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Research Paper

Additive Manufacturing of Polymer by FDM Method in Investment Casting of Gas Turbine Hot Components

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Abstract—today, there is a great desire to achieve additive manufacturing technology for developing to meet specific needs in various industries. This technology has the ability to make parts that are used as an intermediate or final product. FDM technology is an additive manufacturing method that has been developed from the layer-by-layer manufacturing process of materials using computer-aided design. In this research, standard samples in the form of gas turbine nozzle airfoils were printed using three types of polymers namely ABS, PVA and PLA with different densities by FDM method. In order to make a ceramic mold, polymer models were assembled and coated in clusters. After the autoclave and sintering processes, the condition of the surface cracks, the amount of ash remaining in the molds, as well as the dimensional deviations of the cast parts from the optimum polymer model, were investigated and evaluated with a computer model. The results have shown that the lower density of the polymer model causes a greater reduction in the volume of the printed material, and as a result, by preventing the ceramic shell from more damage, it leaves less residual ash in the ceramic mold after sintering process. Also, ABS polymer has the lowest quality and PLA polymer has shown better results in different density percentages than PVA polymer and has a higher quality. As a result, it is possible to use FDM additive manufacturing technology in the production of gas turbine hot components by investment casting process using PLA polymer printed with low density percentage.

Keywords— Additive manufacturing, FDM process, Investment Casting, Gas Turbine Nozzle

1. Introduction

Shortening the development time of a product from design to production is one of the most important goals of using rapid prototyping and manufacturing technology. Another advantage of this method is that there is no need to make expensive molds and mechanical tools for each part. Also, this method provides the possibility of making parts with thin sections and using different raw materials. Using this method, in a short period of time (about a few hours), a three-dimensional physical model of a piece, even though complex, can be made with low cost and high accuracy, and it can be used in review and evaluation design or product [1].

Unlike reduction methods, additive manufacturing is based on a completely opposite basis, i.e. manufacturing by adding materials. In general, additive manufacturing refers to layer-by-layer manufacturing and freezing of raw materials in desired shapes. A wide range of materials such as polymers with low melting temperature to metals and ceramics with high melting point can be used in additive manufacturing technology. In addition, materials in different states including liquid, powder, wire, etc. are easily used in additive manufacturing technology. Although in additive manufacturing processes the manufacturing base is similar, the technologies created are different. Additive manufacturing technologies developed initially included dynamic optical irradiation devices, multilayer component fabrication, fused deposition modeling (FDM), and selective laser melting (SLM). These additive manufacturing processes are usually used to make polymer samples with a low melting point [2, 3].

FDM is a kind of additive manufacturing process that belongs to a larger category of 3D printing, called material extrusion. In the FDM 3D printer, a part is made by placing materials on top of each other. This placement of materials is done selectively. That is, the computer system of the FDM 3D printer, based on the data given to it in advance, decides on which paths to move its nozzle and perform the materialization process in the desired locations. The materials used in the FDM 3D printer are thermoplastic polymers that are guided into the nozzle of the FDM 3D printer in the form of a filament (a thin rope of material). FDM 3D printer is the most common and also the cheapest sub-technology of 3D printers that almost most people get to know about 3D printers for the first time. In figure (1), the schematic of the FDM process is shown [4, 5].

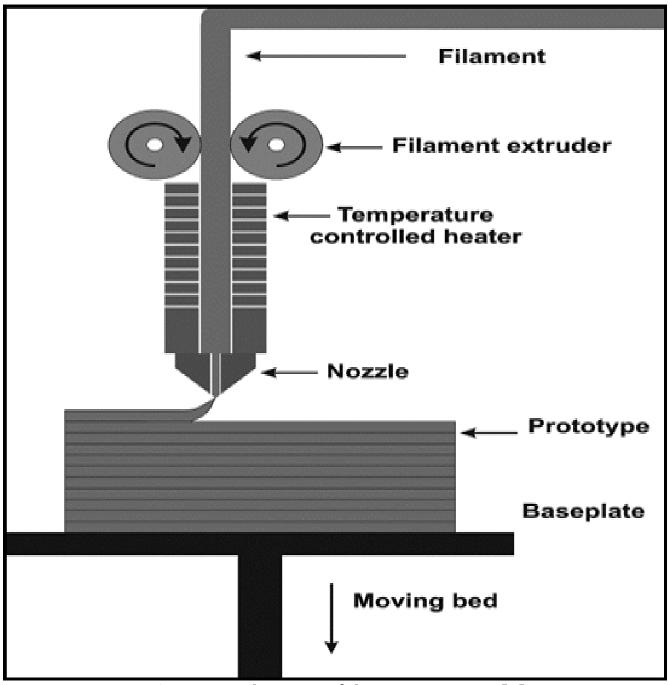


Figure 1. Schematic of the FDM process [4]

The most general weaknesses and strengths of FDM 3D printers are summarized as follows:

- Manufacturing using a 3D FDM printer is the most cost-effective method for manufacturing thermoplastic parts and prototypes.
- The price of the FDM 3D printer is lower than other printers, and its user training is also easier.
- A wide range of thermoplastics can be used in FDM 3D printers. For this reason, these printers can be used to make prototypes and parts used in the final use.
- FDM 3D printer has low resolution and low dimensional accuracy compared to other 3D printing methods.
- Despite all the limitations of the FDM 3D printer, the time for making polymer parts with this method is short.
- The lines created in the parts made with the FDM 3D printer can be seen. For this reason, these parts need surface polishing to achieve the desired surface quality [4, 5].

