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EXPERIMENTAL DETERMINATION OF CRITICAL ORIENTATION OF ABS PARTS MANUFACTURED USING FUSED DEPOSITION MODELLING TECHNOLOGY

The paper presents results of experiments aimed at determination of range of critical orientation for parts manufactured additively using the Fused Deposition Modelling method, out of ABS material. Numerous previous observations of plastic parts manufactured additively using the FDM process allowed concluding, that change of values of the manufacturing orientation (i.e. direction of layer slicing plane) has large influence on the macrostructure of obtained parts, thus affecting their strength and behaviour under load – the material behaves either as a thermoplastic with a yield point or as a brittle material with no yield point. The paper presents methodology and results of experiments aimed at determination of a certain value or value range, at which transition between the two behaviours occurs. The experiments consisted of tensile tests performed on samples manufactured additively in a pre-selected range of orientations. The obtained results – a value range valid for the selected type of load and sample shape – will be useful in future to help select an optimal orientation of part for a defined task.

1. INTRODUCTION

Additive Manufacturing Technologies (AMTs), also known as layered manufacturing technologies or, in recent years, as 3D printing, have developed rapidly over the last decade. This development is related to continuously increasing popularity of these technologies – more and more companies are aware of their advantages, especially in manufacturing of products of customized shape or small series of usable prototypes, mostly out of polymer materials. Application of AMTs for Rapid Prototyping can benefit with significant decrease of time needed for implementation of a new product, as they allow obtaining physical, three-dimensional shapes of nearly any complexity, directly from the 3D digital representation of a product, usually in form of a CAD model. There is no need of using any specialized tooling, besides the manufacturing machine and its standard equipment. Additive manufacturing technologies can be used for Rapid Prototyping, Rapid

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Manufacturing or Rapid Tooling effectively. They are invaluable, when there is a need of quick manufacturing of a physical prototype of a designed part [6],[15].

One of the most widespread AMTs for both industrial and general purposes is the Fused Deposition Modelling technology, which allows manufacturing elements out of wide range of thermoplastic materials. The most widespread build material is acrylonitrile butadiene styrene (ABS), which ensures relatively good strength and acceptable thermal shrinkage. Further processing of the produced elements by means of machining, coating, gluing etc. is possible, to achieve, e.g. surface quality of desired level or to improve mechanical properties. Machines that realize the Fused Deposition Modelling process have small dimensions and are easy to maintain due to relatively simple design, in comparison with other additive manufacturing technologies. They are also quiet and clean, which makes them available for use directly in design studios [6],[11]. Parts manufactured by the FDM technology can be recycled just as any parts made out of pure thermoplastics, there is no much waste – the whole process is not harmful to the natural environment [2],[5]. The most important drawbacks of the FDM process are: necessity of use of support material to prevent the part deformation in plasticized state (the support needs to be removed after the process, which can be a serious limitation to the shape complexity) and low time effectiveness of the process in comparison with other AMTs (producing the same part using for example the 3D Printing technology can be several times faster, depending on the shape and layer thickness).

A final product manufactured using the Fused Deposition Modelling technology can be characterized by technical and economical coefficients. These coefficients are affected by many factors [3] and some of them can be directly controlled by a process engineer (these are known as the process parameters). Values of parameters of the additive manufacturing processes can be very significant – two different sets of values of process parameters applied in manufacturing of the same shape can result in obtaining two products of entirely different properties, e.g. strength [1],[4] or accuracy [11], also with entirely different economical aspect of whole processes (e.g. times of manufacturing can differ by several hundred percent). Each set of process parameters: orientation of a product in the working chamber, layer thickness and method of filling of the layer contour, will influence the part structure. As a result, different values of coefficients such as strength, accuracy or surface quality will be obtained. It will also change the economic coefficients. There are two main parameters taken into account – amount of support material used and time of manufacturing. Both of them can influence cost of the final part drastically.

