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Study Regarding the Influence of the Printing Orientation Angle on the Mechanical Behavior of Parts Manufactured by Material Jetting

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Abstract: *Initially developed as a rapid prototyping tool for project visualization and validation, the recent development of additive manufacturing (AM) technologies has led to the transition from rapid prototyping to rapid manufacturing. As a consequence, increased attention has to be paid to the mechanical, chemical and physical properties of the printed materials. In mechanical engineering, the widespread use of AM technologies requires the optimization of process parameters and material properties in order to obtain components with high, repeatable and time-stable mechanical properties. One of the main problems in this regard is the anisotropic behavior of components made by additive manufacturing, determined by the type of material, the 3D printing technology, the process parameters and the position of the components in the printing space. In this paper the influence of the printing orientation angle on the tensile behavior of specimens made by material jetting is investigated. The aim was to determine if the positioning of components at different angles relative to the X-axis of the printer (and implicitly in relation to the multijet printing head) contributes to anisotropic behavior. The material used was a photopolymer with a mechanical strength between 40 MPa and 55 MPa, according to the producer. Four sets of tensile test specimens were manufactured, using flat build orientation and positioned on the printing table at angles of 0˚, 30˚, 60˚ and 90˚ to the X-axis of the printer. Comparative analysis of the mechanical behavior was carried out by tensile tests and microscopic investigations of the tensile test specimens fracture surfaces.*

Keywords*: additive manufacturing, material jetting, printing orientation angle, mechanical properties, fracture surface*

1. Introduction

Additive manufacturing technologies have developed exponentially in recent years, as they offer a number of advantages over conventional manufacturing technologies, as follows:

-the rapid manufacturing of components with high geometric complexity;

-the optimization of the inner geometry of parts so as to obtain a material distribution correlated to the stress state;

-the manufacturing of lighter parts with various lattice infill patterns [1, 2];

-the manufacturing of a part by use of several materials simultaneously (obtaining variable compositions and variable mechanical properties in the same part);

-the use of shape memory materials and 4D materials (components resulting from 4D printing have the property of changing their shape under the action of external factors: temperature, humidity, electricity, light) [3-5].

Several types of processes can be used for additive manufacturing of polymeric materials. The ISO/ASTM 52900:2015 standard [6] defines six process categories: material extrusion, material jetting, powder bed fusion, binder jetting, vat photo-polymerization and sheet lamination.

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The differences between the six categories are given by the additive manufacturing principle (extrusion of melted material, multi-jet material printing, selective fusion of material in a powder bed, reactive curing, light reactive photopolymer curing, fusion of stacked sheets), by the material feedstock (filament, melted material, powder, liquid, sheet material), by the material distribution system (deposition nozzle, print head, powder bed, vat with liquid, sheet stack) and by the state of fusion of material (thermal reaction bonding, chemical reaction bonding).

In material jetting manufacturing technology, photosensitive polymers in liquid state are disposed on a printing table using multi-jet printing heads. The parts are built up layer by layer on the Z-axis (the orientation of the reference system is adopted according to ISO/ASTM 52900:2015). After a layer is deposited, its height and quality are leveled by a rotating cylinder, positioned next to the printing head and finally it is cured by an ultraviolet light lamp. 3D printers for material jetting technology are usually equipped with at least two printing heads. The first printing head is used to deposit the model material, respectively the material for building the part. The second printing head provides the deposition of the support material that serves as a substrate for the top layers of the model material and is removed after manufacture. Printers with more than two printing heads allow the combination of several model materials, as to obtain multi-material components.

The main advantages of the material jetting technology are: higher manufacturing accuracy compared to other additive technologies, lower roughness, shorter part manufacturing times due to multi-jet printhead deposition, the possibility of using several model materials on the same part (model material mixing) and local variation of the mechanical properties of the resulting composite material [5]. The main disadvantages of this technology are related to the high manufacturing costs (cost of equipment, cost of materials) and the complexity of the maintenance process of the printing equipment (complete cleaning of the material flow circuits is necessary to avoid blockages and manufacturing imperfections) [7].

Additive manufacturing technologies have been used until now mainly in the production of prototypes and small series components for various fields of activity (electronics, robotics, aeronautics, automotive, energy, biomedical applications, etc.) [8, 9]. Widespread use of additive technologies requires optimization of process parameters to achieve superior and stable mechanical properties.

The literature indicates several factors that influence the mechanical properties of components made by additive technologies: type of process, material, printing temperature, thickness of the deposited layer, build orientation, positioning of the specimen on the printing table, infill pattern, infill density, raster angle, working speed, curing time, humidity of the working environment, the use of support material [10 - 14].

