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Dimensional-Shape Verification of a Selected Part of Machines Manufactured by Additive Techniques

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ABSTRACT

The publication covers the complex process of analyzing the accuracy of mapping models produced in AM (Additive Manufacturing) processes with a thermoplastic material – FFF (Fused Filament Fabrication) and polymerization of light-curing resin – PolyJet. The research was conducted with the use of an advanced optical measuring system – the GOM Atos 3D scanner. The part selected for the research in question was the water pump body as a representative example of an element with adequate dimensional and shape conditions (high degree of folding and geometric differentiation) allowing, based on the results of coordinate measurements determined in the research process, to define the potential area of application of AM models made of thermoplastic material and resin hardened with UV light. The performed tests showed the accuracy of individual AM methods at a level within the range declared by machine manufacturers. However, the PolyJet body is characterized by a much higher accuracy of the shape mapping compared to the FFF body. The dimensional accuracy is also higher for the resin model in relation to the thermoplastic model, which results primarily from the thickness of the elementary layer of the model material applied by the printing module defined for individual incremental processes – 16 μm for RGD 720 and 0.2 mm for ABS. Detailed elaboration and analysis of the research results are presented in this publication.

Keywords: dimensional and shape accuracy, coordinate measurements, 3D scanning, additive manufacturing, FFF technology, PolyJet technology.

INTRODUCTION

The dynamic development of AM techniques results in the development of new methods, equipment solutions and model materials [1, 2]. Thus, the scope of application of additive techniques in various industries, medicine, architecture, etc. [3, 4]. The possibility of using a given method depends primarily on the parameters of model materials [5, 6, 7] and the dimensional and shape accuracy of model map ping in the process in question [8, 9, 10]. The data declared by the producers in the vast majority deviate from the actual parameters determined by laboratory tests. The reason for this is the individual conditions of each AM process, which include the operating conditions of the apparatus, process parameters, CAD / STL / RP (Computer Aided Design / Standard Triangulation Language / Rapid Prototyping) numerical data processing or post-processing (final model processing – removal of supporting structures, surface quality improvement) [11, 12, 13]. Therefore, research work is necessary to provide reliable – real values of the above-mentioned parameters for commonly used AM methods and model materials.

Additive techniques, such as FFF and PolyJet, allow the production of parts with very complex and complex dimensional and shape conditions [14, 15, 16]. Obtaining models with this type of geometry is often impossible or very difficult using conventional manufacturing techniques

– plastic processing or subtractive processing. The selection of the additive manufacturing technique for a given element should be preceded by a thorough analysis of the application area of the part and individual parameters of the method, including, in particular, the dimensional and shape accuracy of the numerical model mapping in the manufacturing process, as well as the basic strength parameters of the model material [17, 18]. This publication covers a complex process of dimensional and shape verification of a selected part of machines – a water pump body manufactured by modeling with a thermoplastic material in the FFF process and the polymerization of light-cured resin in the PolyJet process [19, 20]. Additionally, the results of the performed endurance tests for ABS and RGD720 materials are presented. The key strength parameters were determined in the static tensile test, three-point bending test and static torsion test.

It was demonstrated in the research measurement process that the PolyJet technique provides a better dimensional and shape representation. This was confirmed on the basis of a visual assessment of surface finish quality, conventional measurements and advanced optical measurements using the GOM Atos 3D scanner, cooperating with the GOM ScanCobot measuring robot. In both cases, the best mapping accuracy within the model was obtained on the outer side surfaces – parallel to the Z axis of the incremental machine's working space [21, 22, 23]. Different results were obtained on the surfaces parallel to the build plate (in the XY plane). In the case of the PolyJet body, the accuracy of their mapping was determined at a very high level – maximum deviations of +/- 0.06 mm with a very good surface quality. The FFF body was a very complex measurement case from the point of view of the determined accuracy. The surface from the side of the supporting structure was very imprecise. The predominant material shrinkage and numerous surface defects were determined. On the other hand, the outer side showed material allowances – positive deviations and numerous point layers of material, which indicates problems with the mapping of the last layer laid. In the majority of the model, deviations greater than +/- 0.20 mm were observed, thus exceeding the applied thickness of the elementary layer defined in the process. In addition, for the overall dimension of each model, an error was determined that fell within the value declared by the manufacturers of the given devices – for the FFF model – shrinkage at the level of 0.13%, and for the PolyJet model – an allowance at the level of 0.02%. The determined errors are values below the manufacturer's data, which indicates, first of all, correctly developed numerical data for the incremental process, correct operation of a given production device and high-quality model material. However, for individual geometrical features of the model, including e.g. the thickness of the ribs, these deviations do not fall within the declared range. Particularly troublesome areas to be mapped by the FFF method turned out to be edge rounding and chamfering and the channel, i.e. geometry with a variable cross-section, depth and inclination angle in relation to the Z axis of the 3D printer. The conducted research also showed different behavior of materials in the manufacturing process. Shrinkage was observed for the thermoplastic, while for the light-curing resin – an allowance. In order to obtain the accuracy of the mapping for the FFF model at a much higher level than determined in the research process in question, a compensation allowance should be used. The operation should be carried out at the CAD design development stage. Depending on the target application of a given additive manufacturing part, an analysis of the method of placing the model on the 3D printer's working platform is also appropriate – especially the orientation in relation to the Z axis of the machine. It must be taken into account that in the FFF method the supports are removed mechanically – therefore there is a risk of damaging the model, especially if it has thin-walled elements and remains of supports in hard-to-reach areas.