The materials used in an FDM 3D printer have a significant impact on the mechanical properties. On the other hand, using each of these materials has its own challenges. The price of these materials has many differences. For this reason, to create an optimum manufacturing process, attention should be paid to all aspects of using the right materials for the FDM 3D printer. One of the positive points of the FDM 3D printer is wide range of raw materials. This range includes cheap thermoplastics such as PLA and ABS to engineering materials such as PA, TPU and PETG and even to materials with higher performance and resistance such as PEEK and PEI. In figure (3), different polymers used for different industrial applications in FDM method are shown [6].

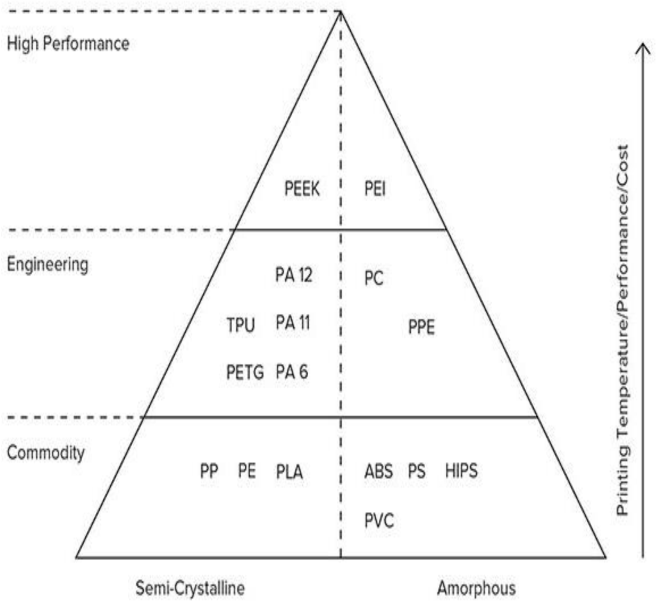


Figure 2. Different filaments used in different applications [6].

In recent years, there has been intense competition in the field of production and supply of hot gas turbine components. The ability to compete in this market is to produce the product desired by the customer with the highest quality, the lowest cost and the fastest time compared to other manufacturers and suppliers. In many cases, the presence of the manufactured part and its presentation to the customer significantly improves the company's competitiveness and the success rate in tenders. By using this method, there is no need to invest a lot to produce a sample part before finalizing the production and sale contract with the customer, and in fact, with the help of the additive manufacturing method, the production speed of the final part can be greatly increased. Also, with accurate determination and application of contraction coefficients, the percentage of trial and error due to lack of precision in the design of production tools, especially molds and rework on parts, will be reduced, which will increase quality and reduce production costs, and ultimately improve competitiveness and profitability. Due to the existence of different types of turbines in the world and the need to provide parts needed for their maintenance and basic repairs, there is a high potential in using this method in the production of all blades, nozzles and accessories of gas turbines. At the same time, the increase in quality and dimensional accuracy, along with the reduction of costs, also provides the possibility of manufacturing aviation gas turbine parts. In industry if the part has a low production circulation, the polymer model is prepared and molded with high speed and dimensional accuracy. If the part has a higher circulation, the incremental manufacturing method can be used while making the sample to obtain the required information in order to make the wax injection mold with high precision. In addition, it is possible to obtain optimum conditions for ceramic mold preparation, casting, metallurgical and mechanical properties of gas turbine hot components before the wax injection mold is prepared using printed polymer models.

2. Experimental Method

In order to print 3D polymer models by FDM method, three types of filaments named Acrylonitrile Butadiene Styrene (ABS), Poly Vinyl Alcohol (PVA) and Poly Lactic Acid (PLA) with different density percentages of 10, 30 and 100% were used. The images of the filaments used in this research are shown in Figure (3).

Figure 3. Images of the filaments used in this research

In order to examine and compare the materials and functional quality of each polymer with different densities and to generalize the test results to hot gas turbine components, polymer models according to figure (4) as standard samples with the same geometry and shape Gas turbine nozzle airfoil was made. The dimensional specifications of the samples (cord length, width and maximum thickness are 70, 20 and 10 mm, respectively).

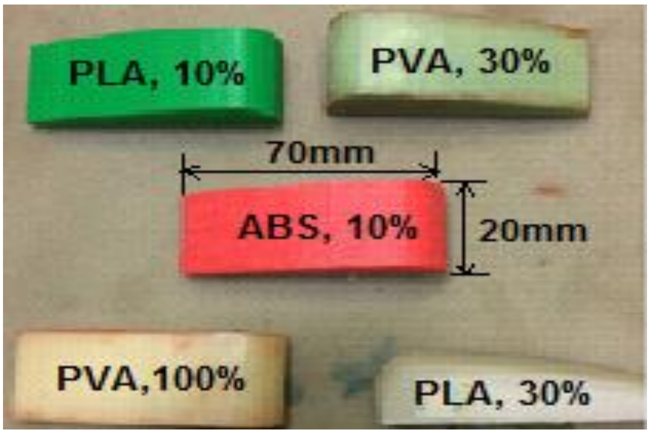


Figure 4. Images of airfoil samples printed with different density percentages

The photo of the FDM 3D printer used in this research is shown in Figure (5). The size of its internal construction space is 400×200×200 mm and it has the ability to print with a resolution of 50 to 400 micrometers. Of course, this interval can be slightly different for different FDM 3D printers. Choosing the resolution of the printer to perform the manufacturing process is up to the designer and operator. If the resolution of the 3D printing process is lower, the surface smoothness of the final part and the ability to create geometric complexities would be more precise. On the other hand, the higher the print resolution, the faster the 3D printing process and the lower the manufacturing cost [7]. This FDM 3D printer allows the user to set some parameters that include nozzle and build plate temperature, build speed, layer height and cooling fan speed. These parameters are generally set by the operator and have been kept constant for all test modes in this research.