One of the major issues encountered in the literature is the anisotropic mechanical behavior of components made by additive technologies. Anisotropic behavior is mainly influenced by the process type, deposition strategy and process parameters. In [15] it is shown that the anisotropic behavior is more pronounced in components made by material extrusion and powder bed fusion technologies. Mechanical tests (tensile, bending, compression) were performed on specimens printed at different orientations relative to the printer reference system in order to characterize the anisotropic behavior generated by the part placement. The orientation of the specimen should be correlated with the printing strategy. The analysis of differences between different test piece orientations/positions is only valid if the paths followed by the printer are identical in relation to the reference system.

The default orientation of the 3D printer XYZ reference system is defined in ISO/ASTM 52900-2015 [6]. Printers using material jetting technology have the print heads disposed parallel to the Y-axis. The tensile specimens (with the main dimensions defined in ISO 527-2: h - width, b_2 - width at ends, l_3 - overall length) can be manufactured using three main build orientations (Figure 1):

-“flat” build orientation, where the area defined by test specimen dimensions (l_3) and (b_2) is placed on the printing table and the thickness of the test specimen (h) is generated on the Z-axis;

- “on-edge” build orientation, where the area defined by test specimen dimensions (l_3) and (h) is placed on the printing table and the width of the test specimen (b_2) is generated on the Z-axis;

- "upright" build orientation, where the area defined by test specimen dimensions (b_2) and (h) is placed on the printing table and the overall length of the test specimen (l_3) is generated on the Z-axis.

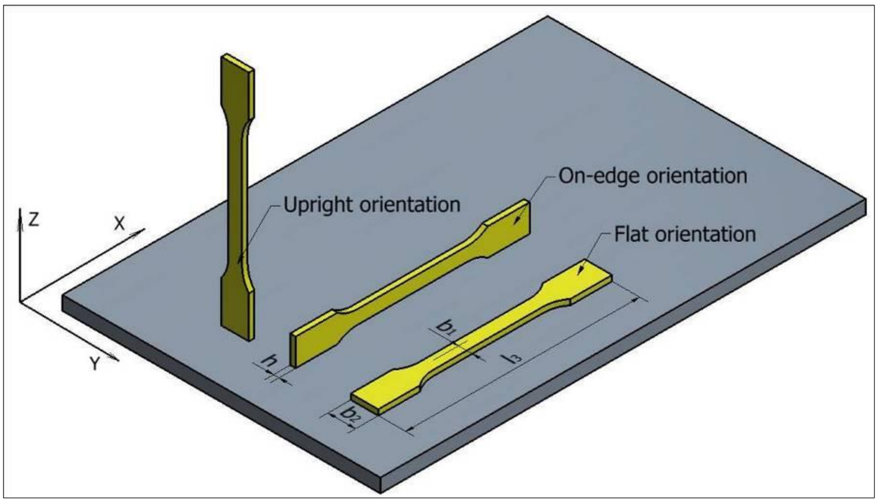

Figure 1. Build orientation of the test specimens

For each of these three build orientations, the specimens can be positioned at different printing angles in relation to the X-axis of the printer. Figure 2 shows alternatives of positioning the specimen at different angles for "flat" build orientation.

Research was also found in literature for intermediate positions, in addition to the three orientations defined in Figure 1. In this case the test specimens were printed inclined in relation to the printing table [16].

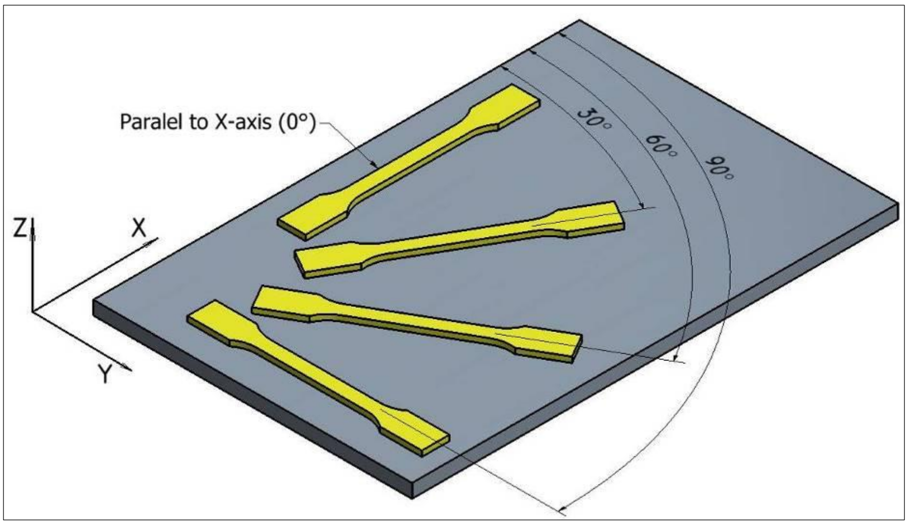

Figure 2. Printing orientation angle

O'Connor et al. [17] analyzed the build orientations influence on the mechanical properties of a polymer printed by powder bed fusion. The results indicate that the strength is superior for specimens printed using on-edge and upright orientation, in both tensile and bending tests.

