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Measurements of Tensile Strength and Elongation of 3D Printed Polylactide Solids Produced with Different Temperatures of Extruder Using Coordinate Measuring Technique and Finite Element Method

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ABSTRACT

In order to determine the largest and smallest deformations during 3D printing, measurements were made for pure polylactide (PLA) using a coordinate measuring technique using a measuring arm. The additive manufacturing process was carried out using four nozzle temperatures: 190°C, 200°C, 210°C and 220°C. The model was properly selected to check the cylindricity, angles of inclination and dimensional deviations from the nominal value of the cuboid. FEM analysis was used to confirm the obtained results. The cylindricity and shape tolerances were shown to be the best at 190°C. The smallest deviations from the angle of 90° have solids made at 200°C and 220°C. In the case of dimensional tolerances of the centers of the holes relative to each other, the best deviations were obtained for the temperature of 190°C and 220°C. The highest stress values during uniaxial stretching using FEM analysis were obtained for samples made with nozzle temperatures of 200°C and 210°C, which are about 31 MPa. For the temperature of 190°C and 220°C, the deviations are the closest to the reference model and are equal to about 30 MPa. In the case of the FEM analysis for single-point bending, the element made at 190°C had a maximum deformation of 0.203 mm, which was the same for the reference model. The largest deviation is noticeable for the printing temperature of 200°C and is 0.211 mm.

Keywords: 3D printing; polylactide acid; FDM method; different temperature of printing, FEM analysis, coordinate measuring technique, dimensional intolerances

INTRODUCTION

An important role in the study of materials is played by the coordinate measuring technique, which is the main area of metrology development. Designing polymer materials processing processes requires engineers to know the advantages and disadvantages of a particular plastic. As a result, the main goal is to eliminate inappropriate parameters that directly cause the processing of a given material to be underdeveloped [1]. A great advantage of the CMT method is its non-invasiveness, which results in the possibility of conducting non-destructive tests [2]. This makes it possible to find errors in the processing process without degradation or destruction of the plastic [3]. In many respects, the coordinate measuring technique is superior to other classical methods of measuring elements [4]. The modern processing market requires continuous improvement of measuring machines that are used in production plants. A very important aspect is also the automation of measurements, which makes this process fast, accurate and efficient [5]. Learning and understanding the coordinate measuring technique directly affects the designed technological processes and should be mandatory knowledge for every engineer, machine builder, automation engineer, robotics specialist, and in particular a metrologist [6, 7].

Coordinate measuring arms are portable measuring devices with high dimensional accuracy that are used in many industrial sectors. Without them, it is hard to imagine the production of, among others, wind turbine hubs or ship engine blocks [8]. Technological progress and the complexity of engineering solutions mean that more and more requirements are placed on machines and devices that should be perfectly matched to other elements [9]. Coordinate measurements consist in the fact that the section is not measured from point A to point B, but on the basis of the X,Y,Z values on the surface of the measured element [10, 11].

3D printing is a huge part of the industry, which is growing every year [12, 13]. The availability of this method of production and the ease of production make it more and more widely used, among others, in the plastics processing industry [14, 15]. Initially, it was used only for prototyping, but with the increase in dimensional accuracy, the production of finished elements began [16]. An important factor influencing the properties of the details made are the parameters of the additive manufacturing process [17]. Reducing the thickness of the layer and the printing speed directly affects the increase in the strength of the element [18]. This is due to the presence of less empty spaces, which generate the risk of cracking [19]. The temperature of the extruder during the 3D printing process has a direct impact on strength [20]. The occurrence of different temperature ranges causes an increase or decrease in dimensional tolerances [21].

Most often, in the case of the production of elements made using additive manufacturing techniques, a biodegradable polymeric material, which is polylactide, is used [22]. It is an aliphatic thermoplastic polyester which undergoes a crystallization process when exposed to a temperature of 60°C [23]. It is very important that it is subject to environmental degradation. It is usually used for the production of foil, disposable cutlery and packaging [24].

Prabhu et al. showed that the parameters of 3D printing have a large impact on the strength properties and dimensional tolerances of the measured elements. Two layer heights and printing speeds were used, which were 0.2 mm and 0.3 mm and 80 mm/sec and 50 mm/sec, respectively. Dimensional deviations in the manufactured elements were examined using the coordinate measuring technique [25]. Additive manufacturing and CMT are closely related as dimensional deviations are common during the manufacture of polymeric materials. This is related, among others, to the phenomenon of shrinkage and the difference in the properties of plastics [9, 26–28].

Pisula et al. carried out measurement tests of gears produced by the FDM method. They used acrylonitrile-butadiene-styrene, polyetheretherketone and polyetherimide for this purpose. The gears were tested under load to measure the wear of the polymer gears. PEEK is the most wear-resistant in terms of operating temperature difference, which has been proven by research using the coordinate measuring technique [29].