Up to the present day, influence of the manufacturing process parameters on mechanical properties of products made using the FDM technology and economical coefficients of the process has been studied thoroughly worldwide [1],[4],[13],[14]. Many researchers focused on optimization of selected parameters in relation to a specific evaluation criterion, for example time of the process [13], accuracy of shape representation [14], surface quality [16] and mechanical properties [17]. General conclusions from all these studies, now perceived as a common knowledge, is that a process parameter which influences values of the product properties in the most significant way is the spatial orientation of the product in the working chamber during the manufacturing process [1],[4],[7],[18].

Full character of relations between the FDM process parameters and properties of the obtained products is not fully described yet, although there are many attempts at experimental determination of these relations [1],[3],[4],[8]. Still, obtaining full characteristics of these relations, usable in practice for selection of optimal process parameter values for a specific part, is still an open problem. The authors of this paper also aimed at solving it at least partially, attempting both experimental [12] and analytical [9] approach to the orientation-strength relation.

Numerous experimental studies conducted by the authors of this paper have led to a conclusion, that the FDM parts made out of the same material can behave in two distinct ways under load – like a brittle or a yield point (ductile) material – depending on the internal macrostructure. The macrostructure is dependent on the manufacturing process parameters, mainly orientation. Aim of the long-term studies conducted by the authors is to discover a value – or range of values – of orientation, at which the transition between the two behaviours occur, for different types of loads. This range of values was named a critical orientation and this paper presents results of experimental studies, which allowed determining the critical orientation for objects subjected to tension.

2. MATERIALS AND METHODS

2.1. PROBLEM DEFINITION

The macrostructure of parts made using the FDM technology consists of material threads deposed in alternate directions, forming layers bound together without material fusion (exemplary layer structure is shown in Fig. 1). Such a process makes the manufactured elements behave in a specific way under load. Even a simple load applied to parts of non-complex shapes will result in a complex stress state inside the element [9].

Fig. 1. View of a single layer of a sample manufactured by FDM technology – visible contour and filling threads (thread width approx. 0.5 mm, layer thickness 0.254 mm) [9]

Mechanical properties of products manufactured using FDM technology are highly dependent on parameters of the manufacturing process. Out of these parameters, orientation in the working chamber is the most important [1],[7]. The base plane of the working chamber is also a slicing plane - it defines direction of division of an element into layers; different orientations will result in different layer arrangement. Together with the layer thickness parameter (usually within a range of 0.1 to 0.33 mm for the most widespread types of FDM processes), the orientation defines a number and general shape of deposed layers.

The product weak spots are present in places where the material is joined – mostly at the layer boundaries. Numerous studies prove that strength of bond between layers can be several times lower than strength of the material itself [4],[11],[16], which results in anisotropic mechanical properties of a single part [13]. Manufacturing the same shape with different orientation values results in significant differences of values of strength coefficients, which may reach even a few hundred percent [3],[7],[11],[18]. Strength of any part manufactured using the FDM technology will always be lower than strength of a product of the same geometry, but with monolithic structure (e.g. produced by injection molding) – this is related to volume errors in form of air gaps, occurring inside the manufactured element [16].

As the structure is largely dependent on the part orientation [19], prediction of the orientation influence on properties of the finished product is of fundamental significance for evaluation of possibilities of FDM technology application in small batch or piece production [20]. Orientation in the working chamber can be intuitively defined as an angular difference between plane slicing an object into layers and a selected, base plane of the object. Orientation may be therefore defined by three rotation angles (rotation between the object and the machine coordinate system), where only two angles are relevant (X and Y axis rotation) – third angle, around the vertical direction (Z axis), perpendicular to the layer slicing plane, has no influence on way of slicing an object into layers, so it does not affect the product properties significantly [10],[12].

During conducted studies, the authors have discovered that the FDM parts behave in two very distinct ways under load – a part can be either “brittle” or with a “yield point” (ductile) – it fails either via the layer disjoint or the thread fracture [8]. The transition between the two behaviours happens in a certain range of orientations [12]. The preliminary research, described in this paper, was aimed at finding out the general range of transition between the material behaviours – this range was named a critical orientation. The critical orientation problem was defined on the basis of preliminary tensile, bending and impact strength tests [12]. A general conclusion from these tests is that the critical orientation lies in range of 5÷30 angular degrees of orientation, as shown in Fig. 2. It means that e.g. for the tension, if the load direction lies in the same plane as the layer slicing plane or is deviated from it by no more than 5°, the part will behave like produced out of a ductile thermoplastic material. On the other hand, if the load direction deviates more than 30° from the layer slicing plane, the part will almost certainly fail by the layer disjoint (also known as the “brittle fracture”) if the maximal loading force value is exceeded.