Zaldivar et al. [18] analyzed the mechanical behavior of six types of specimens printed by FDM with three orientations and also inclined relative to the reference system. The investigations showed that the mechanical properties are significantly influenced by the build orientations. The highest values for the mechanical strength were obtained for specimens made after the "on-edge" layout. For "flat" build orientation better results were obtained for test specimens printed parallel to the Y-axis.

Beattie et al. [19] report higher tensile, bending and torsional strengths for "on-edge" test specimens made of ABS using FDM technology. The lowest values were obtained for “flat” specimens.

Vukasovic et al. [20] tested ABS and PLA specimens printed by FDM with two orientations: “flat” and “on-edge”. Higher values for tensile strength were obtained for “flat” specimens for both ABS and PLA. The compressive strengths were close for the two orientations. The authors showed that the build orientation has a greater influence on specimens made of ABS compared to those made of PLA.

Calignano et al. [21] investigated the mechanical behavior of Polyamide 12 components produced by powder bed fusion and multi jet fusion. Nine layouts for tensile specimens were used. The results showed differences in tensile strength values between the nine types of lay-ups for both technologies. The authors correlate the anisotropy with the pore distribution.

Gay et al. [22] analyzed the influence of the printing angle and specimen spacing on the X and Y axes (specimen spacing - the distance between two adjacent specimens) to the modulus of elasticity in material jetting technology. It is shown that specimen spacing on the X-axis has no significant influence, while orientation angle and specimen spacing on the Y-axis have low influence.

Barclift et al. [23] showed that specimens printed by material jetting with “on-edge” orientation have higher mechanical strength than specimens printed with “flat” orientation. For “flat” specimens, the X-axis orientation resulted in superior properties to the Y-axis orientation, but the differences were small. The same authors found that decreasing the Y-distance between two successive specimens increases the mechanical strength. It is pointed out that the mechanical properties determined experimentally were considerably lower than those specified by the manufacturer.

Cazon et al. [24] indicate that for “flat” specimen the printing angle has no significant influence on the mechanical strength but influences the modulus of elasticity, with the best behavior of X-axis (0˚) oriented specimens.

Abayazid et al. [25] investigated the mechanical behavior for two elastomeric materials made by material jetting. “Upright” specimens have the lowest mechanical strength in tension and compression. The authors showed that the anisotropy generated by build orientation is lower when tensile tests are performed with higher strain rates. This last conclusion is also evidenced by the tests presented in [26] for three types of polymers.

Bass, Meisel and Wiliams [27] showed that “flat” and “on-edge” specimens have higher mechanical strength compared to “upright” specimens. The printing orientation angle in the horizontal plane (0˚ and 90˚) does not cause significant differences in tensile strength. These conclusions are valid for materials with low mechanical strengths made by material jetting technology. The same authors pointed out that mechanical strength increases with increasing time (in weeks) between the date of printing and the date of the tensile test.

The lower strength of “upright” specimens is attributed by Muller and co-authors [13] to the higher number of layers and interaction surfaces resulting from the manufacturing of the specimen along Z-axis.

Tee et al. [4] pointed out that the printing direction has a significant importance on the mechanical properties of composites obtained by material jetting. The lowest tensile strength was obtained for specimens oriented at 45˚ to the X-axis. Regarding the influence of the support material and the resulting surface roughness on the breakage initiation, Tee et al. found that the cracks in the fracture surface of the tensile samples started from the matte interface between the support and the model material.

Kesy and Kotlinski [28] pointed out that the printing orientation angle influences on the mechanical properties of components made by material jetting. The authors attribute these variations to the different exposure to UV light during the printing process.

The large majority of the research presented above for material jetting technology did not reveal considerable differences in mechanical strength depending on the printing orientation angle. Also, most of research has been carried out for sets of specimens arranged in two limit positions: specimens parallel to the X-axis and specimens parallel to the Y-axis. In this paper, the authors investigate the influence of the printing angle on the tensile strength of “flat” specimens disposed in four positions in relation to the X-axis, respectively at 0˚, 30˚, 60˚ and 90˚.

2. Materials and methods

2.1. 3D printing

The investigations regarding the influence of the printing angle on the tensile strength were carried out on four sets of test specimens, marked with A, B, C and D. All samples were manufactured in flat orientation. The type A specimens were printed parallel to the X-axis (angle 0˚- Figure 2), the type B specimens were arranged at 30˚ to the X-axis, the type C specimens were positioned at 60˚ to the X-axis and the type D specimens were realized at 90˚ (parallel to the Y-axis). Three specimens were made for each set.