The article below presents an analysis of the influence of four temperatures during the extrusion process: 190°C, 200°C, 210°C and 220°C on the dimensional tolerances of the produced cuboid. Coordinate measuring technique and FEM analysis were used for this purpose. After extensive literature analysis, available research technologies were used and the problem of additive production of polylactide was presented in an innovative way. The obtained results will allow the optimization of the parameters of the 3D printing process depending on the shape and geometry of the element.

MATERIALS AND METHODS

Materials

In order to determine the largest and smallest deformations during 3D printing, measurements were made for pure polylactide using the coordinate measuring technique. Filament with a diameter of 1.75 mm was manufactured by Spectrum Company (Warsaw, Poland). Rectangular solids were produced on a printer 3D GenceOne (Przyszowice, Poland) with a nozzle diameter of 0.4 mm. In order to properly scan the object, the test material had to be whitewashed with a suitable matting spray. Transparent or translucent materials are characterized by high scattering of laser light, which is why the above atomizer is often used in the coordinate measuring technique.

Method of testing

The coordinate measuring technique was performed using the ROMER Absolute Arm RA-7320 SI measuring arm. The additive manufacturing process was carried out at four nozzle temperatures: 190℃, 200℃, 210℃, 220℃. The model was properly selected to check the

Table 1. Parameters of 3D printing

Parameters	Variant 1	Variant 2	Variant 3	Variant 4
Layer height [mm]	0.5			
Layer width [mm]	0.4			
Plate temperature [°C]	55			
Degree of infill [%]	100			
Extrusion speed [mm/s]	45			
Extruder temperature [°C]	190	200	210	220
Direction of print angle [°]	45			
Infill shape	Lines			

cylindricity, roundness and deviations from the cuboid denomination of the printed elements. Table 1 presents the basic parameters used to carry out the 3D printing process.

RESULTS AND DISCUSSION

The average values of the obtained results for each nozzle temperature during the additive manufacturing of materials for four samples and their standard deviations were calculated from the obtained results. Table 2 presents a detailed description of the symbols used.

The two outer and inner cylinders produced showed some deviations from the assumed dimension (Figure 1). The largest deviations are noticeable for the temperature of 190°C, but they are also burdened with a large statistical error. The repeatability of results in this group is the worst. The most similar shape was observed for the temperature of 220°C. This difference is about 0.2 mm. In this case, there is a noticeable downward trend in the size of deviations with increasing temperature. This may be related to the occurrence of shrinkage. Increasing the process temperature minimizes deviations from the nominal value. Figure 2 shows deviations from the assumed angle between the cylinder and the plane directly adjacent to it. The component was most accurately dimensioned for nozzle temperatures of 200°C and 220°C.

Table 2. Designations of created solid geometry

Symbol	Description
W1	Internal cylinder, located in the left part of the sample
W2	Internal cylinder, located in the right part of the sample
W3	External cylinder
O1	The distance between centers of cylinders
O2	The distance between the center of the cylinder W1 and the short edge
O3	The distance between the center of the cylinder W1 and the long edge
O4	The distance between the outer edges W1 and the inner W2
K	Angle between cylinder W3 and plane

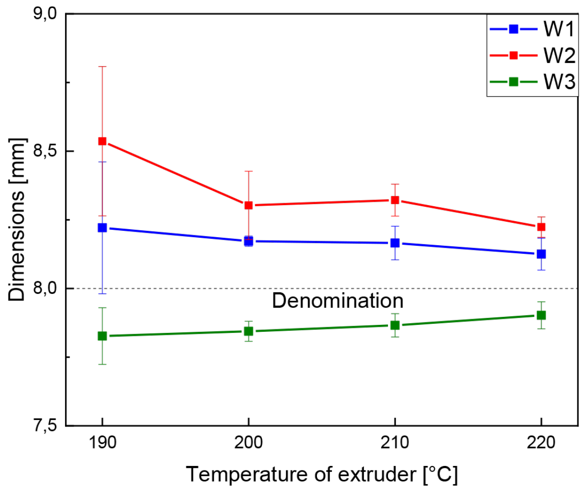

Figure 1. Correlation of nozzle temperatures and rollers deformation

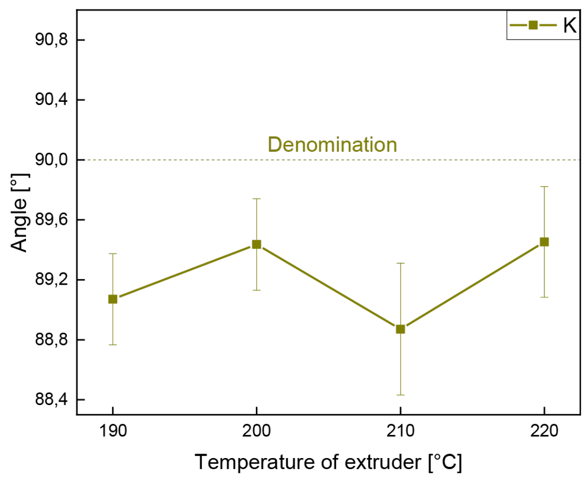

Figure 2. Correlation of the nozzle temperatures and the angle between the cylinder and plane