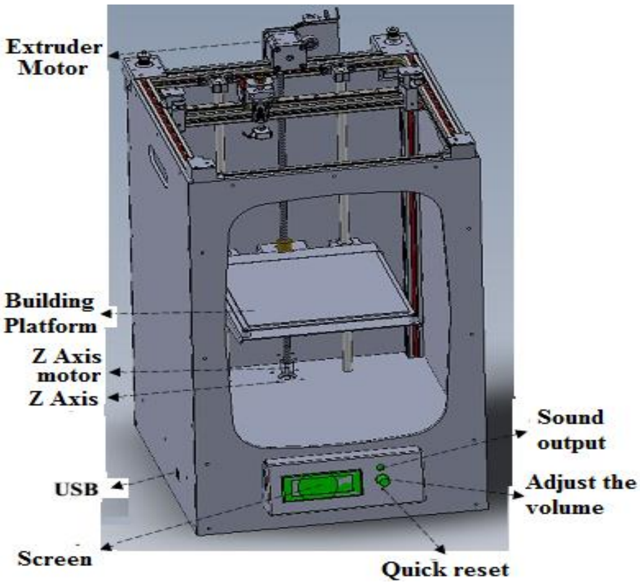


Figure 5 Image of the FDM 3D printer used in this research

In all manufacturing cases, the polymer model was separated from the platform on which it was built and the extra particles were removed from the model. By using cold wax, the surface quality of models made with FDM 3D printer was improved to an acceptable and high level. Then, in order to make a ceramic mold, the printed models were assembled as shown in Figure (6). According to Figure (7), Assembled polymer pattems are immersed into ceramic slurry, drained then coated with fine ceramic sand.

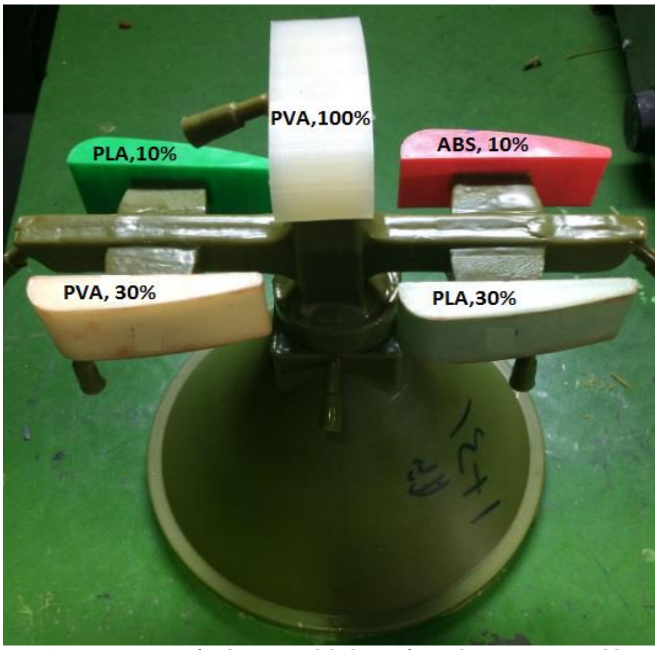


Figure 6. Image of polymer model cluster for making ceramic mold

After steam autoclaving and sintering, the condition of surface cracks, the amount of ash remaining in ceramic molds according to ASTM D 5630 standard [8], the amount of dimensional deviations of printed parts and also the cast part of the optimum polymer model was examined and qualitatively evaluated with the computer model according to Table (1). The nominal chemical composition of the main elements of FSX-414 cobalt base superalloy used in this research in terms of weight percentage is given in table (2).

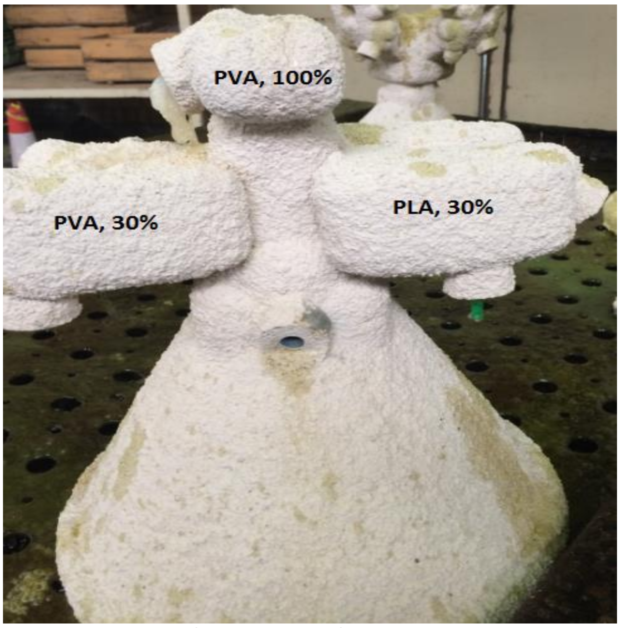


Figure 7. Image of ceramic mold after autoclaving and sintering

Table 1. Determining the variables for polymer model printing and determining the quality evaluation indexes