The main problem described in this paper is finding the more exact values of orientation for the tension loads by way of experimental testing. This has been done by performing a series of tensile tests on samples manufactured with orientations within the critical range. Course and results of these tests are shown in the further part of this paper.

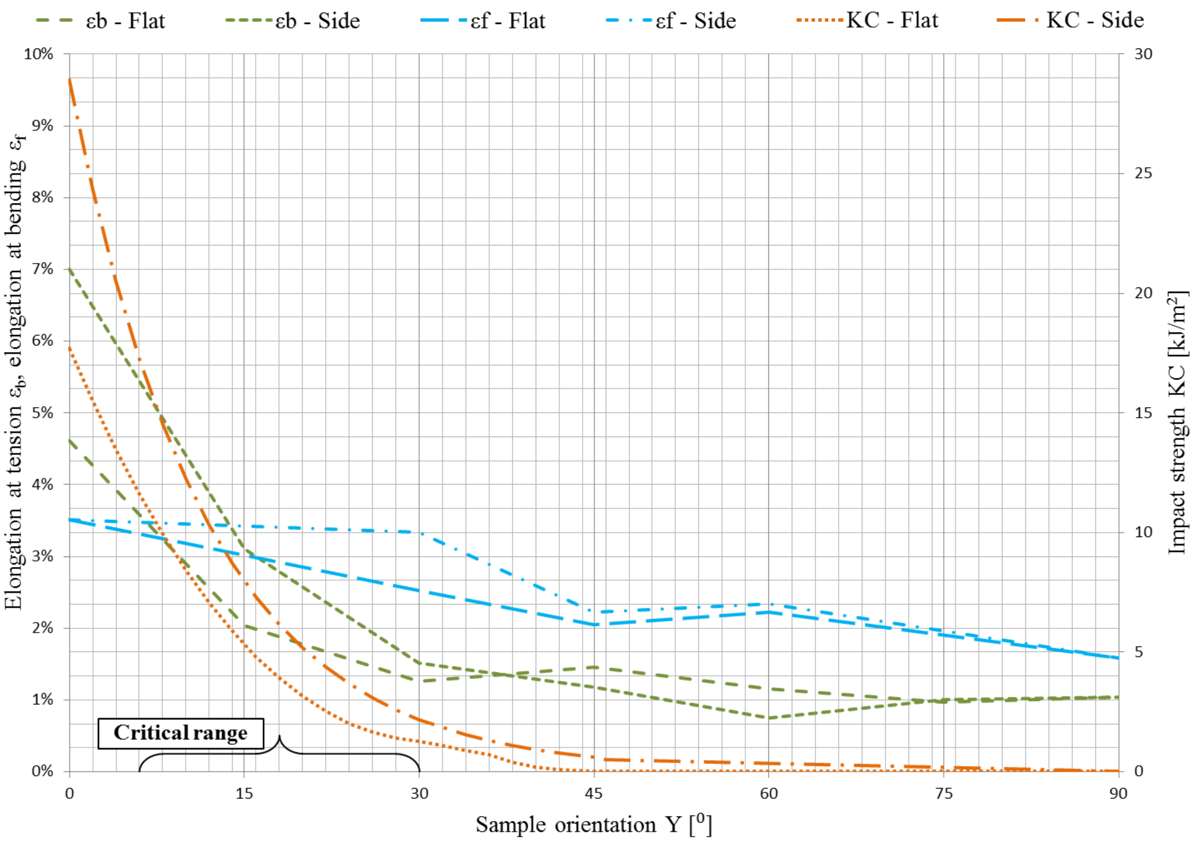

Fig. 2. Plasticity characteristics from the preliminary tensile, bending and impact strength tests, ε_b – maximal strain at tension, ε_f – maximal strain at bending, KC – impact strength, Flat, Side – orientation in X axis (Flat = 0°, Side = 90°) [12]