RESEARCH OBJECT

The analysis of the accuracy of the model mapping in the FFF and PolyJet processes was carried out on the basis of a selected part of the machines – the body of the water pump. The subject element is a representative research structure due to the high degree of geometrical diversity and the dimensional conditions adequate to the selected production equipment. A number of cooling liquid pump housings offered on the market by various manufacturers were analyzed by selecting the reference model in question. The choice was determined by the fact that the body had appropriate conditions for the mapping

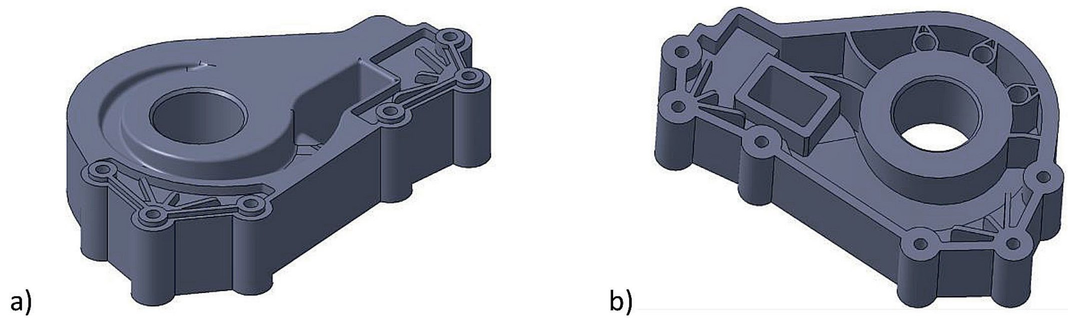


Fig. 1. Research CAD model of the water pump body: (a) view from the top surface, (b) view from the bottom surface

accuracy analysis process – coordinate measurements using the optical 3D scanner system [9, 10]. The geometry of the body consists of, among others: numerous shape changes, ribs, holes, etc. The design of the pump body was developed in an advanced 3D-CAD system using a number of available ones in the Catia V5 environment modeling options. The initial model is shown in Figure 1 (1a – view from the top surface, 1b – view from the bottom surface).

The developed CAD design of the research model of the water pump body was used for further work. On its basis, the process of development, analysis and verification of CAD / STL / RP numerical data was carried out, which is presented in the following chapters.

MODEL MATERIALS

The AM process of physical models of the body was carried out with the use of selected materials. Modeling with thermoplastic in the FFF technique [12, 13, 14] was carried out on the basis of one of the basic materials – ABS (acrylonitrile butadiene styrene). Thanks to styrene, the manufactured elements have an impermeable surface, and butadiene makes them more resistant to low temperatures. ABS is used, among others for the production of housing / body elements of commonly used products, toys, sports accessories, furniture components, pipes for drainage installations, etc. Parts made of ABS material have a certain limited flexibility, which makes them much more resistant to cracking under bending stress compared to other commonly used plastics. The RGD720 material was selected for the resin polymerization process using light from the UV spectrum [15, 17, 20]. The resin in question is characterized by a high level of transparency and good strength properties. It is used for the production of prototypes and research models, including the analysis of, for example, flows, where transparency is required. In addition, the material allows the production of parts with high dimensional and shape accuracy of the model mapping in the PolyJet process and provides high-quality surfa ces.

As an introduction to the dimensional and shape verification of the additive manufacturing part, which is the subject of this publication, a material analysis was developed. It included the determination of key strength parameters of the model materials used, ie thermoplastic ABS and light-curing resin RGD 720. Strength tests were carried out – static tensile, three-point bending and static torsion [5, 6, 7]. The results are presented in Table 1.

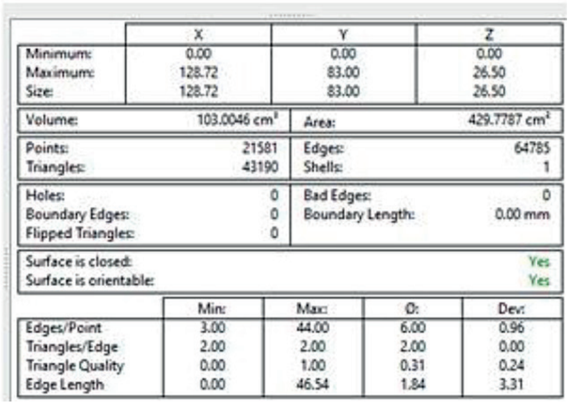
MANUFACTURING PROCESS

Based on the 3D-CAD design of the pump body, the STL (Standard Triangulation Lenguage)

