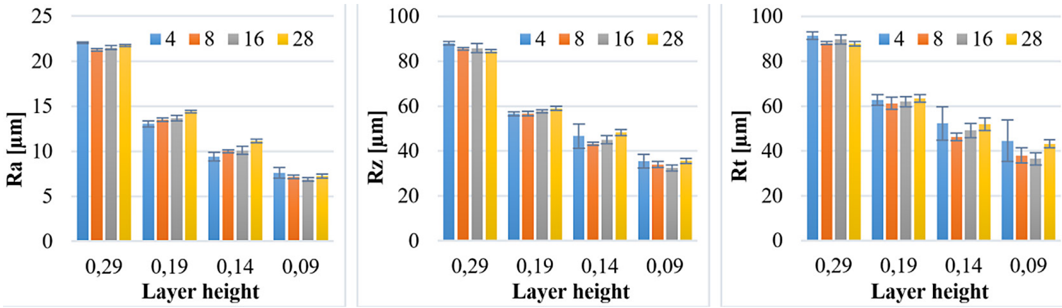

Figure 14. Surface roughness parameter values for selected measurement sections (side width of 4, 8, 16 and 28 mm length) for 3D printed models made with different incremental layer heights

significantly improves the surface roughness of the 3D printed models, which is confirmed by the obtained profiles. This regularity was maintained for the remaining surface roughness parameters (Rz and Rt).

Geometrical analysis of 3D printed model

Application of 3D printed models in the foundry industry is most often limited to the lost wax casting or investment casting methods. However, the use of FFF/FDM 3D printing technology can be an alternative to classical methods of manufacturing foundry patterns for traditional green sand casting. Figure 15a shows a connecting rod model made using additive techniques, while Figure 15b shows the geometric analysis performed between the nominal and scanned geometry in GOM Inspect software.

Taking into account the results presented in the form of a deviation map, it can be clearly stated that despite not taking into account phenomena related to 3D printing, such as filament shrinkage etc., the obtained 3D model meets the standard of the PN-EN 12890 standard. The largest observed difference between nominal and actual dimensions was -0.23 mm for diameter of 40 mm and +0.22 mm hole diameter of 45 mm.

Surface quality inspection

Each production process is hedged by many clearly and easily defined parameters such as: dimensional tolerance, surface roughness, porosity share or mechanical properties. However, despite their fulfilment, visual evaluation of the obtained products is also very often used in the foundry industry (especially in the case of artistic or prototype casting). Figure 16 shows the surfaces of

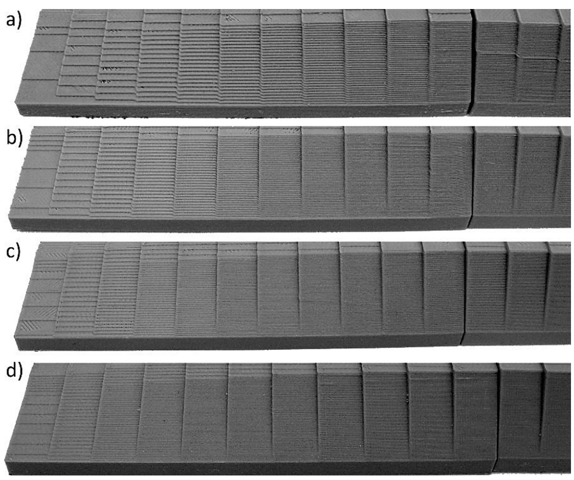

Figure 16. Surfaces of 3D printed models at different angles and with different sizes of the incremental layer: (a) 0.29 mm, (b) 0.19 mm, (c) 0.14 mm, (d) 0.09 mm

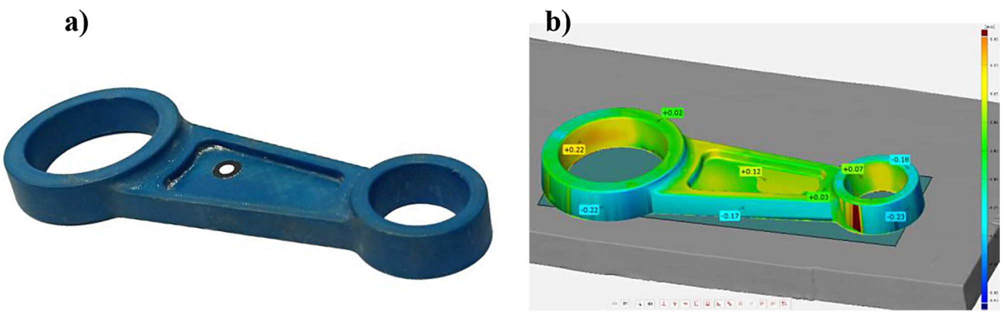

Figure 15. 3D model of connecting rod: (a) 3D printed model, (b) geometry composition

3D printed models at different angles and with different sizes of the incremental layer.