2.2. COURSE OF STUDIES

The conducted studies consisted in tensile tests of samples of a dog-bone shape (Fig. 3), according to the PN-EN ISO 527 standard which describes procedures and parameters of tensile tests of polymer materials. For the studies, samples made using FDM technology on the Dimension BST 1200 machine were used. The samples were manufactured out of the ABS material supplied by the Stratasys company in form of a wire wound on a spool, sealed hermetically in a cartridge. This ensures proper, low levels of humidity required for the process. The support structures were also made out of the ABS material and later removed by mechanical means (break-out support type).

The samples were manufactured in different orientations. Two orientations in the X axis were considered – 0° and 90°, named Flat and Side, respectively. The Y axis orientations were the main variable in the presented studies, differing in 5°, starting from 0°, ending with 30° - within the range determined by the preliminary studies. An ID of a given sample is composed of the name of the X orientation and value of the Y orientation (e.g. Flat-0 means that orientation of the sample is 0° in both axes). Summary of the samples produced for tests is presented in Table 1. The last column contains dimensionless cost coefficients for particular samples, calculated by taking the machine working time and material cost into account and rescaling it to obtain value of 1 for the least costly sample.

Table 1. Summary of samples for the experimental tests

No.	Sample ID	Tensile sample manufacturing time [min]	Tensile sample support material [cm^3]	Cost coefficient
1	Flat-0	22	2.0	1.0
2	Flat-5	57	9.3	1.8
3	Flat-10	81	14.9	2.6
4	Flat-15	109	20.7	3.5
5	Flat-20	134	25.8	4.3
6	Flat-25	161	30.6	5.2
7	Flat-30	181	34.4	5.8
8	Side-0	46	2.3	1.5
9	Side-5	84	6,9	2.7
10	Side-10	82	8.1	2.6
11	Side-15	102	10.1	3.3
12	Side-20	123	13.2	4.0
13	Side-25	142	15.3	4.6
14	Side-30	157	17.3	5.1

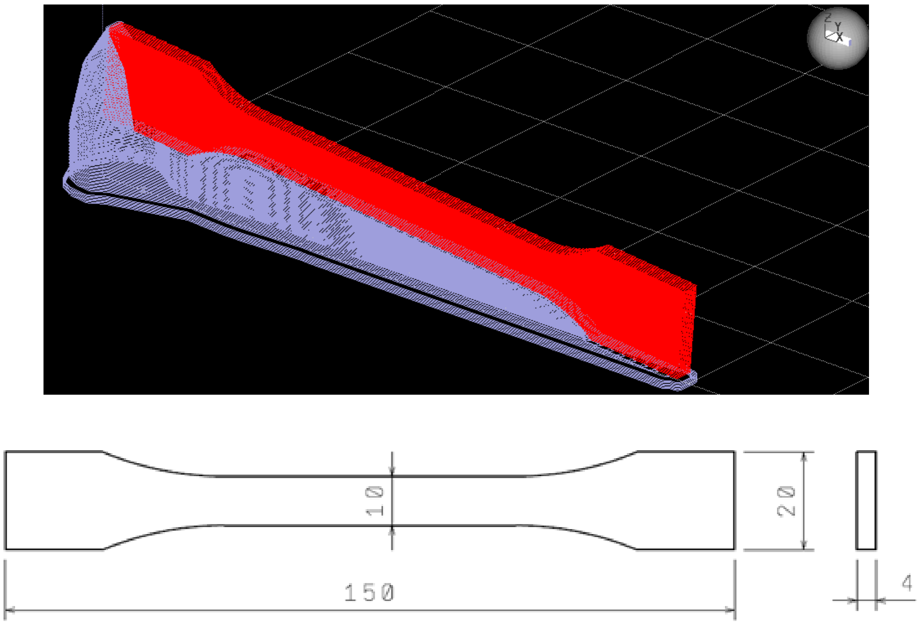

Fig. 3. Shape of samples for the experimental tests, top – sample planned for manufacturing in a certain orientation, bottom – sample dimensions