The model material was a photosensitive polymer with the following mechanical properties indicated by the manufacturer: tensile strength: 40-55 MPa, elongation at break: 5-20%, modulus of elasticity: 2200-3000 MPa, flexural strength: 70-85 MPa, flexural modulus: 2000-2500 MPa, water absorption (24hr): 1.1 - 1.5 %. This material is a blend of acrylate, acrylic monomer/oligomer and a photoinitiator.

The specimens were obtained by material jetting using a 3D-Printer, model Objet 30 Desktop with two multi-jet printing heads, one for the support material and one for the model material. The equipment is supplied with model and support materials in liquid state. The deposited layers are uniformed with a roller (cylinder), that is disposed in the area of the printing heads and cured with UV light. The printing heads move in the X and Y axis. The printing table moves in the Z-axis. The maximum dimensions of the printing space are: 294 mm (X-axis), 192.7 mm (Y-axis) and 148.6 mm (Z-axis), with a resolution of 600 dpi on the X and Y axis and 900 dpi on the Z-axis. The thickness of the deposited layers was 0.028 mm (Z-axis). As the total thickness of the specimens was 3 mm, it results that one specimen was made of 108 layers. It has to be noticed that during the printing process the orientation of the printhead relative to the XYZ reference system of the printer does not change (the print head remains parallel to the Y-axis).

For all specimens, a glossy finish type was applied, meaning that support material was placed only on the printing table and thereby deposited none but on the bottom of the samples. After printing, the support material was removed from the specimens' surfaces by high pressure water jet cleaning.

2.2. Tensile tests

The tensile tests were carried out on a testing machine from Mecmesin, model MultiTest-dV with the capacity of 2500 N, in accordance with ISO 527-1, using specimens type 1A (ISO 527-2) with the thickness h = 3 mm. The effective width and thickness of the printed specimens were measured at three points using a digital caliper.

The measurement of the test force was realized with a 2500 N force cell with a resolution of ± 0.5%. The displacement was measured with a displacement transducer included in the machine case. The positioning resolution of this transducer was 0.001 mm. The test speed was 5 mm/min and the speed resolution was 0.1 mm/min. The specimens were tested in constant speed mode until break. Screw-nut devices were used to fix the specimens. These devices are self-centering during the test.

Stress-strain curves and maximum tensile strength values were obtained from the tensile tests.

2.3 Microscopic analysis of the fracture surfaces of the tensile specimens

After carrying out the tensile tests, the fracture surfaces of the samples were analyzed by means of a confocal laser scanning microscope (CLSM) from Keyence, model VK-X200.

3. Results and discussions

Figures 3 and 4 show the variations in specimen thicknesses and widths measured before the tensile tests. The values were measured in three points, respectively in the middle and at the limits of the calibrated area of the specimens. The average value and the deviation field of the three measurements was calculated for each sample and dimension.

It can be seen that the measured thicknesses range between 3.00 and 3.20 mm. The most significant differences between the average thickness and the nominal dimension required by the standard (3 mm) were found in the A1, B3, C1 and C3 specimens. The largest scatter of the measured thickness values was found in specimens C1 and D1.

The measured widths are in the range 10.00-10.20 mm. The largest differences between the nominal width (10 mm) and the average of the three measured widths were found in specimens A1 and A2. It can be seen that all three measured widths are higher than 10.20 mm for these two specimens. The largest scatter of measured width corresponds to the specimen C2.

Analyzing the values presented in Figures 3 and 4 one can observe that all measured thicknesses and widths had positive deviations (the measured dimensions were higher than the standard nominal dimension). These positive deviations may have been caused by the adhesion of the support material to the model material or by the printing process (blocked nozzles, material deposited on the levelling roller etc.). No correlation between the printing orientation angle and the dimensional deviations can be concluded.