The quality assessment of the surface is often an individual matter for the customer and most often depends on the intended use of the final product. It can be assumed that for research purposes, the acceptable surface was the one for which the residue from the 3D printing process, i.e. the reproduction of a single layer, is invisible or almost invisible. As a result of the visual analysis, it was found that for a incremental layer height of 0.29 mm the acceptable surface starts from 16 degrees, while for smaller layers this parameter was similar and amounted to 6 degrees of draft angle.

After carrying out an analysis of the 3D printed models, it was decided to evaluate the assumptions by making an AlSi7Mg aluminum alloy castings. The surface quality of aluminum alloy castings made using 3D printed patterns with different incremental layer heights is shown in Figure 17. The castings were made using the gravity casting method in green sand consisting of: 93% quartz sand and 7% bentonite clay. The humidity of green sand was 3%.

Based on the castings shown above, it can be concluded that the reproduction of the drafted surface is similar to the printed models. It should be also emphasized that casting in a green sand molds, the granularity of the sand, humidity, degree of its compaction or even the flatness of the surface play a very important role in the reproduction of the surface quality.

In order to confirm the above assumptions, it was decided to make an additional series of castings representing a typical casting (half of the valve body) made using this technology. The casting was gravity made of aluminum alloy and grey cast iron in green sand mold. Measurement of surface roughness of 3D printed model and castings were performed in the places and directions shown in Figure 6a. The models draft angle was 2°, the rounding radii are 1.5 mm, casting pattern was printed with an incremental layer of 0.09 mm of Z-ABS. The 3D printed model, aluminum alloy and cast iron castings are shown in Figure 18.

The results of the surface roughness measurement of the model and castings are presented in Table 1. Due to the characteristics of the sand casting method and, consequently, the size of sand grains, both castings made of cast iron and aluminum alloy had a surface roughness approximately 60% greater than surface roughness of 3D printed model. This means that no post-processing of 3D printed models is needed before using them to produce prototype castings.

Most of the industrial castings have pattern inscriptions such as grade, batch number, etc. The reproduction of these markings is particularly an important in the case of 3D printed models because, as has been shown with small external elements as well as internal ones, there is a high probability that due to the nature of 3D printing process, they will not be reproduced. The reproducing of letters on the pattern and castings is shown in Figure 19. The letters were 1 mm deep and the thickness was from 0.9 to 1.4 mm.

As can be seen, the reproduction of the markings on the 3D printed model is not precise. The letters, compared to the CAD geometry, are not uniformly thick. Despite the use of the smallest incremental layer, it is hard or impossible to obtain a casting draft angles inside the small pockets like letters, which may result in the separation of the green sand and formation of defects.