Table 1. Strength parameters of model materials

Model material	Static tensile test								Three-point bending test					static torsion test			
	Maximum load [N]	Tensile stress at maximum load [MPa]	Deformation at maximum load [%]	Displacement at maximum load [mm]	Young's modulus [MPa]	Load at break [N]	Tensile stress at break [MPa]	Strain at break [%]	Maximum load [N]	Bending stress at maximum load [MPa]	Displacement at maximum load [mm]	Modulus of elasticity in bending [MPa]	Deformation at maximum load [%]	Maximum torsional torque [Nm]	Torsion angle at maximum torque [°]	Torsional moment at break [Nm]	Torsion angle at break [°]
RGD720	2397.42	59.94	4.21	4.24	2194.03	1396.58	34.91	6.71	151.37	90.82	7.98	2503.71	4.67	88	74	76	141
ABS	1371.06	34.28	2.72	2.72	1879.13	1251.93	31.30	3.60	127.96	76.78	8.91	2481.95	4.94	38	64	34	69

model was developed – a format dedicated to the AM process consisting in approximating individual surfaces of the model with a triangle mesh defined according to the key tessellation parameters – deviation tolerance and angular tolerance [1, 2]. The high-resolution tessellation standard offered by Autodesk Inventor software was used for this research. The STL model of the body was subjected to verification of the triangle mesh in order to identify possible errors, including, in



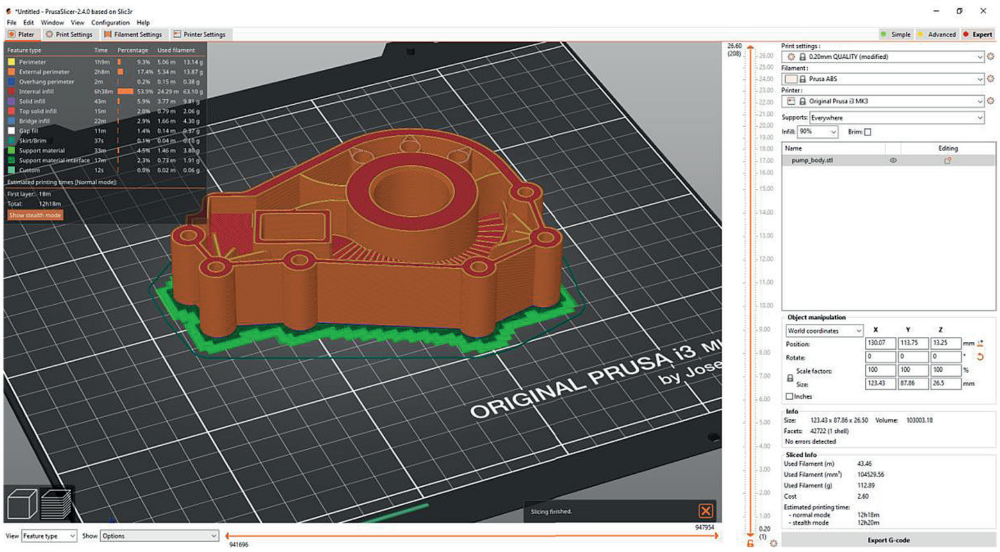
	X	Y	Z
Minimum:	0.00	0.00	0.00
Maximum:	128.72	83.00	26.50
Size:	128.72	83.00	26.50

Volume:	103.0046 cm³	Area:	429.7787 cm²
Points:	21581	Edges:	64785
Triangles:	43190	Shells:	1
Holes:	0	Bad Edges:	0
Boundary Edges:	0	Boundary Length:	0.00 mm
Flipped Triangles:	0		
Surface is closed:			Yes
Surface is orientable:			Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	3.00	44.00	6.00	0.96
Triangles/Edge	2.00	2.00	2.00	0.00
Triangle Quality	0.00	1.00	0.31	0.24
Edge Length	0.00	46.54	1.84	3.31

Fig. 2. Verification of the triangle mesh of the body STL model in the Autodesk Netfabb environment

a)



b)

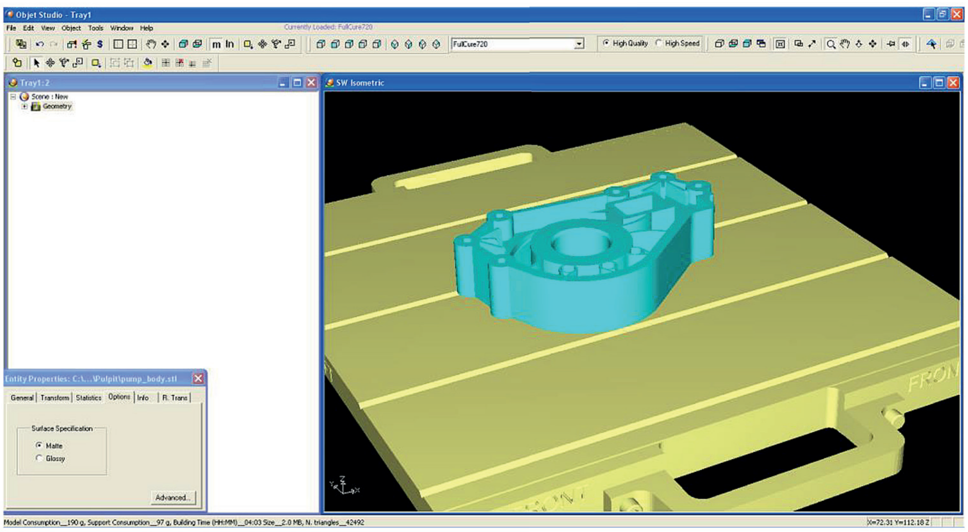


Fig. 3. Development of an incremental process on virtual work platforms – (a) Prusa slicer and (b) objet studio

a) b)