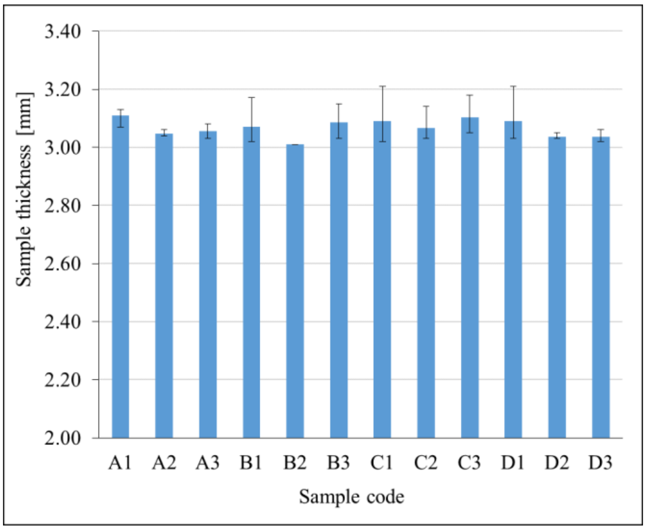

Figure 3. Variation of test specimens thickness

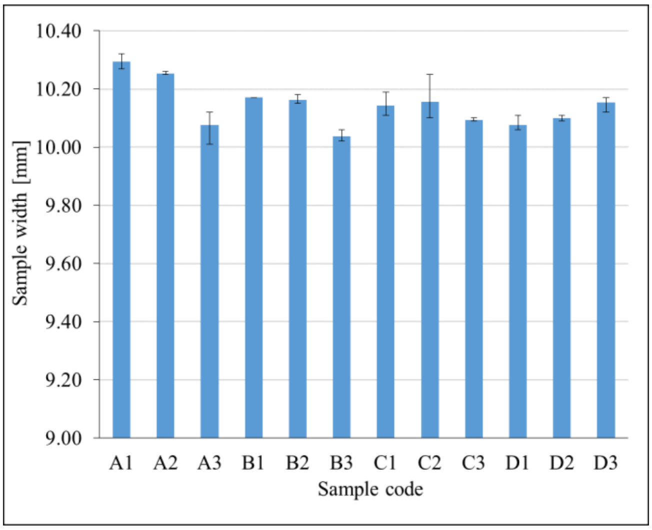

Figure 4. Variation of test specimens width

In order to point out differences in the mechanical behavior of the samples, the fracture surfaces were also analyzed. Figure 5 shows the appearance of specimens A, B, C and D after performing the tensile tests. Most of the specimens failed in the middle area, breaking in a plane perpendicular to the direction of the tensile force. Therefore, it may be concluded that the breaking direction is not influenced by the printing orientation angle.

Figure 5. Appearance of specimens after tensile test

Figure 6 shows the mean values of the ultimate tensile strength in dependence of the printing angle for the four sets of specimens. The scattering of the results is also shown in the same figure. All mean values of the mechanical strength are slightly lower than the values indicated by the producer, respectively 40-55 MPa. The highest mean value of the ultimate tensile strength is found for the A-set of specimens, while this set had also the highest scatter of results. The lowest ultimate tensile strength values occur in type C specimens (positioned at 60˚ relative to the X-axis). The difference between the mean value of the ultimate tensile strength of the A-set specimens (39.58 MPa) and the mean value of the ultimate tensile strength of the C-set samples (35.70 MPa) is 3.88 MPa, while the standard deviation of the values of the A-set specimens is 2.57 MPa.

Based on the insignificant differences between the mean values of the ultimate tensile strength and the appearance of the breaking surface, it may be considered that the printing orientation angle of the specimen (in XY plane) does not influence the mechanical behavior for the parts printed by material jetting.

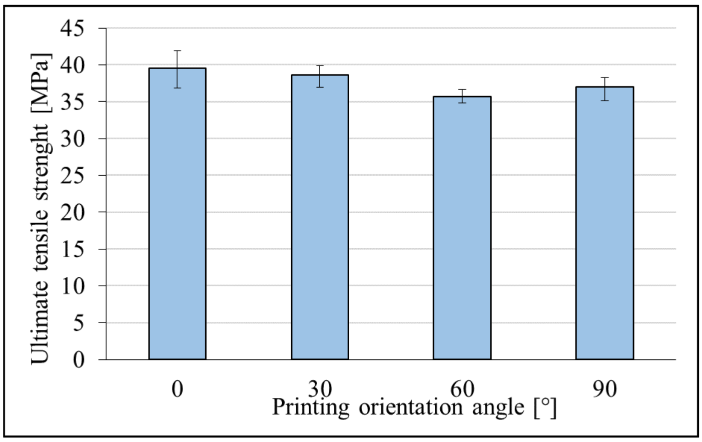

Figure 6. Variation of the ultimate tensile strength in dependence of the printing orientation angle

The stress-strain curves for the four sets of specimens are shown in Figures 7-10. As it can be observed, the ultimate tensile strength values are reached at a strain around 4%, except specimen A1. Considering the close values of the ultimate tensile strength for the four specimen sets, as well as those of the corresponding strains, it may be concluded that the behavior of the material in the elastic zone is similar for all printing angles. It is necessary to use an extensometer in the tensile tests for a more precise characterization of the elastic behavior and for the calculation of the elasticity modulus.