Polymer model print variables		Quality evaluation index		
Filament type	Density percentage	Cracking rate of ceramic mold after autoclave	The amount of residual ash in ceramic mold after sintering	Dimensional deviation of cast part with computer model
ABS	100	-	-	-
ABS	30	-	-	-
ABS	10	A crack with a length of 70±1mm was observed	7±1gr as remainder ash was observed	-
PVA	100	A crack with a length of 60±1mm was observed	8±1gr as remainder ash was observed	-
PVA	30	No crack	5±1gr as remainder ash was observed	-
PVA	10	No crack	No residual ash	-
PLA	100	A crack with a length of 70±1mm was observed	5±1gr as remainder ash was observed	-
PLA	30	No crack	2±1gr as remainder ash was observed	-
PLA	10	No crack	No residual ash	low but within the acceptable range

Table 2. Nominal chemical composition of the main elements of FSX-414 cobalt base superalloy used in this research in terms of weight percentage

Composition,%	C	Si	Cr	Mo	Ni	Fe	Mn	W	Co
FSX-414	0.3	0.9	29.0	2.0	10.0	1.0	0.5	7.5	Bal.

3. Results and Discussion

3.1. Using ABS polymer with densities of 100, 30 and 10%

Due to its favorable thermoplastic properties, ABS polymer is a widely used material for 3D printing. Tensile modulus and tensile strength of ABS polymer are 2270MPa, 46MPa respectively which make it suitable for modern applications and an alternative to conventional materials. This material with a melting temperature of 221 to 227°C is easily melted and formed during 3D printing.

The assembled image of the standard sample made of ABS filament with 10% density on the industrial wax cluster is shown in Figure (6) and the image of the ceramic mold after the sintering and blue test is shown in Figure (8). As can be seen in blue test, a 70 mm crack is visible on the surface of the ceramic mold. In fact, this size of the crack in the ceramic mold can lead to the rejection of the ceramic mold before the casting process. These materials undergo thermal expansion by being exposed to high pressure and heat in the autoclave and sintering. On the other hand, ceramic shells have a very low coefficient of thermal expansion, so it causes the shell to crack [9]. The amount of expansion has an adverse effect on the dimensions of the piece. If the density of these materials is higher, its expansion is higher and the possibility of cracking of the ceramic mold increases. On the other hand, since ABS polymer compounds are made of acrylonitrile, it has very little flexibility, and for this reason, the ceramic mold cracks after the autoclave stage, even with a low density percentage. Also, this material shrinks during printing and during the cooling step due to its thermoplastic property, the shrinkage rate of ABS polymer is 8% [7] and it is considered a relatively high number in the precision casting industry.

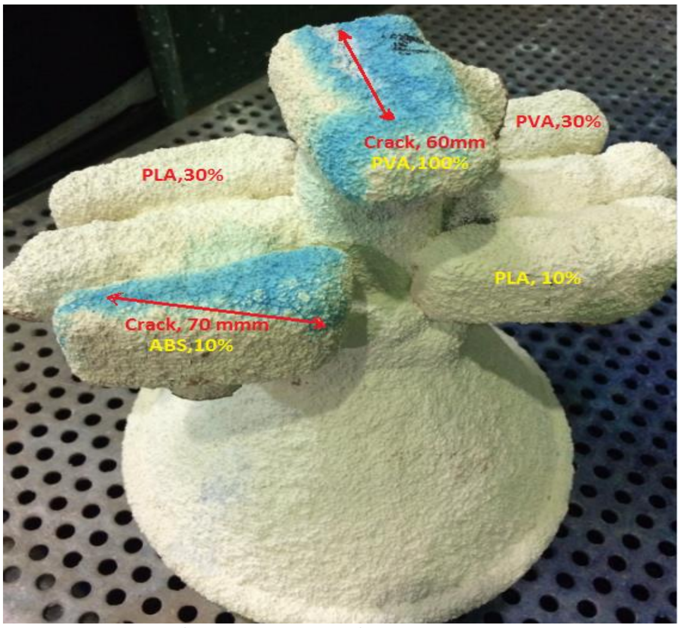


Figure 8. Image of the ceramic mold after the sintering and the color test

Also, in the examination with a Broscope, according to the image in figure (9), the amount of remaining ash was observed to be about 7±1gr, which is much higher than the maximum acceptance amount (1.5gr). The reason for checking the amount of remaining ash of the filaments is that they usually do not melt during the autoclave and after burning and exiting the ceramic mold like industrial wax, and they leave the ash and combine with the melt in the casting process and causes the formation of surface defects in the metal piece. Therefore, this parameter is one of the key indexes and is of great importance in evaluating the quality characteristics of polymers. Since in the best case of ABS filament density (10% density), a severe crack was observed along cord of airfoil in a ceramic mold, so it seems that continuing to work with this material at higher density percentages did not yield better results and it is meaningless.

Figure 9. Broscopy image of residual ash in ABS sample with 10% density

3.2. Using PVA polymer with densities of 100, 30 and 10%
PVA polymer is a synthetic polymer that can only be used in a certain temperature range due to its thermoplastic properties. In addition to high flexibility, this material also has excellent mechanical properties, good adhesion and high resistance to solvents, and has a melting point of 180 to 190°C.