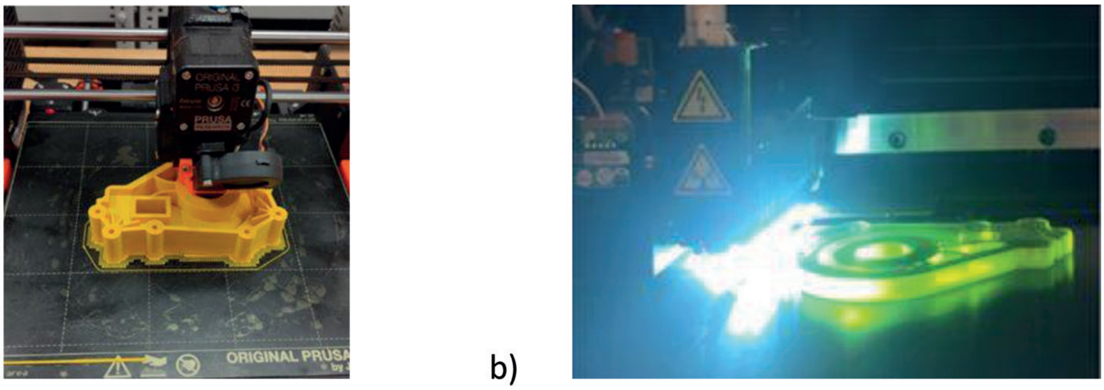


Fig. 4. Additive manufacturing processes – (a) FFF and (b) PolyJet

a) b)

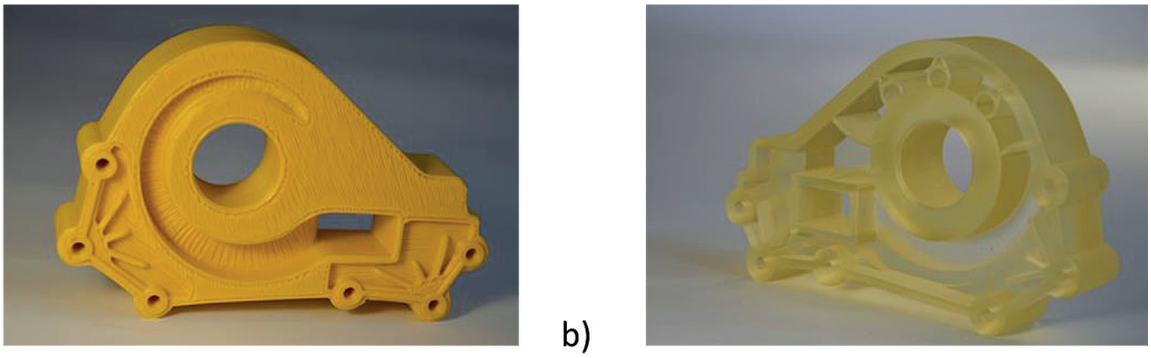


Fig. 5. Body models – (a) FFF and (b) PolyJet

particular, the lack of elementary triangles, shortening of individual coordinates of the triangles vertices, mutual penetration of triangles, surface discontinuities with changes / transitions of geometry characteristic for a given model, etc. The STL model of the body and the process of its verification are shown in Figure 2.

The body's STL model was further processed in software dedicated to individual techniques – Prusa Slicer (Figure 3a) and Objet Studio (Figure 3b), which resulted in the development of a comprehensive RP (Rapid Prototyping) execution procedure.

The manufacturing process was carried out using the Original Prusa i3 MK3 (FFF – Figure 4a) and Stratasys Objet Eden 260V (PolyJet – Figure 4b) apparatus.

The incrementally produced physical models of the pump body were post-processed by removing the supporting structure – in the process of mechanical treatment for FFF and rinsing in a water pressure washer for PolyJet [1, 2, 3]. The prototypes prepared for the verification and measurement procedure are shown in Figure 5 – FFF pump body model – Figure 5a, PolyJet pump body model – Figure 5b.

DIMENSIONAL AND SHAPE VERIFICATION OF PUMP BODY MODELS

The first stage of research was the physical verification of the incrementally produced models and conventional measurements in characteristic areas. The model produced in the FFF technology has numerous surface defects [12, 14]. In the case of the upper and lower surfaces of the body, significant differences in the quality of their mapping were observed. A much worse finish was found for the upper surfaces. This is due to the fact that on this surface the model was placed on the working platform of the FFF apparatus, and thus these areas were supported by supporting structures. The individual work paths of the print head were found to be visible. The mapping with the lowest accuracy was identified on the chamfers and rounds and within the channel. For comparison, placing the model on the working platform during the production with PolyJet technology was the same as FFF, and the quality of its surface (on both sides of the model) is much higher. The chamfers and rounding of the edges are very well reproduced. The model is precisely finished. The surfaces are of very high

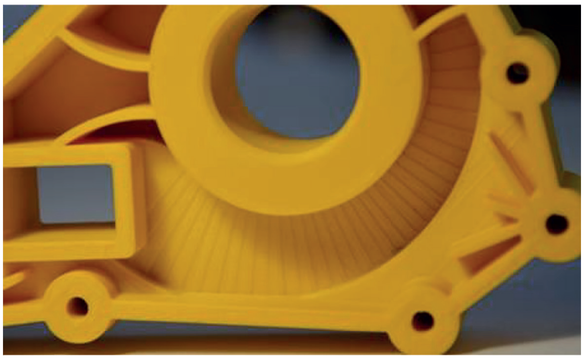


Fig. 6. The step effect characteristic of the FFF technology

quality, even in the most problematic area, i.e. within the canal. Moreover, the step effect typical for this technology was found for the FFF model. It occurs within the canal (from the bottom of the body). This phenomenon is shown in Figure 6.