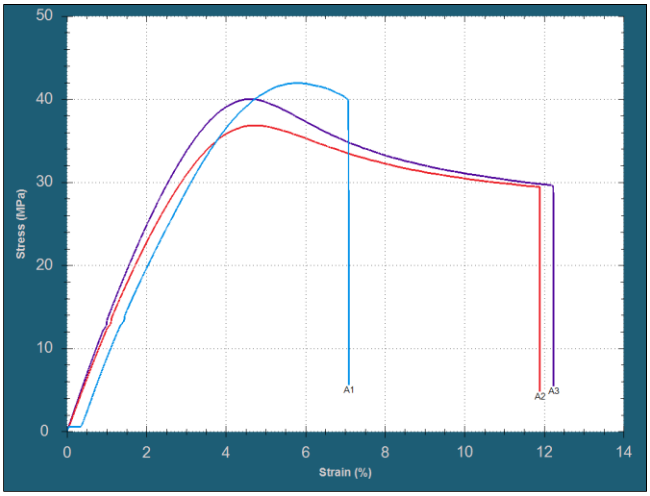

Figure 7. Stress-strain curves for A-specimens

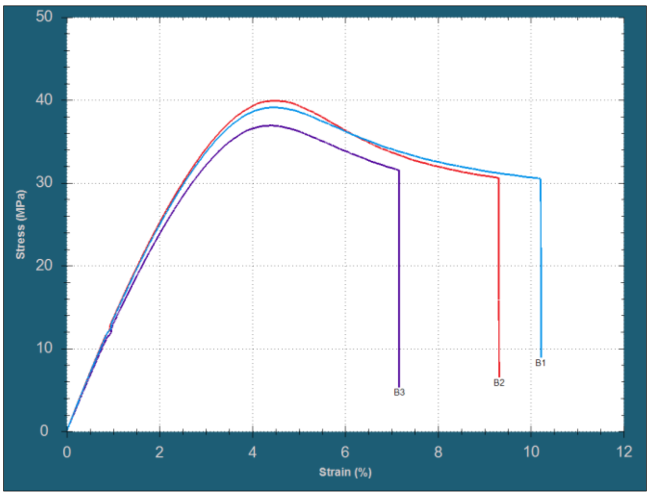

Figure 8. Stress-strain curves for B-specimens

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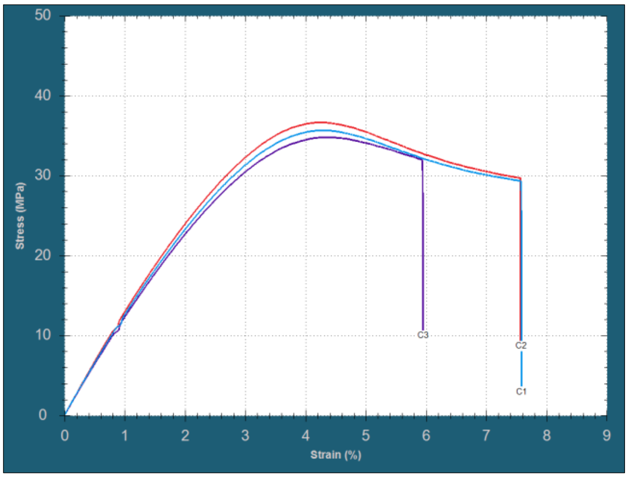

Figure 9. Stress-strain curves for C-specimens

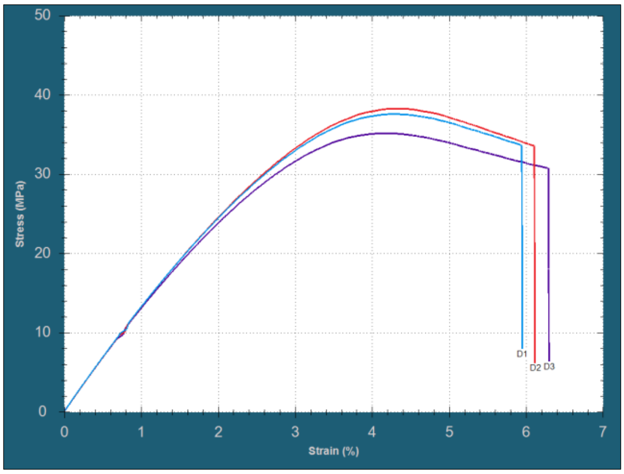

Figure 10. Stress-strain curves for D-specimens

Figures 11-17 show the fracture surfaces of the four types of specimens, examined by confocal laser scanning microscopy. As one may observe, the breaking surfaces of the samples are very much alike, exhibiting a brittle breaking appearance. In all cases, the failure started from the matte contact surface between the support and the model material and then propagated radially in the fracture surface. Furthermore, in Figure 14 remaining support material can be seen on the bottom of sample D1, where the fracture initiation point is localized. The profiles depicted in figures 15-17 reveal a slightly different behavior of the printed material at rupture. There is a tendency to form a slope between the region of crack initiation and the region with final material rupture.