Figure 3 shows the correlations of the nozzle temperature in relation to the distances O3 and O4. The best parameters were obtained for the printing temperature of 190°C. After exceeding this value, the size of deviations from the intended shape gradually increases. These parameters are related to the shifts of the opening in relation to individual planes. The greatest error is in the samples made at 220°C. This is due to the too high temperature of the additive manufacturing of the material. Physical phenomena occurring during the melting and cooling process increase dimensional inaccuracies. The final shape of the opening and their location directly affects the subsequent results of the Finite Element Method analysis. The more regular the shape, the better the strength and deformation properties. The temperature of 190°C is the most stable for the production of polylactide.

Deviations between the centers of the rolls were also measured (Figure 4). There is a noticeable increase in the dimensional deviation from the intended one as the nozzle temperature decreases, after exceeding 190°C. Comparable results were obtained for the temperature of 220°C and 190°C, amounting to approximately 37.9 mm. This means that the centers of the rollers are deviated by only 0.05 mm from each other.

FEM analysis

An analysis using the Finite Element Method using the ANSYS software with the Static Structural module was carried out. Solids scanned with a coordinate measuring arm were designed in the FEM analysis program. Polylactide has not been defined in the program database. In order to properly design the process of uniaxial stretching and bending of the manufactured elements, a new material was created in the program library, which is the basis for the calculations obtained from the test. The values used for the simulation were used from the static tensile and bending tests.

Figure 5 shows the dimensions of a 3D model of a solid made of polylactide, printed with different printing temperatures. The appearance of the FEM mesh, which was used to simulate stresses and strains during stretching and bending, was also shown, which was 0.5 mm. The following material properties adopted for calculations, were taken from tests performed on real objects (Figure 6). All tests checking material properties were performed at room temperature.

The bending force that was included in the FEM calculations is derived from physical bending tests. On this basis, the value of the bending moment was determined. In order to simulate stretching, the force value of 2348 N and the bending moment were used, respectively for individual samples:

- Reference model: 89.68 Nm,
- PLA190 – 89.248 Nm,
- PLA200 – 89.267 Nm,
- PLA210 – 89.23 Nm,
- PLA220 – 89.255 Nm.

Figure 7 shows the scheme of performing the FEM analysis for one-point bending with a fixed force. On the basis of the moment values, the deformation and stress were calculated for the

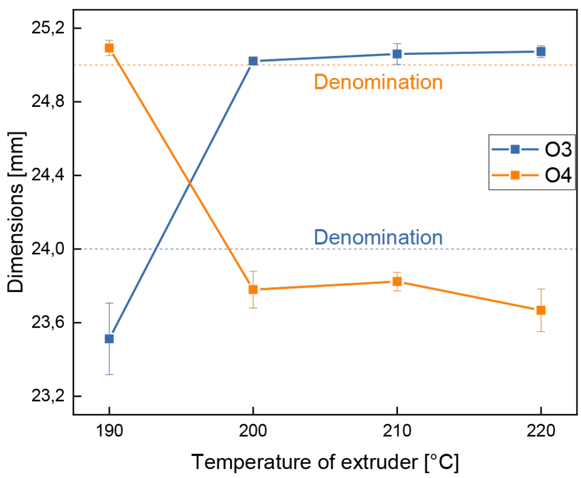

Figure 3. Correlation of nozzle temperatures and designated distances

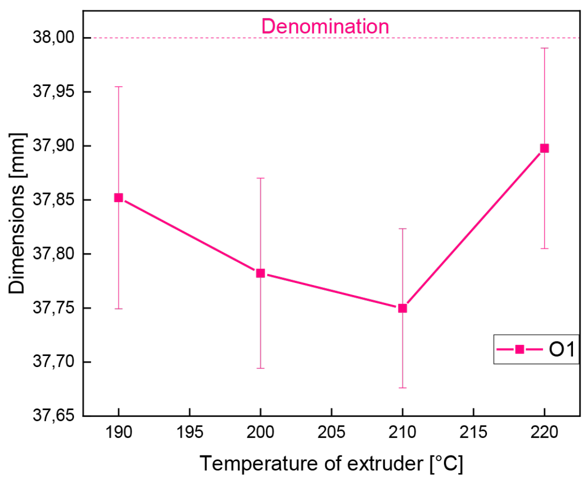

Figure 4. Correlation of nozzle temperatures and the distance between the centers of the rollers W1 and W2

a)

b)