The assembled images of standard samples of PVA filament with densities of 100 and 30% on the cluster of industrial wax are shown in Figure (5) and the image of the ceramic mold after the sintering step and blue test is shown in Figure (8). As seen in the blue test, a 60 mm crack was observed on the surface of the ceramic mold in the sample with 100% density, but no crack was observed in the sample with 30% density. This size of the crack in the ceramic mold can lead to the rejection of the ceramic mold before the casting process. Also, in the Broscopy examination of these samples, the amount of remaining ash for 100% and 30% density was about 8±1 and 5±1gr, respectively. Broscopy images of the remaining ash in the ceramic mold of these samples are shown in figures (10) and (11), respectively.

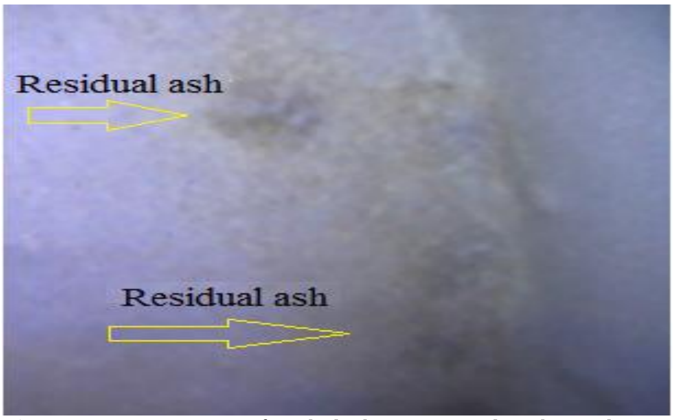


Figure 10. Broscopy image of residual ash in ABS sample with 10% density

Figure 11. Broscopy image of residual ash in PVA sample with 30% density

Figure (12) shows the printout of the PVA sample with 10% density, which has a sticky state and a lower surface quality due to the higher melting temperature of this material compared to other polymers.


Figure 12. Low density quality in PVA model

The assembled image of the standard sample of PVA filament with 10% density on the industrial wax cluster is shown in Figure (13) and the image of the ceramic mold after the sintering step and blue test is shown in Figure (14). As it can be seen in blue test, no Turkish was observed in this sample after autoclaving and sintering. Also, in the examination with a broscope, according to the picture in figure (15), the amount of residual ash measured was almost zero.

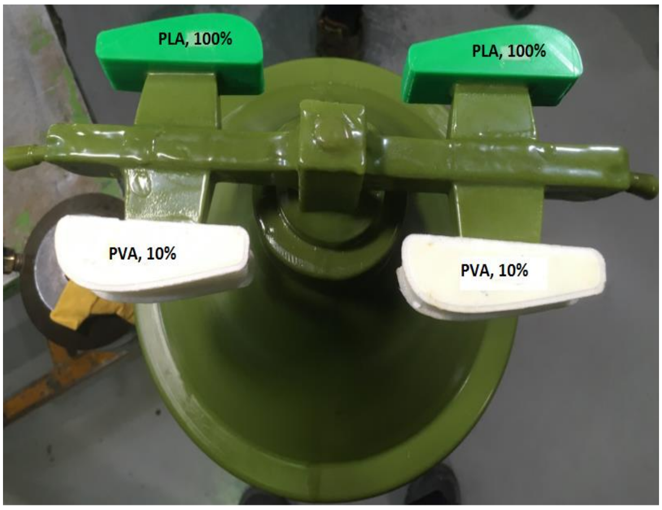


Figure 13. Image of polymer model cluster for making ceramic mold

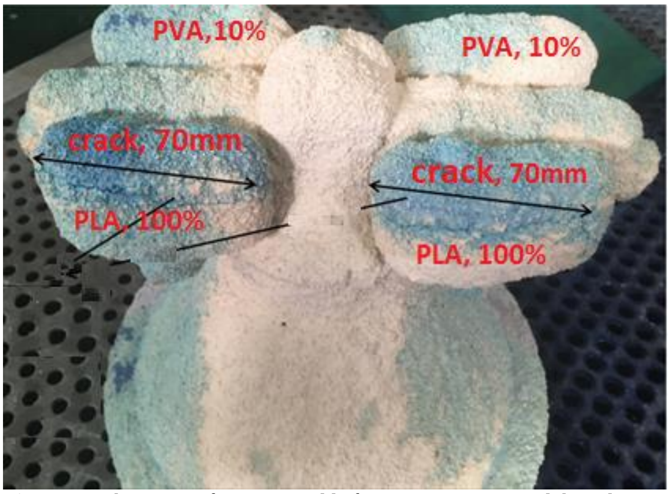


Figure 14. The image of ceramic mold after sintering step and the color test

Figure 15. Broscopy image of residual ash in PVA sample with 10% density

3.3. Using PLA polymer with densities of 100, 30 and 10%

PLA polymer has been developed as a popular material in manufacturing parts and prototyping with industrial applications. This polymer can be easily melted in the temperature range of 145 to 160°C and molded while maintaining its mechanical quality [10]. Assembled images of standard PAL filament samples with densities of 10 and 30% on industrial wax clusters are shown in Figure (6) and the image of 100% density is shown in Figure (13). The pictures of the ceramic mold of these samples after the sintering step and blue test are also shown in figures (7) and (14). As can be seen in blue test, after the autoclave and sintering steps, no crack was observed in the PAL samples with densities of 10 and 30%, but in the samples with densities of 100%, there was an all-over crack of 70mm is observed on the surface of the mold. The lower density percentage of the polymer model causes a further reduction in the volume of the material in the printed part, which prevents shell damage. In the studies conducted regarding crack observation, since PLA polymer is considered a type of polylactic, it has a slight contraction during the melt to solid transformation [10], and for this reason, in the autoclave process, due to the level of surface expansion, although small, in the case of 100% density, cracks have been observed in the shell of the ceramic mold. At the same time, at a density of 10%, crack was not observed in the ceramic mold of the standard samples.

