Mechanical characteristics of short fiber composite samples located behind circle, rectangle, triangle obstacles

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Abstract. The article investigates the influence of the weld line on the mechanical characteristics of flat samples on tensile strength according to ISO-527-2, cut from a plate with an obstacle, molded from polyamide-6, reinforced from 30% short glass fibers. There are considered circular, rectangular, triangular obstacles. Melt front, weld line location and reinforcing fiber orientation are calculated in Moldex3D. The stiffness and strength of the samples were predicted in ANSYS using an anisotropic nonlinear composite material model obtained in the Digimat by reverse engineering method. The transversely isotropic criterion of Tsai Hill in the first pseudo-grain failure statement was used for predict strength. The paper presents the influence of the weld line on the stress, deformation and first pseudo-grain failure strength criterion. The greatest contribution to the samples mechanical characteristics was made by the rectangular obstacle.

1. Introduction

Injection technologies are used to produce large batches of spatially loaded products of complex shape. The addition of short fibers to binders significantly changes the mechanical characteristics of the material, allowing it to increase its stiffness [1, 2]. Short-reinforced composite materials can be used to create spatially-loaded structures of complex shape, for example, aerospace joints, as well for creation tips of lattice structures [3]. The flow of material inevitably leads to a change in the orientation of the reinforcing fibers. The stiffness and strength of composite materials is largely determined by the orientation of the reinforcing fibers, therefore, when designing products from short-reinforced composite materials, it is necessary to simulate all stages of their production [4]. Studies of the mechanical characteristics of composite material reinforced by short fibers are based on the work of Eshelby, who studied the elasticity of a field with an ellipsoidal particle [5-7]. Tandon and Weng based on Eshelby's theory determined the elasticity characteristics of a composite material reinforced by unidirectional short fibers [8]. The calculation of the characteristics of a composite material reinforced by short fibers with an arbitrary orientation tensor is presented in [9, 10]. Finite element modeling of microstructure of a representative volume is used for calculate the mechanical characteristics of the composite material reinforced by short fibers [11]. The study of the stiffness and strength of short-reinforced composites on temperature is presented in [12]. The weld lines are formed at molding products of complex topology in the case of combining flows after flowing around obstacles [13]. Weld lines, that occur when two mix flows are connected in the mold, influence the strength of the product in this area [14]. Takayama [15] investigate weld lines in samples from short fiber reinforced polypropylene and shows that weld strength tended to decrease as the fiber content increased. The study
[14] is devoted to studying the influence of the weld line when flowing around a triangular and rectangular obstacle on the mechanical material characteristics. A feature of [14] is the comparison of the mechanical characteristics of samples cut out behind an obstacle with samples located near the gate. The aim of the work is to compare the stiffness and strength of samples located on the weld line when flowing around circular, rectangular, triangular obstacles, with the stiffness and strength of samples located on the plate in the region of uniform flow far from the weld line along and across the molding direction.

2. Materials and research methods

The calculation of plate molding is carried out in the Moldex3D system. The size of the plate is 200x150x4 mm. The calculation was carried out on a mesh with solid elements obtained in ANSYS Meshing and transferred to Moldex3D by means Rhinoceros. The technique of mesh creation in ANSYS Meshing for Moldex3d presented in [16]. The meshes consists of 29...35 thousand hexagonal elements located in 8 layers (figure 1).

The plate material is polyamide-6 reinforced by 30% glass fibers – PA6 Armamid PA SV 30-1ETM (figure 2a). Melt temperature is 250 °C, mold temperature is 110 °C. Injection-molding machine is the Negri Bossi VE210-1700 with screw diameter 60 mm. Flow rate is 33 cm³·s⁻¹. Hexagonal elements and sweep meshing technique allow to increase calculation accuracy of fiber orientation along the plate thickness. An example of melt front calculation is shown in figure 2b. The values of the reinforcing fibers orientation tensor are calculated in Moldex3D and exported in the o2d file format, supplemented by mesh file in the cdb file format.

![Meshes on panes with obstacles](image)

Figure 1. Meshes on panes with obstacles: (a) circle (29 127 elements), (b) rectangle (29183 elements), (c) triangle (35 759 elements).
We study the influence of the weld line based on the estimation of the stiffness and strength of material samples cut from a plate according to ISO 527-2 [17] (figure 3a), numbered as shown in figures 3b-d. The samples location on the plates is shown in figure 3.

![Molding calculation in Moldex3D](image)

**Figure 2.** Molding calculation in Moldex3D: (a) material model, (b) melt front in plane with circular obstacle.

![Samples on the plates](image)

**Figure 3.** Samples on the plates: (a) ISO 527-2 type I BA sample; plates with obstacle: (b) circle, (c) rectangle, (d) triangle.
Using the Digimat MAP, the components of the fiber orientation tensor are transferred from the hydrodynamic calculation mesh to the stress-strain state calculation mesh (figure 4). The mesh for calculating the stress-strain state can include not all the entire molding area, that way simulating the process of cutting products and removing technological elements of the half-finished product (figure 4a). The mesh for calculating the stress-strain state of ISO 527-2 tensile specimens is structured and consists of 2550 hexagonal elements. The fibers orientation data on the mesh for calculating the stress-strain state are obtained from the fibers orientation data calculated on the Moldex3D mesh by interpolation (figure 4b).