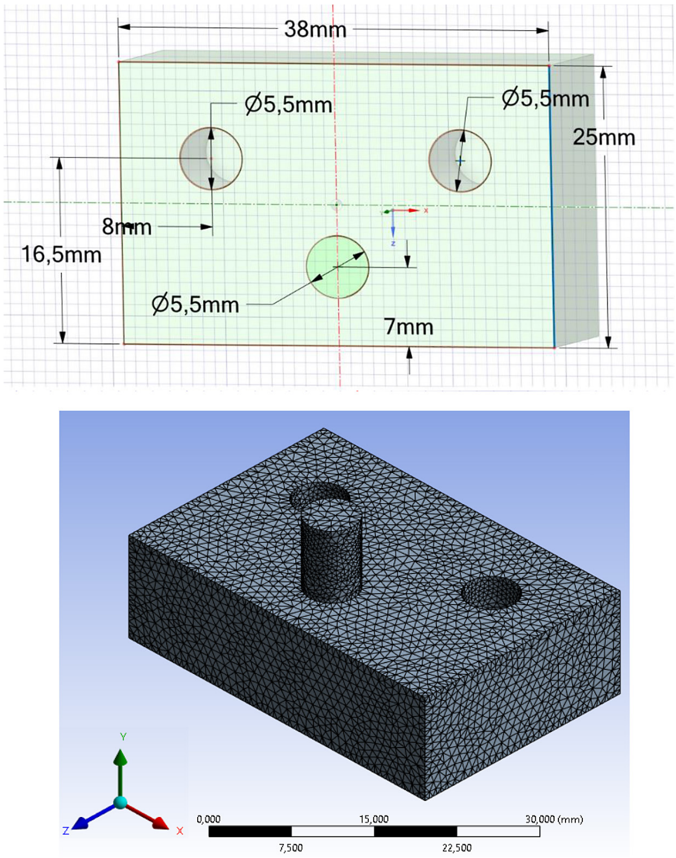

Figure 5. Model of the tested sample: a) dimensions of PLA 3D model solid with different printing temperatures; b) mesh of the PLA solid

Properties of Outline Row 4: PLA 2

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1215,6	kg m^-3
4	Melting Temperature	155	C
5	Isotropic Elasticity		
6	Derive from	Young's Modulus and Poisson...	
7	Young's Modulus	2E+09	Pa
8	Poisson's Ratio	0,35	
9	Bulk Modulus	2,2222E+09	Pa
10	Shear Modulus	7,4074E+08	Pa

Figure 6. Material properties of PLA adopted for calculations

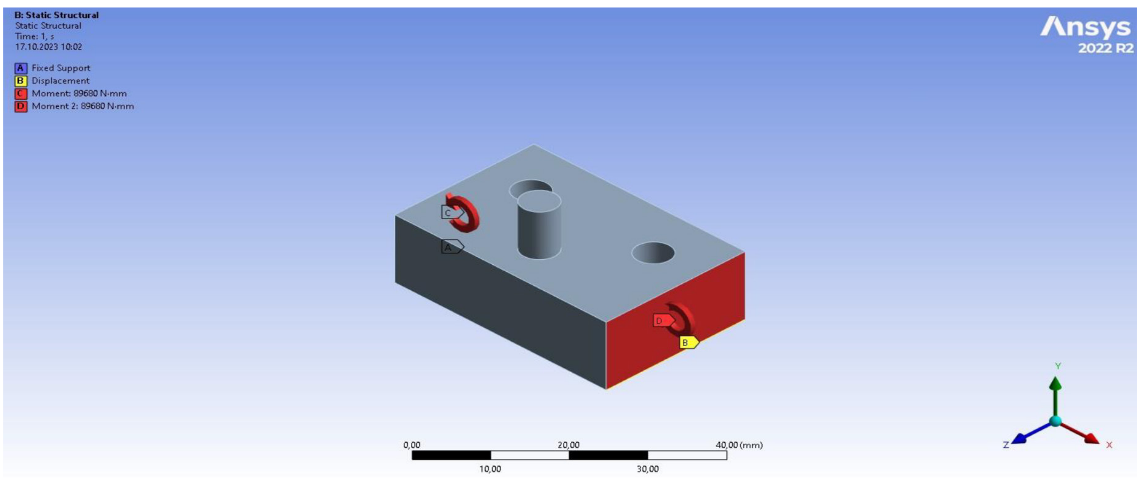

Figure 7. Scheme of performed one-point bending with fixed force

modeled solid produced additively with the nozzle temperature of 190°C, 200°C, 210°C, 220°C. The moment was determined as the quotient of the force value and the arm.