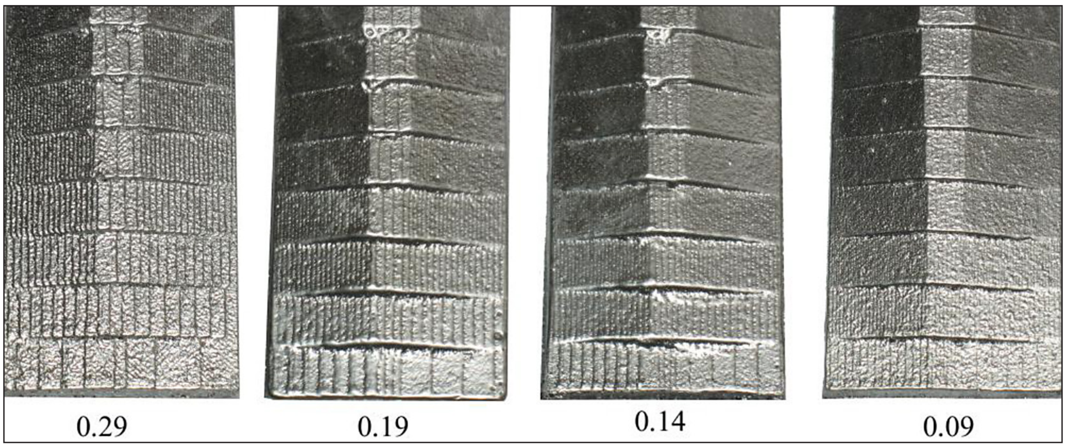

Figure 17. Surface of casting made of aluminum silicon alloy

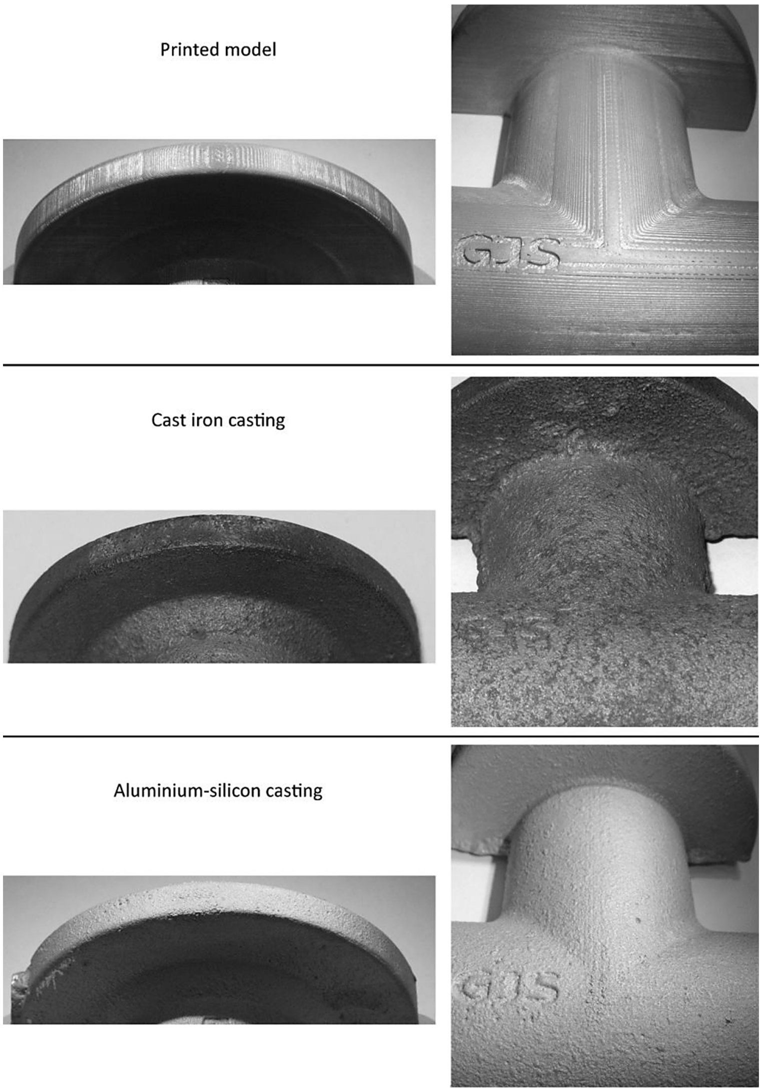

Figure 18. The 3D printed model, aluminum alloy and cast iron castings

Table 1. Value of surface roughness Ra for the analyzed surfaces

Measurement area	Results [μm]		
	3D printed model	Cast iron	Aluminum alloy
1	5.33	8.25	8.07
2	5.47	9.54	8.45
3	0.62	12.27	6.34
4	4.45	Out of range	7.58

Figure 19. Reproducing letters at: (a) printed model, (b) cast iron casting, (c) aluminum-silicon casting

For cast iron casting, the letters are not clear and the edges are poorly reproduced, which is related to the high value of the pouring temperature and the green sand sintering. On the other hand, the casting made of aluminum alloy was characterized by an acceptable level of marks reproduction. In both cases, in order to improve the reproducibility of the markings, a different font or inserts made of a different material e.g. metal should be used.

CONCLUSIONS

This article presents and analyzes the feasibility of utilizing 3D printing technology for the production of casting patterns. It has been demonstrated that 3D printed casting patterns, and the castings produced using them, meet the tolerance requirements stipulated in foundry standards (dimensional tolerances of ±0.1 mm), which significantly reduces production costs. Furthermore, it has been proven that using the smallest incremental layer height for printed patterns (0.09 mm) results in the lowest surface roughness of gravity castings (Ra = 6 µm for aluminum castings). However, due to the characteristics of sand molds, it is recommended to use an incremental layer height of 0.14 mm and an infill of approximately 30%, which further shortens tooling fabrication time while still meeting foundry standards. Given the inherent characteristics of 3D printing technology and potential defects in 3D-printed patterns, it is advisable to conduct organoleptic and dimensional inspections of the manufactured parts and, where feasible, rectify any defects. The casting standard permits the grinding of casting patterns, which could be a significant advantage for the practical application of this technique. In conclusion, by implementing appropriate quality control for 3D-printed casting patterns, with particular emphasis on maintaining dimensional accuracy, it is possible to achieve comparable results in gravity sand casting to those obtained using traditionally manufactured patterns, such as those produced by CNC machining.

Subsequent research will focus on analyzing the effect of 3D printing parameter modifications on the dimensional variability of foundry patterns in the context of their use for sand casting, and specifically regarding the surface quality characteristics of the manufactured castings.

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