Figure 11. CLSM image of the fracture surfaces of the A1 specimen

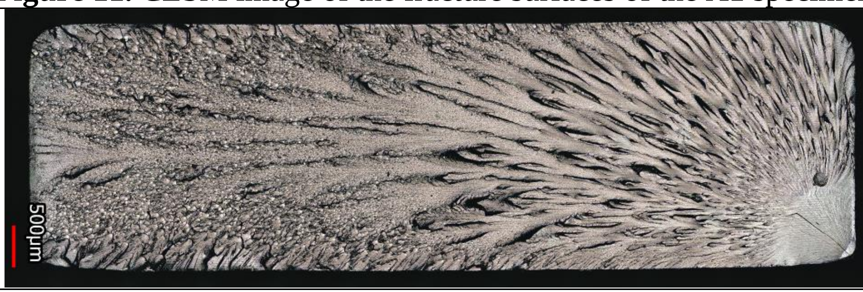

Figure 12. CLSM image of the fracture surfaces of the B1 specimen

Figure 13. CLSM image of the fracture surfaces of the C1 specimen.

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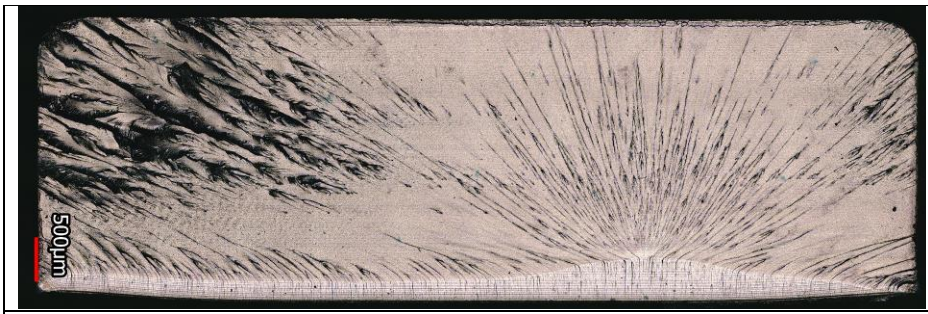