The sample geometry was prepared in a 3D CAD system and imported to the CatalystEX software for manufacturing preparation. In this software, the layer slicing process was performed automatically, along with generation of the support structures (Fig. 3). The samples were manufactured using solid (monolithic) internal filling with 45° raster, in a “criss-cross” manner (each subsequent layer different from each other by 90°). The layer thickness was 0.254 mm – these are the standard values of manufacturing parameters in the industry-standard Stratasys systems. Three samples were manufactured for each sample type for the tests. After manufacturing, each sample was measured using a digital calliper and the measurements were introduced to the software of the strength testing machine. For the tensile tests, the Zwick Roell Z020 machine was used, with all parameters compatible with requirements of the PN-EN ISO 527 standard. The samples were subjected to tension at 10 mm/s until failure.

3. RESULTS

Results of the tensile tests are presented in Table 2 (mean values from all the samples). It also contains information about economical coefficients of the selected samples. The sample behaviours during tests is also shown – the “yield” behaviour means that 100% samples failed by thread fracture after plastic deformation – yield point was recorded (the material behaved like a ductile thermoplastic). The “brittle” behaviour means that 100% samples failed by layer disjoint, with no plastic deformation. The “yield/brittle” notion means, that both failure mechanisms were recorded during tests. The two deformation coefficients show deformation at a maximum load and deformation at a sample failure.

Table 2. Results of the tensile strength tests

No.	Sample ID	σ_m mean	σ_m std. dev	ε_b	ε_m	Behaviour	Cost coeff.
1	Flat-0	19.0	0.21	4.6%	1.9%	yield	1.0
2	Flat-5	18.2	0.12	2.9%	1.7%	yield	1.8
3	Flat-10	18.0	0.22	2.0%	1.7%	yield	2.6
4.	Flat-15	18.1	0.56	2.0%	1.8%	yield	3.5
5	Flat-20	18.1	0.08	2.5%	1.8%	yield/brittle	4.3
6	Flat-25	16.1	1.55	1.4%	1.4%	brittle	5.2
7	Flat-30	13.8	2.88	1.3%	1.3%	brittle	5.8
8	Side-0	22.9	0.04	7.0%	2.0%	yield	1.5
9	Side-5	21.3	0.36	5.0%	1.6%	yield	2.7
10	Side-10	21.1	0.40	4.2%	1.6%	yield	2.6
11	Side-15	21.6	0.66	3.1%	1.9%	yield	3.3
12	Side-20	18.9	0.31	2.1%	1.5%	yield	4.0
13	Side-25	17.4	2.55	1.7%	1.3%	yield/brittle	4.6
14	Side-30	17.3	0.75	1.5%	1.5%	brittle	5.1

Where: σ_m – tensile strength, ε_b – maximal strain, ε_m – strain at fracture.

Examples of both behaviours with the corresponding force-deformation diagrams are shown in the Fig. 4. The table is completed with the cost coefficient column, to visualize relation between economic and strength coefficients. The values from Table 2 are shown in diagrams in Fig. 5 and 6.