The effect of the stepped model construction occurs for surfaces inclined in relation to the Z axis of the 3D printer and is especially visible when reducing the angle of inclination and increasing the area of the surface in question – automatic algorithms of the tool software divide a given surface into a number of components that can be implemented with individual parameters of the manufacturing process, including in particular layer thickness defined [1, 2, 4]. The channel of the body is an elementary example of this phenomenon – the geometry of the channel is characterized by a variable cross-section and increasing depth – inclination in relation to the upper surface of the model.

Based on the conventional measurements carried out along with the initial physical verification in the characteristic areas, the greatest discrepancies in the accuracy of the mapping within thin-walled elements with a thickness of 1 mm and 1.5 mm were found. The models were produced in the same orientation – with the upper surface of the body on the working platform, due to the geometric conditions enabling the comprehensive removal of the generated supporting structure, which mainly concerns machining for the FFF method. The ribs on the outside (upper surface in relation to the work platform) have been mapped with an allowance for both models. On the other hand, from the platform side, in the model made with the FFF technique, a material allowance was fund – the maximum deviation +0.22 mm, and in the model made with the PolyJet technique – material shrinkage at the maximum level of –0.05 mm. Additionally, for the FFF model, no mean value of the measurements consistent with the nominal dimension in any of the analyzed characteristic areas was determined. For the PolyJet model, the nominal values were confirmed in several cases – for the thickness of the ribs on the side of the platform and the outer diameter of the central sleeve on the side opposite to the platform. At the same time, it was found for the FFF model a much larger dispersion of the results for a given geometric feature compared to the PolyJet model. This mainly proves the lower shape accuracy of the FFF model.

The key stage of the research work in question included the process of optical measurements with the use of a 3D scanner [8, 9, 10]. The GOM Atos Q apparatus was used due to its intended use for very complex measurement tasks and the guarantee of extremely precise measurements for small and medium-sized parts. The scanner uses the technology of blue light in a narrow band, which allows effective filtering of light noise from the environment [10, 21, 22]. Structured light in the form of stripes is projected onto the tested object from a centrally placed projector. Advanced cameras are installed on both sides of the projector to record the deflection of the projected light fringes within the geometrical changes of the measured part. Measurements of the pump body models were carried out in fully automatic mode in cooperation with the GOM ScanCobot robot and a rotary table. Such apparatus configuration ensures process reliability and its maximum efficiency. By moving along automatically defined paths, GOM ScanCobot is responsible for collecting the necessary scans at the required measuring positions. Successive positions of the scanner are changed by means of the robot arm, and subsequent positions of the parts – by turning the table.

Before starting the measurement procedure, models were prepared – several markers/reference points were placed on their surfaces – the so-called measurement markers that are identified on each elementary scan. In the case of the PolyJet model, an earlier, additional operation of applying, using an airbrush, a thin matting layer was necessary due to the transparency of the RDG720 material. The software dedicated to the measuring equipment remembers the positions of individual markers in space, thus enabling precise connection of all images/scans made in the scanning process. An advanced measurement process for the FFF and PolyJet models was then performed.

Fig. 7. The process of mapping the PolyJet model based on the scans made

The comprehensive measurement procedure was carried out in a dedicated GOM Inspect software environment, which ensures the acquisition of measurement data, their processing and analysis, as well as the development of test-measurement results. The models were scanned in two series of measurements, from a dozen to several dozen elementary images / scans corresponding to the outer sides of the body models. The selected process is shown in Figure 7.

The process of dimensional and shape verification of the pump body prototypes produced with the FFF and PolyJet techniques included in the initial phase the analysis of the collected measurement data and the development of possible correction / repair in the event of error identification, including, in particular, surface discontinuities, defects in hard-to-reach areas, etc. Then, a number of representative maps of dimensional deviations in relation to the CAD base design and inspection sections were developed, on the basis of which it was possible to precisely assess the accuracy of model reproduction in incremental processes. The characteristic areas of the body