In the examination with a Broscope, according to the images of figures (16) and (17), the amount of remaining ash for filament with a density of 100 and 30% was observed to be about 5±1gr and 2±1gr respectively, which it is higher than the maximum acceptance rate. Moreover, as shown in the picture (18), there is no trace of polymer ash with a density of 10%, which is the result of the print materials leaving, in this mold. As mentioned, the melting temperature range of PLA polymer is lower than that of ABS and PVA polymers, and this is the main reason for the complete burning of this material in the autoclave and sintering and the absence of ash in this material. Also, the lower density percentage of the polymer model causes a further reduction in the volume of the material in the printed piece and minimizes the remaining ash in the sintering process. PLA polymer has the same behavior as PVA polymer in different density percentages, but due to the presence of less residual ash, PLA polymer with a density of 10% is a better option for continuing work and performing accurate casting tests. In addition, the model printed with PLA polymer has a higher surface quality than the PVA model under the same conditions of density.

Figure 16. Broscopy image of residual ash in PLA sample with 100% density

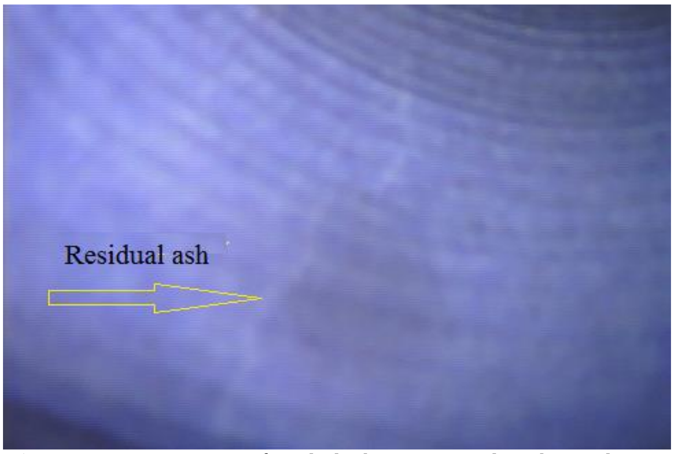


Figure 17. Broscopy image of residual ash in PLA sample with 30% density

Figure 18. Broscopy image of residual ash in PLA sample with 10% density

3.4. Precision casting of gas turbine nozzle with PLA polymer printed by FDM method

At this stage, according to the comparison of the quality results obtained for different polymers, the PLA polymer with 10% density, which is printed by FDM method, is used as an example that can be cited with industrial use for validation and feasibility of manufacturing gas turbine nozzles using the method Precision casting under vacuum is used. Figure (19) shows the image of the polymer gas turbine nozzle from the FDM process. As can be seen in the picture, the ceramic cores are placed in the cores cavity after capping, and then according to figure (20), the interface between the muscle and the nozzle is sealed with red wax and the whole piece is repaired and cleaned. In general, the quality and surface smoothness of printed filaments is generally lower compared to industrial wax (in the traditional method) due to the presence of all-over grooves in the piece. Therefore, before assembling the 3D model cluster, the parts printed by FDM method are usually modified by cold wax. For this reason, the only difference between polymer models and industrial wax models is the cleaning time, which is longer for polymer models. Therefore, the smoothness of the surface cannot be considered as a control parameter for these parts.

Figure 19. gas turbine nozzle made of PLA Polymer with 10% density printed by FDM method

Figure 20. PLA model of gas turbine nozzle with 10% density printed by FDM method After cleaning and finishing process

Figure (21) shows how to assemble the polymer part on the wax branch. Figure (22) also shows the image of the ceramic mold after layering. In order to ensure the release of materials during the wax removal stage, the ceramic mold sintering temperature was chosen to be 1050°C. Then the process of melting and casting of this piece was done in a furnace under vacuum with FSX-414 cobalt base superalloy ingot. The image of gas turbine nozzle casting parts is shown in figure (23).

Figure 21. Cluster image of a gas turbine nozzle polymer model made of PLA with a density of 10%

Figure 22. Ceramic mold of the gas turbine nozzle made of PLA Polymer with a density of 10%

Figure 23. Gas turbine nozzle made of FSX-414 superalloy, PLA with a density of 10%

The images of the examined sections to compare the amount of dimensional deviations of the cast gas turbine nozzle with the computer model are shown in figure (24) and the small amount of deviations are shown in figure (25). As can be seen, the gas turbine nozzle has a good dimensional adaptation in sections A-A, B-B and A-A in the airfoil. The amount of cord and thickness are all within the allowed design range. Examining the results of dimensional control by optical method, it can be seen that the dimensions of the cast parts are in acceptable agreement with the computer model.