The numerical analysis of the designed cuboid in a static uniaxial tensile test is presented above (Figure 8, Figure 9). Differences between particular groups are noticeable. For a model made on a pattern drawn in a CAD program, the occurring stresses are the smallest. In fact, the use of different nozzle temperatures contributes to the change in stress and strain values. The printing parameters selected during the incremental production of the material directly affect the shape of

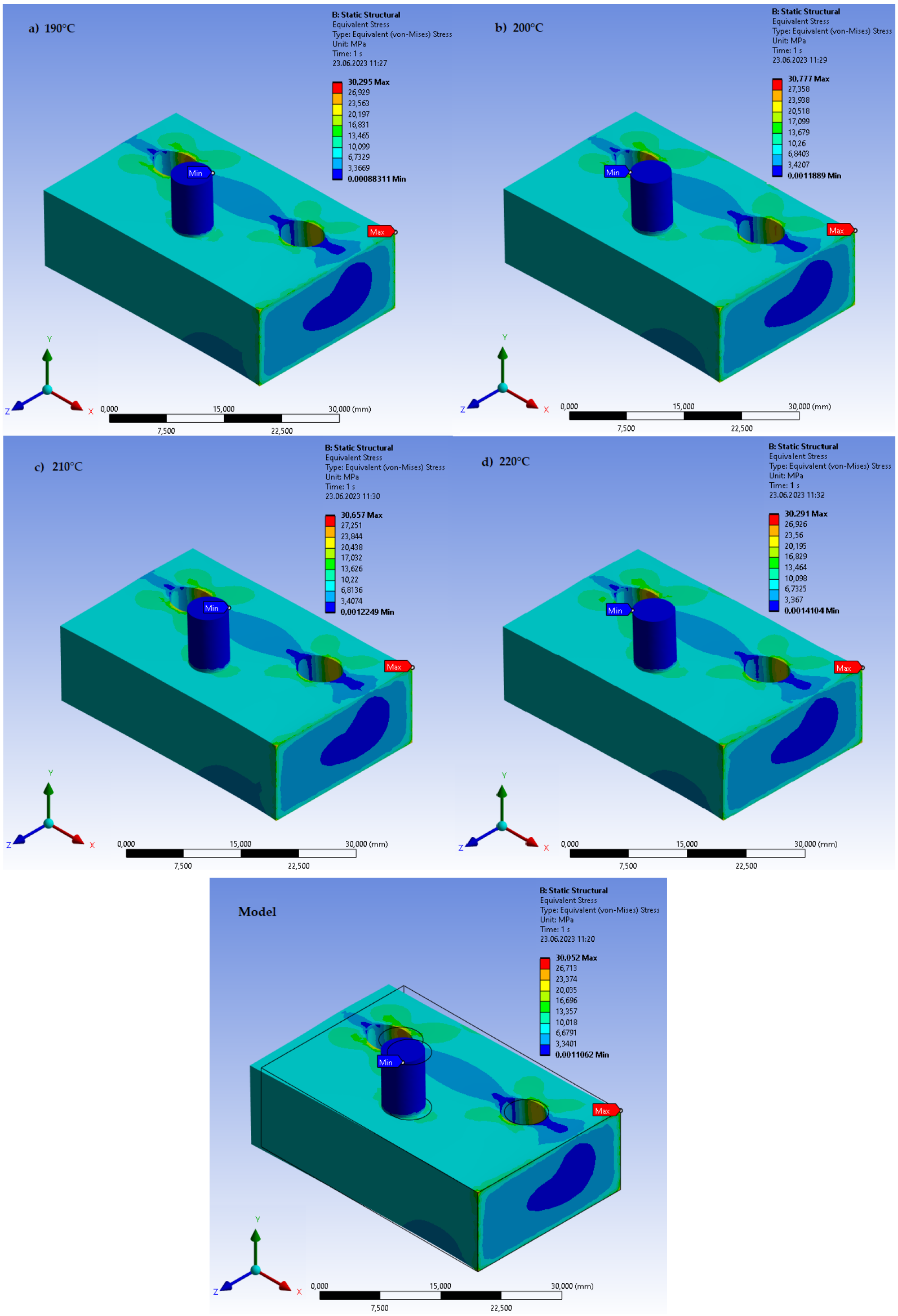

Figure 8. FEM analysis of stresses occurring in the designed solid for four temperatures of the nozzle and reference model during stretching

the manufactured elements. In the case of openings, cylindrical structures and corners, dimensional deviations may occur, which in turn cause differences in strength and deformation during static loads.

The highest stress values were obtained for samples made with nozzle temperatures of 200°C and 210°C, which are about 31 MPa. For the temperature of 190°C and 220°C, the deviations are the closest to the reference model and are at