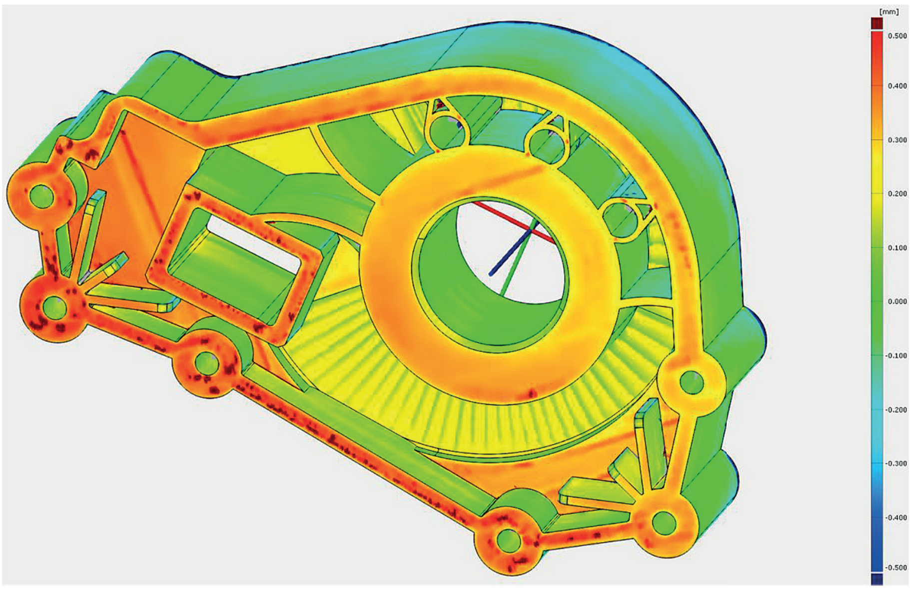


Fig. 8. Map of dimensional deviations of the FFF model from the top to the platform

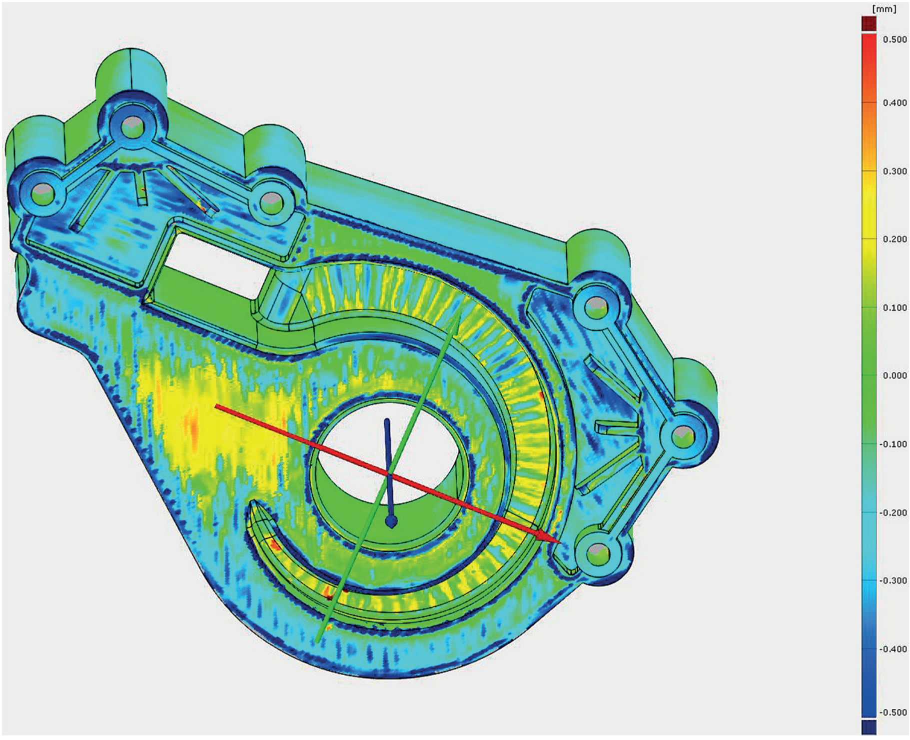


Fig. 9. Map of dimensional deviations of the FFF model from the bottom in relation to the platform (supported surface)

were analyzed, with particular emphasis on the complicated, from the point of view of the possibility of additive manufacturing, elements of the structure in question. The dimensional deviation maps for the FFF model are presented in Figures 8 and 9. Figure 10 shows the selected inspection section for the FFF model.

The deviations determined in the measurement process show clear differences in the accuracy of mapping the opposite sides of the FFF pump housing. Significant material shrinkage was found at the support surface. The greatest deviations, reaching even -0.97 mm, occur at the edges. The surface in question is characterized by low