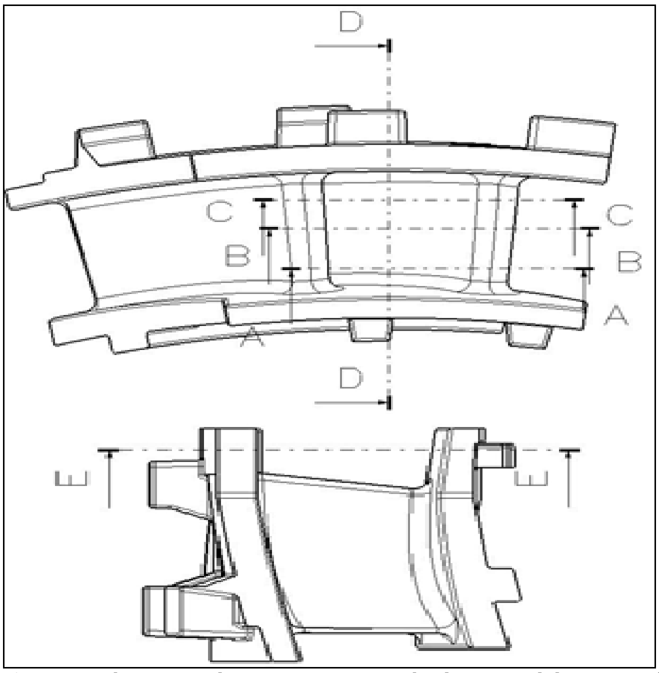
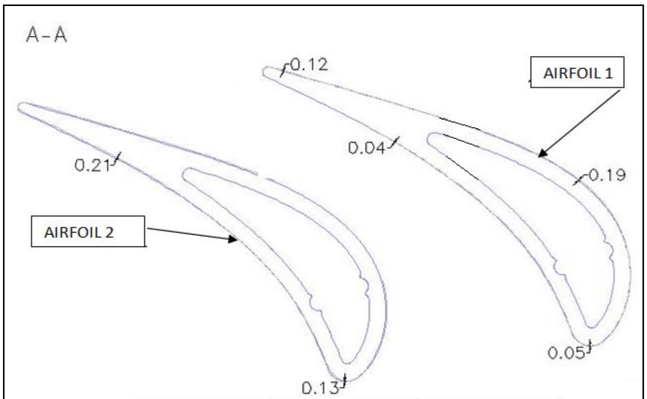
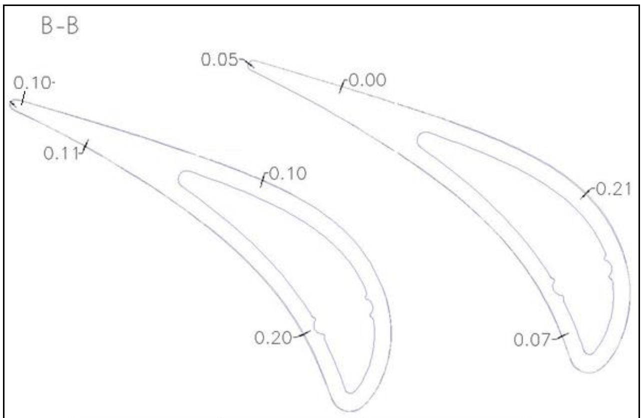


Figure 24. The examined sections to compare the dimensional deviations of the cast gas turbine nozzle with the computer model



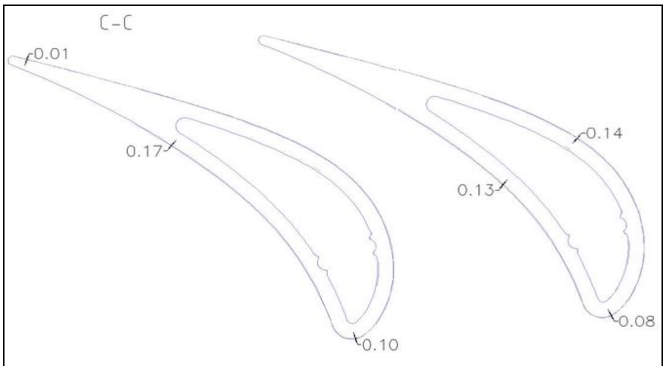
Section A-A	Chord (±1)	T max (±0.4)
Model	76.7	15.52
Airfoil 1	76.8	15.7
Airfoil 2	76.9	15.63

A- Section A-A



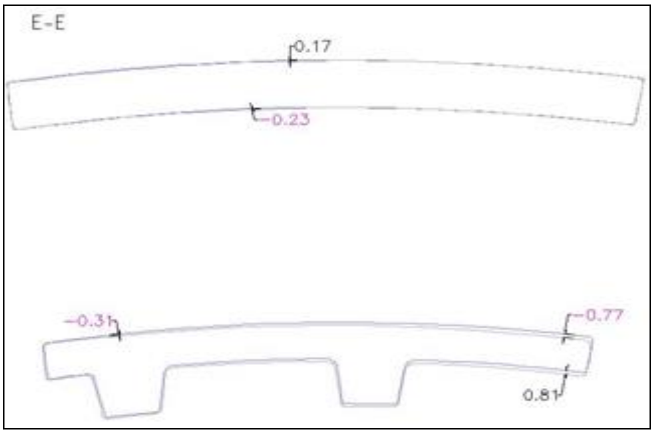
Section B-B	Chord (±1)	T max (±0.4)
Model	79.91	16.16
Airfoil 1	80.2	16.3
Airfoil 2	80.1	16.4

B- Section B-B



Section A-A	Chord (±1)	T max (±0.4)
Model	83.07	16.88
Airfoil 1	83.3	17.1
Airfoil 2	83.2	16.93