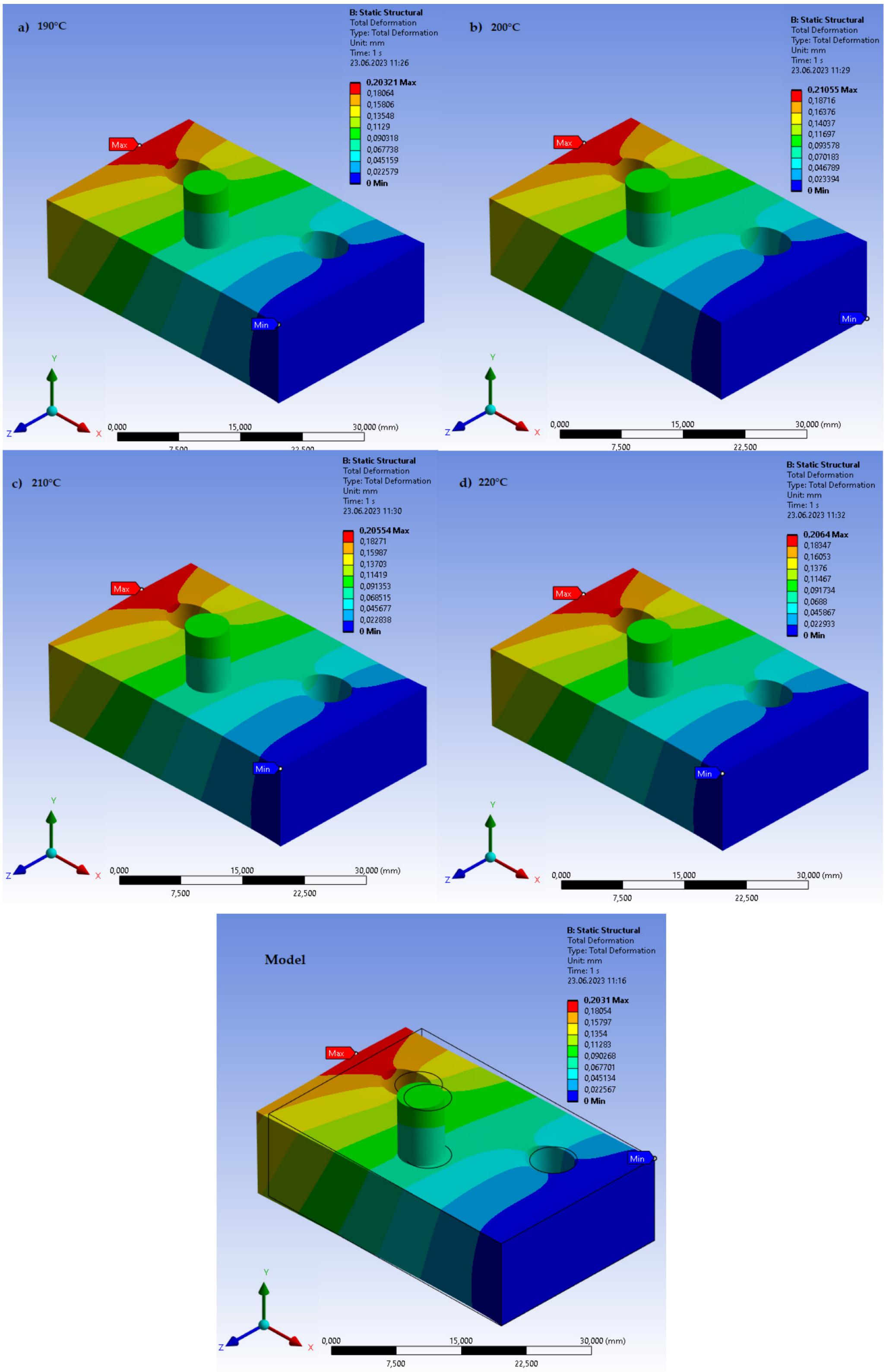

Figure 9. FEM analysis of deformations occurring in the designed solid for four temperatures of the nozzle and reference model during stretching

the level of about 30 MPa. Differences in resistance to static loads are also related to shape deviations, which can be of great importance during the production of precise elements. None of the manufactured elements obtained values identical to the reference model. The obtained different parameters indicate the need to analyze not only the selection of the material, the shrinkage of which will affect the stress concentration, but also paying special attention to the temperature of the process. The variety of polymeric materials and their wide range of thermal transformation processes makes it extremely difficult if the goal is to produce the most durable structure.

The values of the deformations obtained during the uniaxial tensile test were also analyzed. The element made at 190°C had a maximum deformation of 0.203 mm, which was the same for