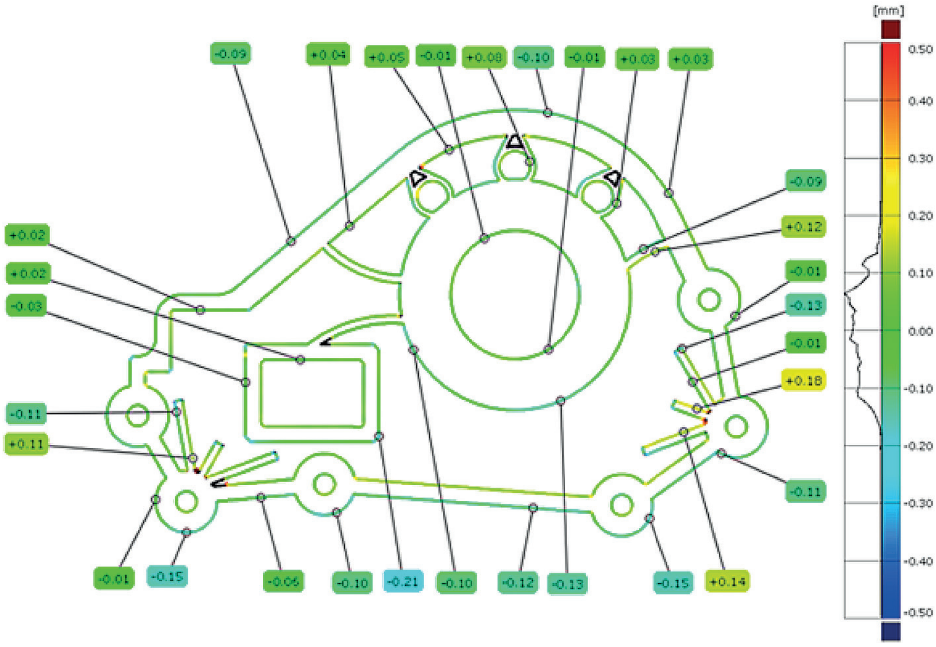


Fig. 10. Inspection cross-section of the FFF model

quality, the waviness is manifestem in the occurrence of alternating positive and negative deviations, which in the predominant area range from -0.30 mm to +0.24 mm, with the predominance of negative deviations. Moreover, the most problematic area turned out to be the channel – the area of a recess along an irregular path with variable cross-section and depth. Within it, following the central path, the allowance and shrinkage of the material are alternately determined. On average, the deviations in the area of the canal range from -0.20 to +0.25 mm, and the share of the allowance and shrinkage is at a similar level. What's more, there are also point material allowances of up to +0.47 mm. However, they result from the difficult process of removing the support structure. Significant differences in the accuracy of the FFF model were also found within the ribs. On the roundings at the point of direct contact with the supports, positive deviations of up to +0.53 mm and negative deviations up to -0.66 mm were determined. The surface opposite – the upper one in relation to the work platform has been mapped for the most part with a material allowance of over +0.30 mm. On the outermost edges, however, the deviations are smaller than in the remaining area (+0.24 mm). Numerous

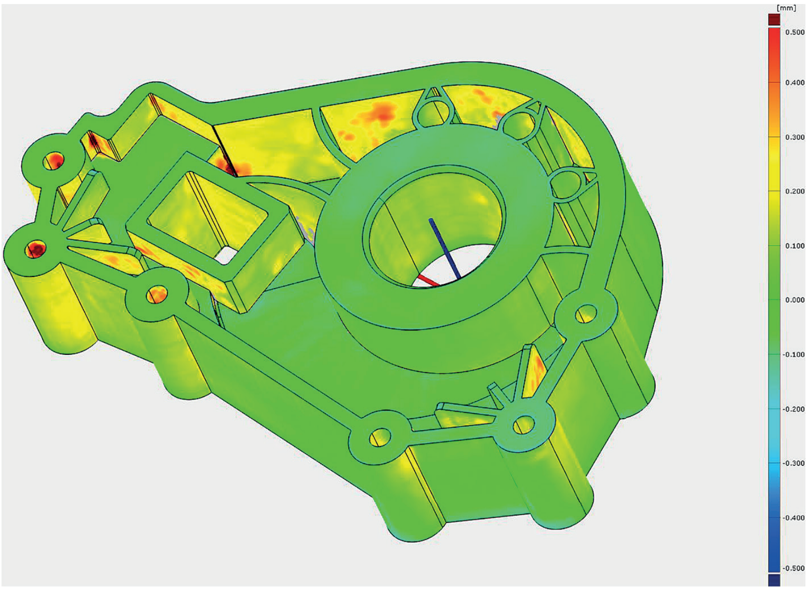


Figure 11. Map of the dimensional deviations of the PolyJet model from the top to the platform

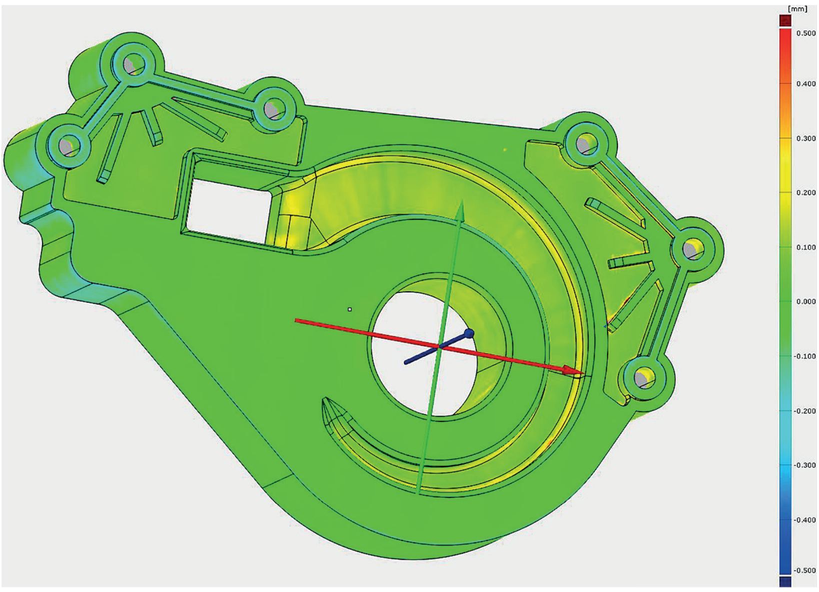


Figure 12. Map of the dimensional deviations of the PolyJet model from the bottom relative to the platform (supported surface)