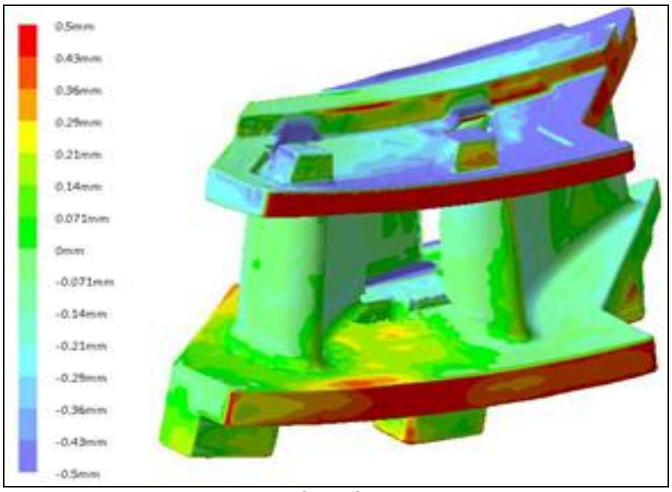
C- Section C-C



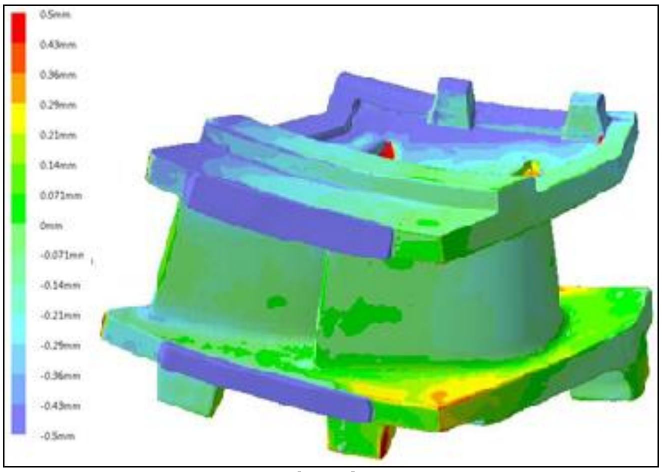
E- Section E-E

Figure 25. Comparison of dimensional deviations of cast gas turbine nozzle with computer model at differenet sections

Also, a comprehensive comparison of the dimensional deviations of the nozzle at all levels is shown as a colored contour in Figure (25). According to the results, it can be seen that the nozzle dimensions are in good match with the computer model. The only deviation of the nozzle is on the side of the attack edge, where the edge of the nozzle is deflected outwards by 0.81 mm. This slight deviation in E-E and D-D sections is also clear and can be fixed in the nozzle machining step and does not cause problems.



A- Leading edge View



A- Trailing edge View

Figure 26. Comparison of dimensional deviations of cast gas turbine nozzle with computer model in color contour a) Leading edge view b) Trailing edge view

4. Conclusion

In this research, three types of industrial polymers ABS, PVA and PLA were printed in order to use them in manufacturing of gas turbine nozzles by FDM method with different density percentages, and after qualitative review and evaluation, the results were obtained as follows:

1. Due to the low flexibility as well as the relatively high percentage of contraction and expansion of ABS polymer, a severe crack of 70mm length after performing the autoclave and sintering steps in the ceramic mold shell of the printed model with a low density percentage (10%), have seen. Also, the amount of ash remaining after the sintering was measured at 7±1gr, which is much higher than the maximum allowed amount (1.5gr). Therefore, it is not suitable to use this polymer to make the gas turbine nozzle by precision casting method.
2. In blue test of the PVA polymer model ceramic mold shell with 100% density, a 60 mm long crack was observed, but no crack was observed in the sample with 30% density. This size of the crack in the ceramic mold can lead to the rejection of the ceramic mold before the casting process. Also, in broscope examination, the amount of remaining ash for 100% and 30% density state was found to be about 8±1 and 5±1gr, respectively.
3. PVA polymer standard sample with 10% density has not been observed crack in the shell of the ceramic mold after sintering. Also, in the examination with a Broscope, the amount of residual ash measured was almost zero.
4. Due to the higher melting temperature of PVA polymer compared to other investigated polymers, it has more adhesive property and as a result the final surface of the samples printed by FDM method has lower quality and it takes more time to repair and parts cleaning are required.
5. No crack was observed in blue test of the shell of the PLA polymer model ceramic mold with densities of 10 and 30%, but in the sample with 100% density, a 70 mm long crack was observed. The amount of remaining ash for 100% and 30% density states was about 5±1 and 2±1gr, respectively, but it was zero for 10% density state.

6. The lower density percentage of the polymer model causes a further reduction in the volume of the material in the printed piece, which prevents shell damage and minimizes the remaining ash in the sintering process.
7. PLA polymer with the same density percentage of has a better quality compared to ABS and PVA polymers in relation to evaluation indexes such as the low rate of cracking of the ceramic shell in the autoclave, the low amount of residual ash in the ceramic mold sintering step, and also It has less dimensional deviations in the gas turbine nozzle compared to its computer model.
8. It is possible to use FDM additive manufacturing technology in the production of gas turbine hot Components by precise casting method using PLA polymer print with low density percentage.

Data Availability
None.

Conflict of Interest
Authors declare that they do not have any conflict of interest.

Funding Source
None.

Authors' Contributions

Author-1 researched literature and conceived the study. Also designed of experimental and wrote the first draft of the manuscript. Author-2 printed polymer models and made ceramic molds and castings. Author-3 compared the dimensional deviations between the cast part and the computer model, and data analysis. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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