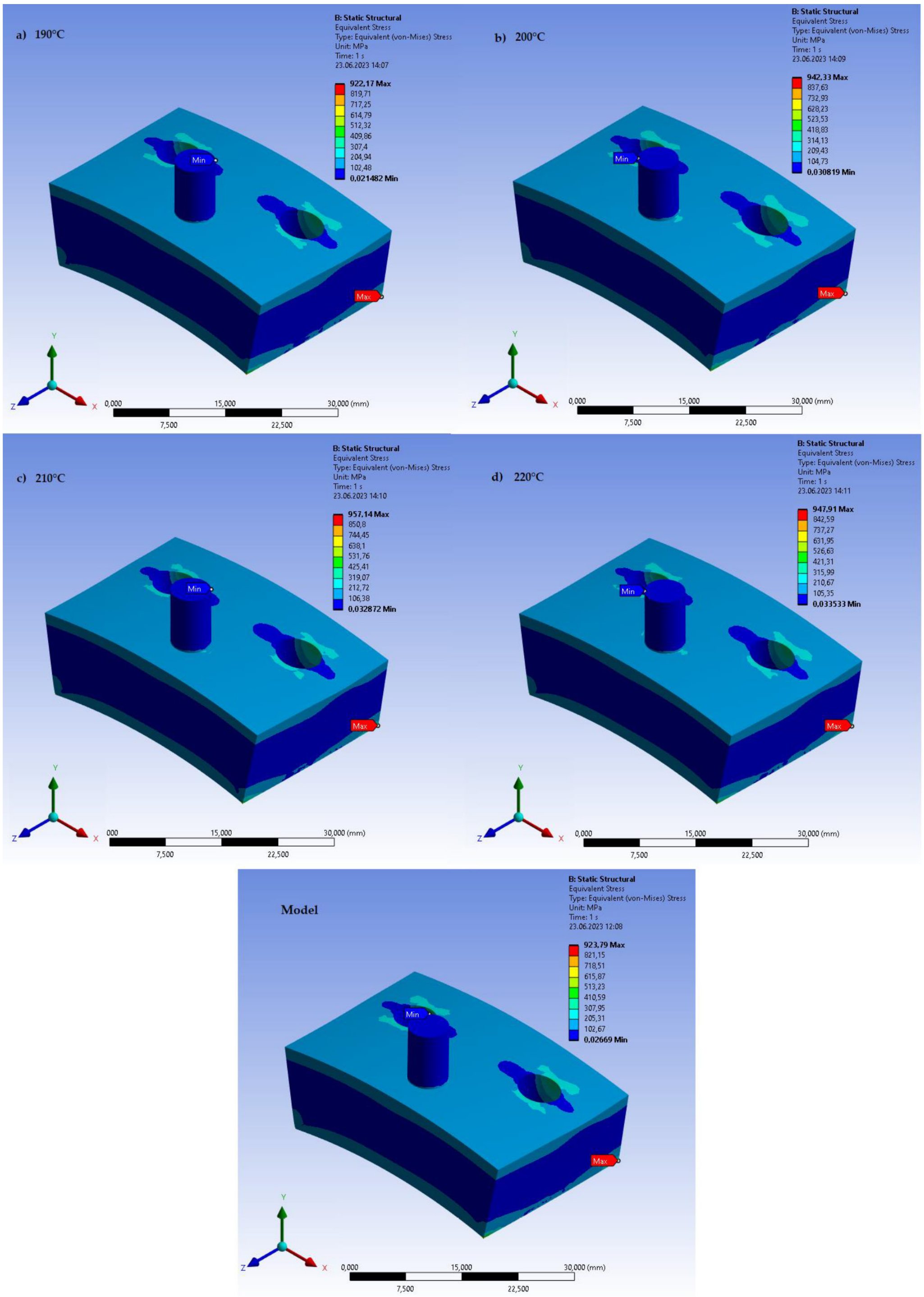

Figure 10. FEM analysis of stresses occurring in the designed solid for four temperatures of the nozzle and reference model during bending

the reference model. The largest deviation is noticeable for the printing temperature of 200°C and is 0.211 mm. The differences in the obtained values are due to the occurrence of different scales of shrinkage in polymeric materials depending on the processing temperature. In the case of uniaxial stretching of the manufactured element, after analyzing the results obtained, the material with the nozzle temperature of 200°C has the worst parameters, and the best at 190°C.