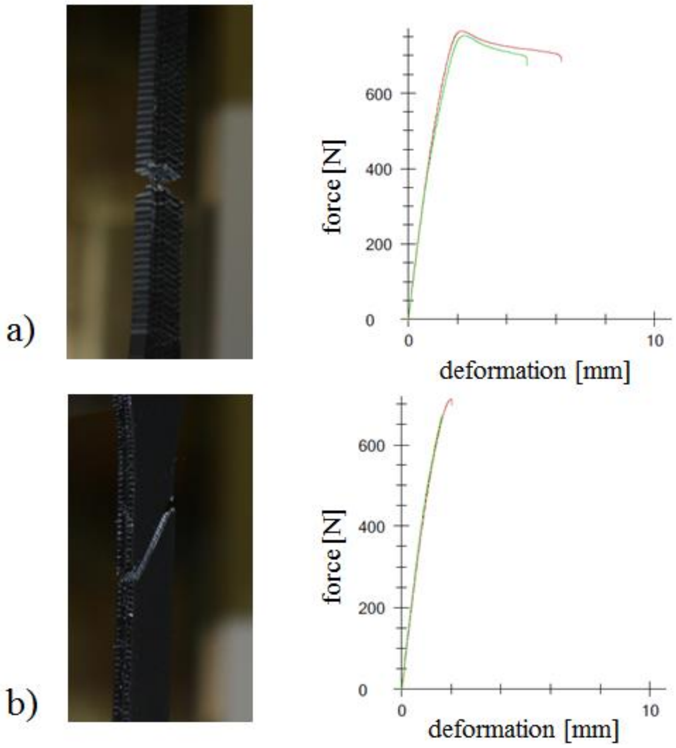

Fig. 4. Failure mechanisms in tensile samples: a) Flat-0 – ductile with a yield point, b) Side-30 – brittle

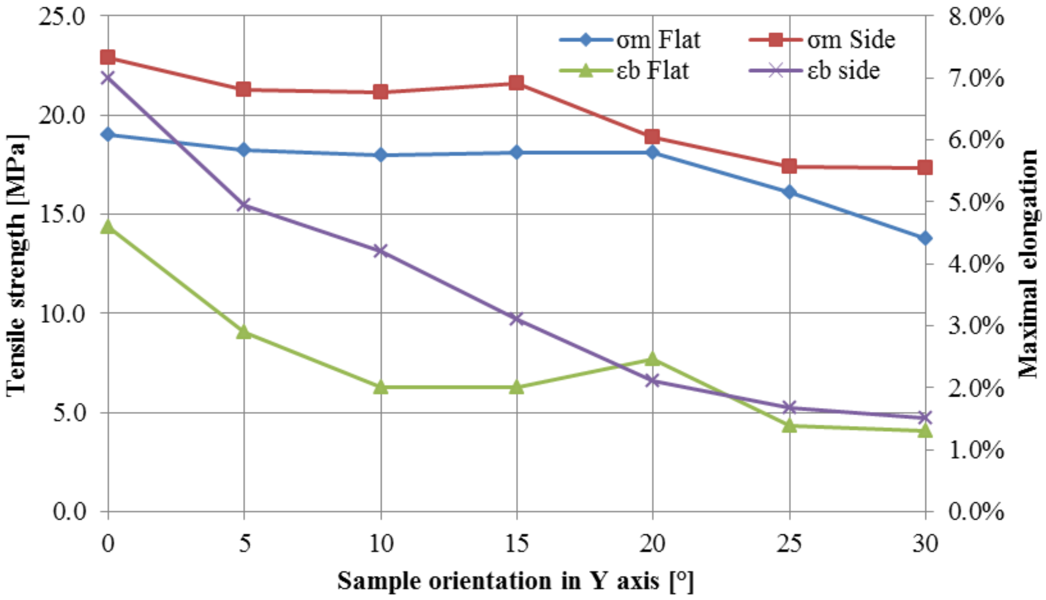

Fig. 5. Tensile strength and maximal elongation in the critical orientation range