![Figure 4: Transferring the orientation tensor values from the molding calculation mesh to the static structural mesh using Digimat MAP. Example of plate with circle obstacle, sample 1.](image)

For the static structural calculation, an anisotropic material model is used, previously obtained in Digimat MX by reverse engineering, so that the properties of the composite as a whole correspond to the experimentally obtained dependences of stresses on strains for the images cut at an angle of 0°, 45° and 90° to the flow direction in without obstacle. The material consists of two phases – 30% mass fraction of linearly elastic glass fibers with density 2600 kg·m⁻³, Young modulus 74 GPa, Poisson's ratio 0.22, fiber aspect ratio is 10.888 and 70% mass fraction of J2_plasticity polyamide binder model with density 1400 kg·m⁻³, Young modulus 2.82 MPa, Poisson’s ratio 0.36726, yield stress 25 MPa, power law of hardening model with 122 MPa hardening modulus and 0.396 hardening exponent. For failure prediction Tsai Hill 3D transversely isotropic model with first pseudo-grain failure (FPGF PGA) formulation was used. The representative volume cell was divided into 12 pseudo-grains, and destruction occurred when 75% of all pseudo-grains were destroyed. Axial tensile strength limit is 155.66 MPa, in-plane tensile strength limit is 57.385 MPa, transverse shear strength limit is 44.644 MPa.

3. Results and discussion
Using the melt flow calculation in Moldex3D, we investigated the distribution of the melt front isoline (volume share), the size and location of the weld line, and obtained the orientation tensor of the reinforcing fibers at each point of the plate (figure 5). Weld line at figure 5 is defined as the line where meeting angle between two melt fronts is in the range from 0° to 135° (0° corresponds to head-on converge of two melt fronts).
The fibers behind the obstacle (figure 6) have more random orientation, while the fibers in the external flow are mainly orient in the flow direction, with the exception of fibers in the center of the plate thickness and in the wall region, which is in accordance with the results of work [18].

**Figure 5.** Melt front isoline (volume share) and weld lines on panes with obstacles: (a) circle, (b) rectangle, (c) triangle.

**Figure 6.** Fiber orientation on panes with circle obstacles – vector is the predominant direction of the fiber, color is the probability of fiber orientation in this direction.
Samples cut from plates are loaded by tension by fixed support of one of the ends and force condition to the other end (figure 7a). Calculated samples tension, where stress of samples is force divided by area of cross section (20 mm²), strain is differences between sample working area deformation divided by length of this area (30 mm) (figure 7b) shown in figure 8.

![Figure 7. Stain-stress task: (a) loading scheme, (b) average strain calculation.](image)

![Figure 8. Samples tension calculation (1 – blue solid, 2 – rad dash, 3 – black dot) on a plate with an obstacle: (a) circle, (b) rectangle, (c) triangle.](image)
End of lines indicate the fracture samples beginning – first time when maximum value of FPGF criterion become equal to one. In sample 3 (along flow direction), the fibers are oriented mainly along the sample, in sample 2 - mainly perpendicular to the direction of the sample. The fibers in the sample 1, located after the weld line, are oriented more randomly than in sample 2, so its stiffness is slightly higher than the stiffness of sample 2, but significantly lower than the stiffness of sample 3.

Stress and deformation fields at tensile samples with a force of 800 N are shown at figure 9. Stress field of samples 2 and 3 correspond to the fiber orientation layers, shown at figure 6 and correspond to the results of work [18] – the most stressed regions in the perpendicular sample 2 are near the plate surface and in the center of the thickness, while the most stressed regions in sample 3 are located in the middle layers of the plate — the places where the fibers are most likely to be located along the flow. Violation of the fibers orientation field in the weld line after the obstacle lead to a stress field in the sample 1 shown in the figure 9a.

The stiffness of the longitudinal sample 3 is significantly higher than the stiffness of the transverse samples 1 and 2, which is reflected in smaller total deformations of the sample 3 (figure 9f). The unevenness of the stress-strain state of the specimen 1, containing the weld line, leads to its bending under tension (figure 9b).

![Stress and deformation fields](image)

**Figure 9.** Results of stress-strain analysis (samples on a plate with a circular obstacle): (a), (b) sample 1; (c), (d) sample 2; (e), (f) sample 3; (a), (c), (e) equivalent (von Mises) stress, MPa; (b), (d), (f) total deformation, mm.

The distributions of the Tsai Hill criterion in a transversely isotropic formulation using the model of the first pseudo-grain failure at ultimate load are presented in figure 10. The sample 1 failure begins from weld line location. The sample 2 does not contain a weld line and its failure can begin evenly over its entire working area. The longitudinal sample 3 failure begins near the extension location.
4. Conclusion
The influence of the weld line on the stress-strain state of short fiber reinforced composite material samples was investigated. Samples containing the weld line are slightly stiffer than samples cut across the molding of plate in a place that does not contain the weld line. The contribution of weld line to the samples stiffness is less than the change in the sample orientation with respect to the molding direction of the plate. The greatest contribution to the samples mechanical characteristics was made by the rectangular obstacle. Using an anisotropic model of short fibers reinforced composite material allows to take into account the influence of the weld line on the mechanical characteristics of thermoplastics products.

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