Figure 14. CLSM image of the fracture surfaces of the D1 specimen

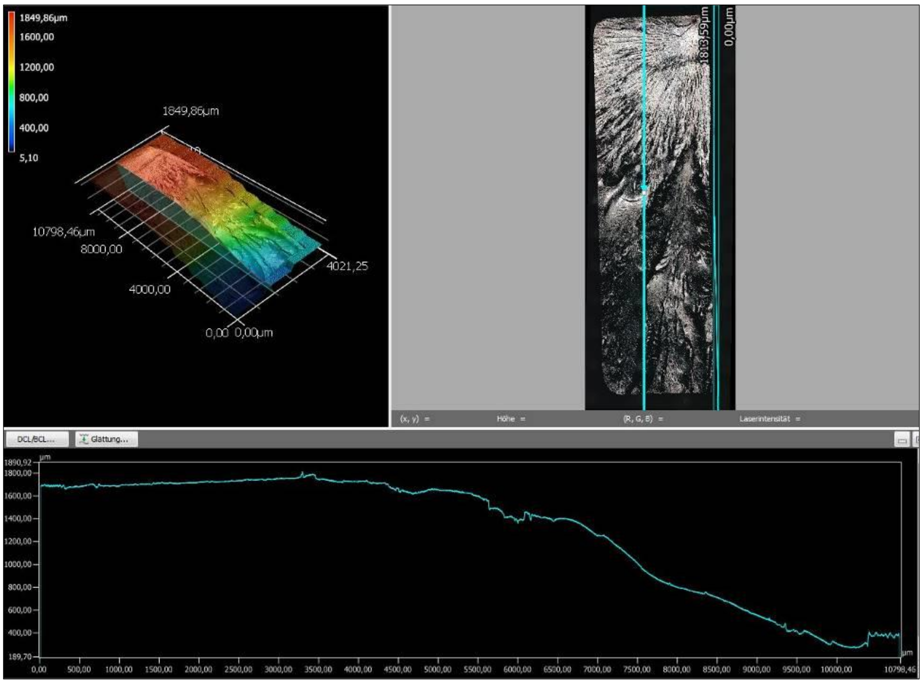

Figure 15. CLSM image of the A1 specimen fracture profile

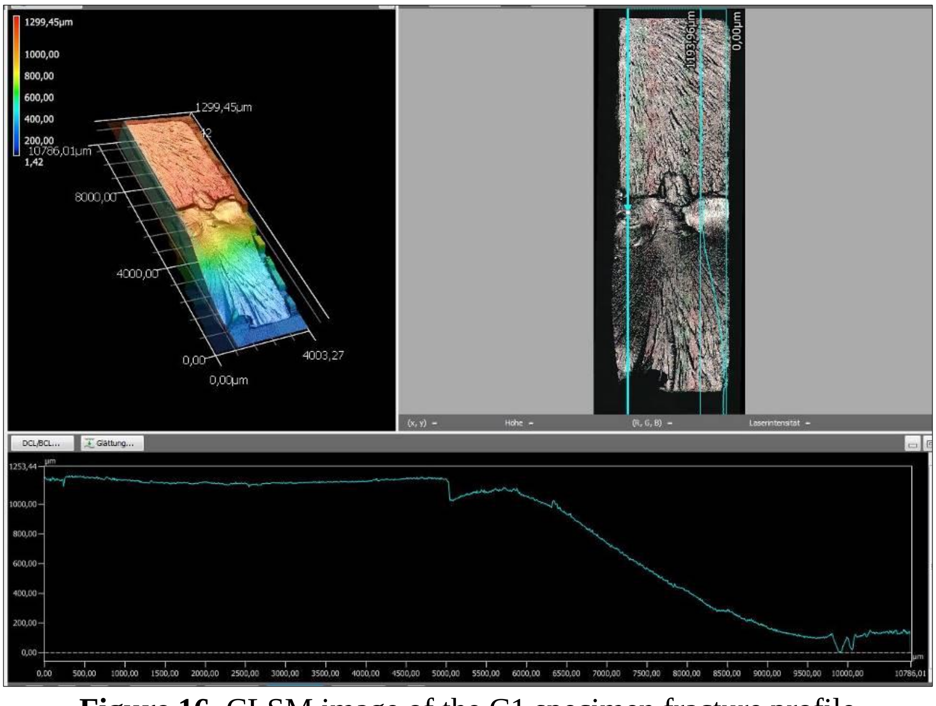

Figure 16. CLSM image of the C1 specimen fracture profile

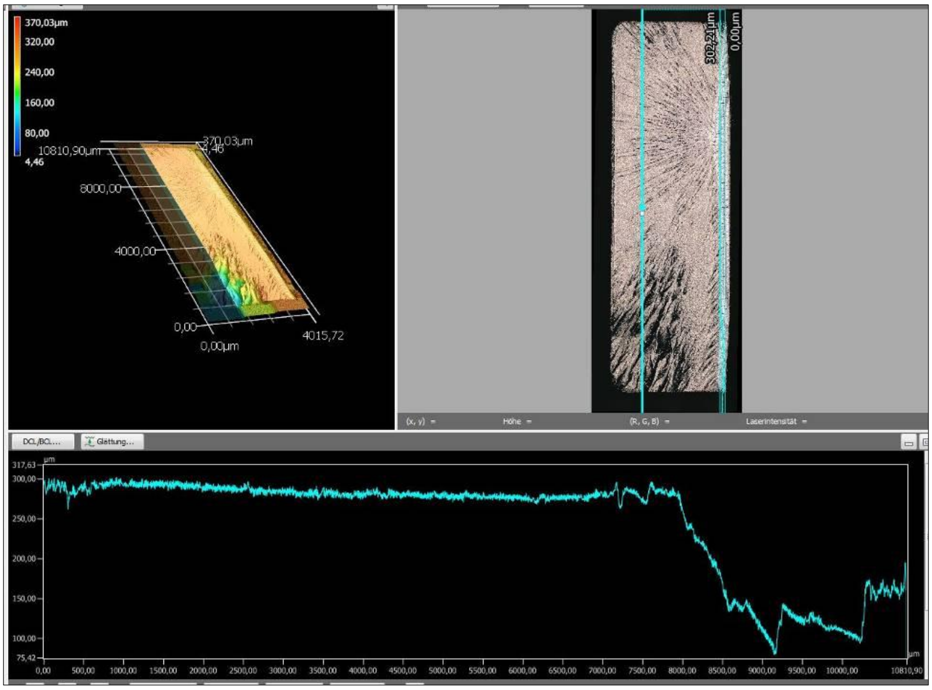

Figure 17. CLSM image of the D1 specimen fracture profile

4. Conclusions

Several factors that can influence the anisotropic behavior of components obtained by additive manufacturing technologies are presented in the literature. These factors are related to the material and process type, deposition strategy and process parameters. In this paper, the influence of the printing orientation angle (in XY plane) on the tensile behavior was analyzed. The research was carried out on four sets of specimens manufactured by material jetting using a photopolymer. The specimens were positioned at 0˚, 30˚, 60˚, 90˚ relative to the X-axis of the 3D printer. The mechanical tests and the microscopic analysis of the breaking surfaces conduced to the following conclusions:

- for all specimens, the ultimate tensile strength values obtained were slightly below the lower limit of the range of values indicated by the photopolymer manufacturer;
- most of the specimens showed a breaking surface perpendicular to the direction of the testing force (specimen's axis). No correlation between the positioning of the specimen on the printing table and the orientation of the breaking surface could be pointed out;
- for all specimens, the failure started from the contact surface between the support and the model material, revealing a radial propagation along the fracture surface. Therefore, attention has to be paid to the surface roughness determined by the use of support material;
- the differences between the ultimate tensile strengths obtained for the four sets of specimens were not significant. Consequently, it can be concluded that in case of material jetting the printing orientation angle has no influence on the mechanical behavior of the manufactured parts and does not contribute to the anisotropic behavior of the material.

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