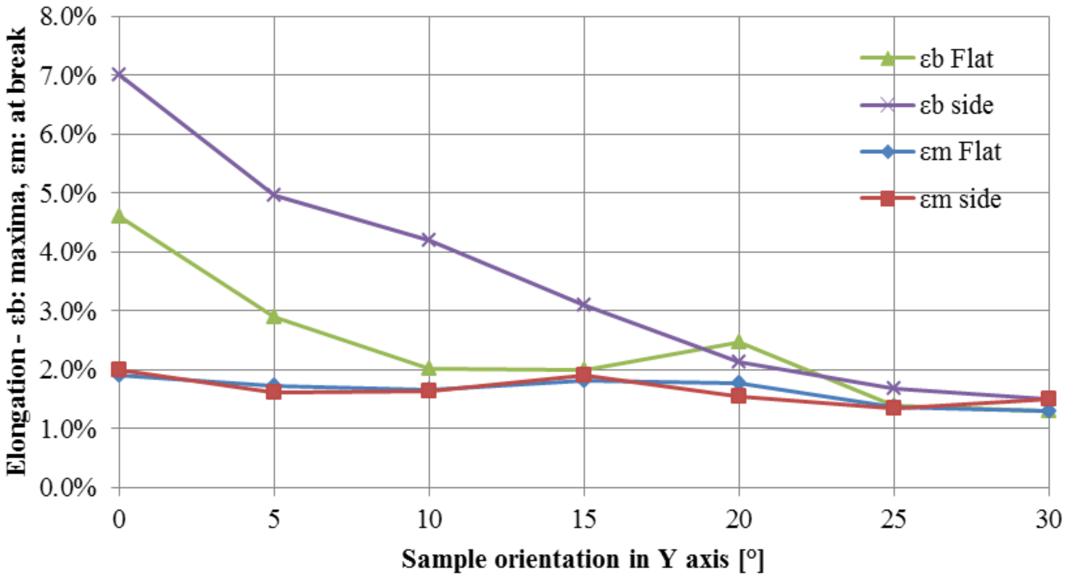

Fig. 6. Maximal elongation and elongation at break in the critical orientation range

In the samples with the manufacturing orientation in Y axis higher than 25° (for both X orientations), no yield point is present – they behave as made out of a brittle material, the elongation at break is equal to elongation at maximal force and the measured elongation is very small (no more than 2%). In the tensile test, the Y orientation value is a value of angle between the loading force and the layer slicing plane, so it can be said that the higher the angle, the lower the strength. If this angle is a non-zero value, the applied force is carried not only by the material threads – a certain portion of the load is carried directly by layer bonds, which are very weak due to lack of material fusion between adjacent layers. Therefore, after a certain angle is reached, the layer bond maximal strength is reached faster than strength of the material itself. This causes a disjoint of the layers, macroscopically observed as a brittle fracture [12]. In the presented studies, value of this angle can be assumed as 20° for the Flat series and 25° for the Side series. It was assumed and confirmed by visual observation of the samples after tests, that if both elongation values are equal, the orientation value of a given sample is above the critical value and the behaviour is “brittle”. More tests are required around the “yield/brittle” area to determine the exact point, at which the transition occurs, but the critical orientation for the tensile tests can be assumed as 25°, which will be true for most cases.

After putting together all the tensile test results gathered so far, relation between orientation and tensile strength for the tested ABS samples was determined. It is presented as a diagram in Fig. 7. In the diagram, an attempt was made to determine an empirical equation for calculation of strength as a function of orientation in Y axis. The two obtained rough equations will be refined in further studies. In future works, the authors will also introduce more values of the X orientation, aiming at a single equation using the two orientations as a basis for the tensile strength calculation. It is necessary for preliminary strength determination in an automated FDM process optimization algorithm, which is also in progress by the authors [9].

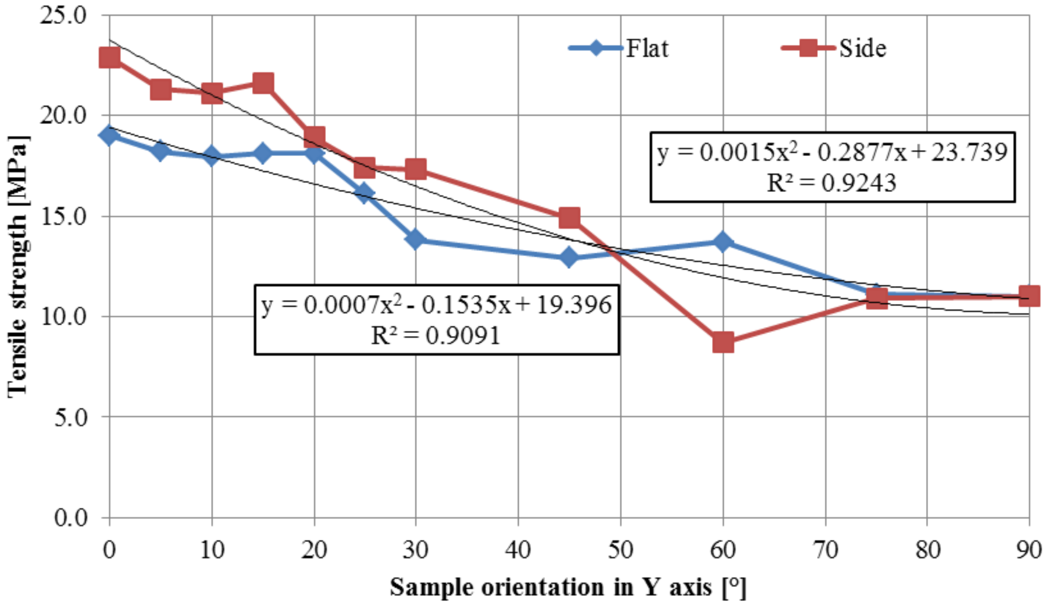

Fig. 7. Relation between sample orientation and tensile strength, with equations of trend lines