point surpluses of the material are noticeable (up to +0.58 mm), which indicates a large inaccuracy in the reproduction of the last printed layer. The channel, as one of the most troublesome areas to reproduce, was, however, more precisely mapped from this side. Despite the occurrence of the step effect, and noticeable every single layer, the deviations in this area amount to an average of about +0.20 mm. Side surfaces – the resultant overall dimensions of the body are smaller than the corresponding nominal values. In this area, as well as on the upper surface, shrinkage of the thermoplastic is observed. Deviations are negative from the outside in the thicknesses of individual extreme walls (mostly), and positive from the inside. The ribs, averaging the occurring deviations, were mapped with an excess – a positive deviation.

The dimensional deviation maps for the PolyJet model are shown in Figure 11 and 12. Figure 13 shows the selected inspection section for the PolyJet model.

When subjecting the general analysis, the determined measurement results of the PolyJet body are much more accurately mapped to the support surface in relation to the FFF model. A high-quality surface of a homogeneous character in the dimension of dimensional deviations was found. Additionally, the deviations determined in this measuring area have a very low value and are mostly in the range from –0.06 mm to +0.01 mm. A detailed analysis of the support surface confirmed the largest deviations in the form of material allowance in the area of the channel, especially in the roundings. The maximum determined error was identified at the mouth of the channel – it was +0.17 mm. By averaging the results of the dimensional inspection in the channel, a value of about +0.13 mm was determined. The largest negative deviations (-0.14 mm) were found near the cylindrical surfaces, where the mounting holes were made. The deviations on the outer surface – opposite to the support surface – are also much smaller (maximum -0.10 mm) and evenly distributed. There were no surface distortions or point allowances, as in the case of the FFF model. In the major part of the channel, deviations ranging from 0.04 mm to 0.06 mm were observed. The highest contraction in relation to the nominal model (-0.16 mm) was determined at the beginning of the canal, where its cross-sectional area is the smallest. In the case of side surfaces and thickness dimensions of individual elements and walls, the situation is very diverse. A dispersion of the deviations ranging from about -0.20 mm to +0.54 mm is observed. The smallest deviations (negative or positive up to +0.05 mm) were determined mainly at the outermost edges of the model. On the edges from the inside, at individual elements (walls, ribs, openings), significant allowances were observed. The largest positive deviations occur in the hole diameters, thus causing the holes of the PolyJet model to be smaller than the nominal diameter. The allowances are not evenly distributed within a given element, as was found, for example, for ribs. The analysis confirms that within the elementary rib, on the one hand, negative deviations and on the other – positive deviations were determined.

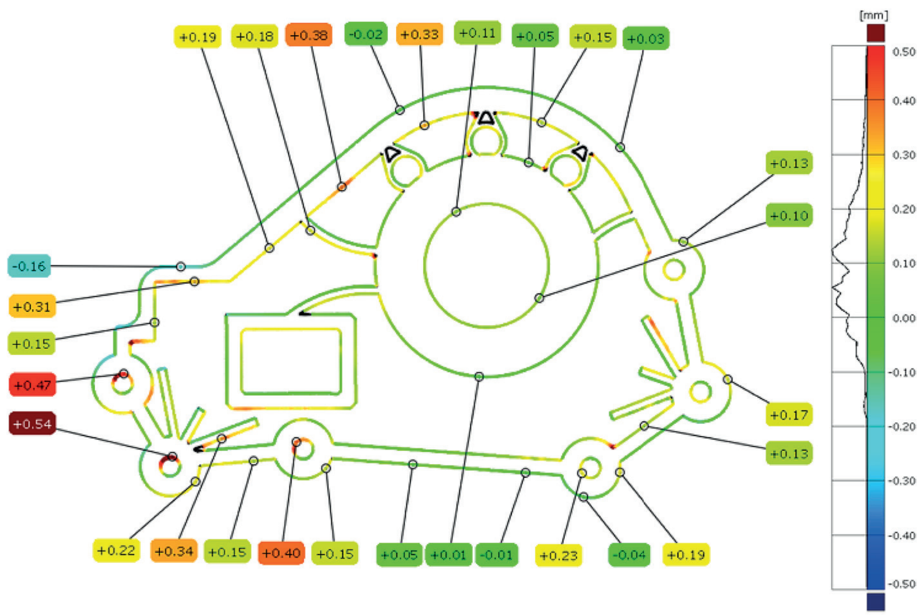


Fig. 13. Inspection cross-section of the PolyJet model

CONCLUSION

In conclusion, it was found that for the PolyJet pump body much better results of the dimensional and shape accuracy of the numerical model representation in the AM process were determined than for the FFF body. However, certain limitations in the use of PolyJet technology should be taken into account, including, above all, the economic factor – significantly higher equipment, material and operating costs.

The developed comparative analysis will allow to determine the potential areas of application of parts produced by modeling with a thermoplastic material – FFF and light-curing resin polymerization – PolyJet in terms of the determined dimensional and shape accuracy of CAD models in the AM processes in question, taking into account the key strength parameters of the model materials used – ABS thermoplastic and light-curing RGD720 resin.

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