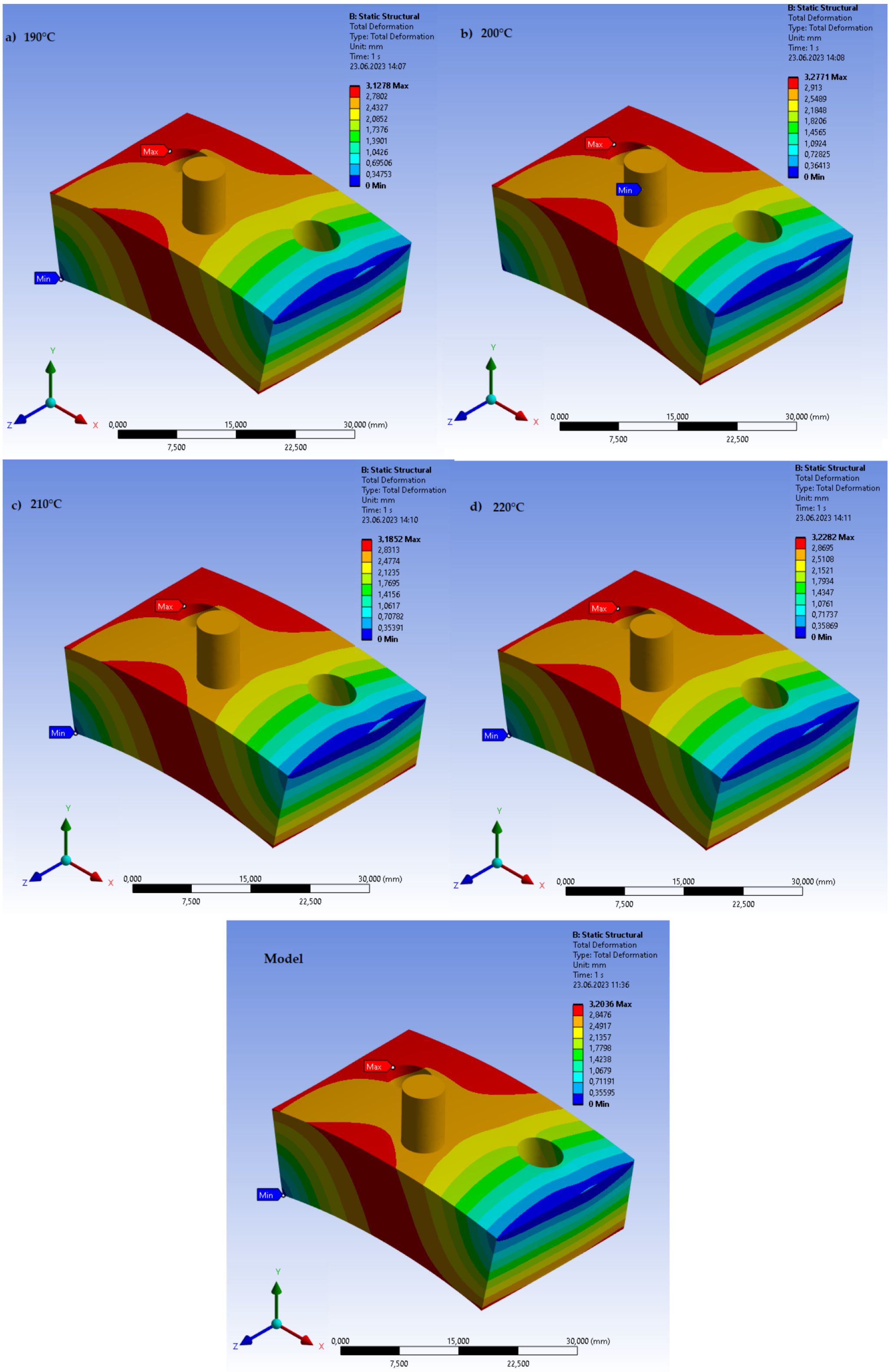

Figure 11. FEM analysis of deformations occurring in the designed solid for four nozzle temperatures and reference model during bending

All four measurement groups were analyzed, of which the largest deformation, amounting to 3.277 mm, has a sample made with a nozzle temperature of 200°C. For the denomination, this value was 3.204 mm. The smallest deformation was recorded for the printing temperature of 190°C, which was equal to 3.128 mm. The stress values of the designed solid analyzed in terms of the Finite Element Method prove that there is a clear tendency between the individual parameters. In the case of stress, the highest values of 957.14 [MPa] were obtained for the nozzle temperature of 210°C, and the closest to the nominal for 190°C, the result of which was equal to 922.17 MPa. Calculations for the standard element showed a difference of only 1 MPa between the temperature of 190°C and the prototype. The discrepancy between the denomination and the samples made with the printing temperature of 210°C was equal to 35 MPa (Figure 10, Figure 11).

As in the case of the previous analysis, this proves that the same groups of the best and the worst parameters were selected. These results are duplicated for each of the tested solids.

CONCLUSIONS

After comparing the obtained results for coordinate metrology and the analysis of the Finite Element Method, the occurrence of trends of individual results in groups was noticed. The least susceptible to deformation and stress is polylactide made with a nozzle temperature of 190°C and then 220°C. In the case of this group, the stresses are close to the reference model and oscillate in the range of about 30 MPa, and the strain is about 0.203 mm for the static tensile test. The largest deviations were observed for samples made with nozzle temperatures of 200°C and 210°C. Dimensional measurements have shown that the smallest deviations have a sample made with a printing temperature of 220 ° C. This is due to the occurrence of much greater shrinkage during the cooling of the heated polymer. This is a temperature slightly exceeding the scope of application, while the results did not show significant differences in formability and ability to transfer stresses during the FEM analysis

In the case of cylindricity measurements, the best results were obtained for the nozzle temperature of 190°C, while the deviations increase when the extruder temperature is increased. Measurements of the angle between the cylinder and the plane showed slight deviations for temperatures of 200°C and 220°C. The best dimensional tolerances of the manufactured cuboids are shown by samples made at 190°C. Each time its value is increased, the intolerance increases. This may be due to the phenomenon of shrinkage of the polymeric material. In the case of the distance between the centers of the holes relative to each other, the smallest deviations were obtained for the temperature of 190°C and 220°C.

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