It is also worth noting, that the standard deviation values of recorded strength are changing, depending on the orientation. A general trend is that the standard deviation increases with the orientation. For the low values of orientation (more close to the typical flat or side orientation), tensile strength of the tested samples is more repeatable and predictable. For the "brittle" samples, value at which samples fail is more random.

4. CONCLUSIONS

The studies presented in the paper allowed to find out the orientation values, at which transition of one type of material behavior to another occurs – the critical orientation. The two methods of failure of the additively manufactured samples are by thread failure or by layer disjoint. Macroscopically, they are perceived as a ductile material with a yield point and a brittle material. It can be safely assumed, that the transition occurs around the angle of 25° for the tensile tests presented in the paper. It can be stated, that if difference between the load direction and the layer slicing plane is greater than the critical orientation value, the probability of part failure via layer disjoint is very high and the plastic deformation will be almost non-present, with the part presenting a brittle behavior. If said difference will be lower, the probability of failure via layer disjoint highly decreases and the plastic deformation increases, being the highest when the load direction lies in the layer slicing plane. It is noteworthy, that the maximal recorded strength value is more repeatable for the samples with the lowest orientation – the standard deviation value is highest for the "brittle" samples.

In general, the tensile strength and plastic properties of the ABS parts manufactured using the additive FDM process by layer deposition are much worse than properties of the same parts manufactured out of the same material using the injection mold process or other processes allowing to obtain monolithic parts with material fusion and no internal gaps or empty spaces – lack of solid bond between layers and threads and presence of internal volume errors are the main reasons for weak strength of polymer parts manufactured additively using the FDM process.

The results of the presented studies should be a help for engineers who plan to use additive manufacturing by the Fused Deposition Modelling method for parts which can be subjected to tensile loads. The rough estimation equations presented in Fig. 7 could allow to calculate strength of certain parts – they are not applicable to all the shapes, but can be a help to determine, for example, if some long and slim parts of certain products will fail under a specific load. In the same context, it can be also used to predict if the Fused Deposition Modelling manufacturing process will be carried out successfully – it is a frequent case (by the authors' experience) that certain long and slim parts manufactured in vertical orientation (such as the tensile test samples) fail to be manufactured, as their strength is so low, that they are destroyed during the manufacturing process. The determined relations can help to predict such a situation and avoid it.

Comparison of the strength and cost coefficient allows drawing an interesting conclusion – it is preferable to focus on economical effectiveness coefficients such as manufacturing time and costs, as the orientations which result in in lower number of layers (shorter manufacturing time) often allow obtaining better strength. Still, this is true only for simple geometries. For more advanced shapes it can be true only for selected areas of such shapes, such as assembly elements, allowing consideration of various manufacturing strategies, for example by dividing a complex part into sub-parts and manufacturing them separately, with beneficial orientations, and then assembling together. More studies are required on this matter.

In the future, a set of detailed guidelines will be formulated for the additive manufacturing process engineers on how to select a proper orientation knowing the purpose and probable load of the manufactured part. The authors plan to develop an automated algorithm for optimization of process parameters (focusing on orientation) for a selected part to fulfill certain criteria, including strength. Full, verified, empirically obtained equations – relations between strength and orientation values – will play a large role in this algorithm, as they will be used for pre-selection of groups of parameter values. The future studies will consist in producing more ABS samples, to find out the more exact values of critical orientation, also for different loads. The authors also plan to test samples of other materials (e.g. PLA, often used in low-cost FDM machines) and different manufacturing systems, including the low-cost FDM machines.

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