Determination of critical filament length for composites fabricated using additive technologies

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Abstract. The paper shows the results of an experimental-theoretical study aimed at investigating the adhesive properties of the filament-matrix interface. The characteristic fields of strain when pulling a single filament from the matrix are shown. The filament length at which the load reaches a "plateau" is experimentally determined. According to this effect, it is possible to estimate the value of the critical filament length for a certain material, at which a local fiber break in the matrix does not affect the strength of the entire structure.

1 Introduction

When designing composite structures, it should be taken into account that the material and the product are created simultaneously. Application of traditional composite technologies such as, for example, vacuum infusion and contact molding practically does not limit the complexity of the product shape, i.e. it is possible to produce a part with complex surface curvature, variable thickness and other changes in geometric dimensions. But it is impossible to change the structure of the material: the above technologies use fabrics or prepirgs in which the number and arrangement of fibers are predetermined. From the technological point of view it is good - the fabric material is easy to pack into bobbins or sheets, and the properties of the material are known from the beginning. However, when manufacturing composite structural elements, the greatest interest is in the laying of continuous fibers along the lines of the highest stresses, i.e. curvilinear reinforcement. Recently appeared 3D printers with the possibility of reinforcing plastic with continuous fibers in the printing process allow to create optimal constructions with complex structure, in which local heterogeneity and anisotropy of fiber composites properties are used most effectively.

The authors set the task, with respect to printed fiber-reinforced plastics, to study the influence of the length I of the filament embedment (Fig. 1) on the adhesion characteristics of the filament-plastic joint. The data for fiber composites fabricated by conventional methods is available [1, 2], but there are not many results for materials fabricated using additive technologies. Moreover, they all differ depending on the type of 3D printer, printing settings, materials, etc. This is the reason for the relevance of the present study.

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Since not the monofibers themselves, but filaments consisting of thousands of monofibers are used in the production of real composite structures, the further research will be related to them.

2 Effective filament length

The problem of determining adhesive strength in fibrous composites has been known for a long time. There are many models describing the mechanisms of fracture and strength realization in the fiber-matrix interface. Also known is the concept of effective fiber length $L_e$. Two types of stresses are applied to a continuous long fiber placed in a matrix under uniaxial tension: normal stresses - inside the fiber - and shear stresses - along the fiber-matrix interface. In the case of transverse fiber rupture (according to Rosen [3]), the normal stresses at the defect location are equal to zero, and only shear stresses occurring at the interface act on the fiber. Moreover, the value of these stresses gradually grows, reaching a constant (unperturbed) value at some distance from the place of rupture. Most often, the effective fiber length is understood as just the distance along the fiber from the transverse rupture site, at which the fiber "remembers" its defect; beyond this site, the fiber behaves as unruptured.

In this study, the authors depart slightly from the standard theory primarily because they consider a filament rather than a single cylindrical fiber. Therefore, the concept of effective filament length will be defined differently.

According to the simplest adhesion model, it is assumed that the strength of the fiber (filament)-matrix interface is a constant of the material and is determined by the ratio:

$$\tau^* = \frac{P}{S}$$

(1)

Where $P$ is the ultimate tensile load, $S$ is the side surface area of the filament.

Then it can be assumed that the load values $P$ will be small at low values of $l$. At the same time, an increase in length $l$ will lead to an increase to some value $P^*$, when the maximum possible adhesive strength is realized.

Thus, the effective (critical) length of the filament $l^*$ is the minimum value of $l$, at which the maximum possible adhesive properties are fully realized. If the filament length is less than the critical length, the maximum load along the filament decreases.

Two failure mechanisms can then be realized: in the ideal case, as the length $l$ of the filament embedding increases, the load will increase up to the strength of the filament itself. If the adhesive strength is higher than the strength of the filament, it will break, if it is lower, the filament will be pulled out of the polymer matrix. Fig. 2 shows the typical dependence of load on displacement when pulling out the filament for specimens with different bundle lengths placed in the polymer matrix. The graphs also show that the realization of the second fracture mechanism - pulling out the filament - is accompanied by overcoming the friction force, which decreases as the contact area gets smaller.
3 Problem formulation

Determination of the effective length consists in experimentally finding the length of the carbon filament located in the plastic matrix at which the tensile (Fig. 1) load is stabilized. Adhesive bonding occurs at the fiber-matrix interface, in our case carbon filament-PLA plastic. The surface area of the bond is characterized by the embedment length $l$ and the filament diameter $d$ (Fig. 1): $S=\pi dl$. When the specimens are fractured, the force $P$ required to pull the filament out of the matrix is measured, i.e., the shear adhesion strength is determined (Fig. 3). The adhesion strength for each specimen is calculated using formula (1).
Fig. 3. The dependence of adhesive strength on filament length.

The strength determined using this formula is idealized because the cross-section of the filament often deviates quite strongly from a circle (Fig. 4). To strictly adhere to this relationship, and consequently to obtain an "unconditional" value of $\tau$, it is necessary that:
1) the cross-section of the filament was circular;
2) the diameter of the filament section embedded in the matrix was constant;
3) the filament is uniformly (without breaking the continuity) covered with polymer;
4) the apparent and true contact areas of the filament and polymer were the same;
5) the shear stresses at the interface between the binder and the filament were equally distributed.

Fig. 4. The cross section of a glass filament used for 3D printing.

Since it is impossible to fulfill all these conditions simultaneously, the pattern observed in the experiment (Fig. 5) shows the decrease of the ultimate stresses with increasing length $l$ of the filament embedded in the matrix.
Fig. 5. Dependence of adhesion strength on filament-matrix contact area for epoxy resin and glass fiber.

The value of the effective filament length was also determined experimentally using modern methods of recording displacement fields. The picture of strain field distribution along the embedment length is the main source of information for analysing the stress-strain state during filament pulling. According to the objectives of the work, the strain distribution patterns were obtained for specimens with different lengths of filament embedment. The analysis of these patterns allowed us to obtain the effective length, i.e. the length of the filament embedment, below which the adhesive strength of the interface is realized ineffectively.

4 Making specimens and testing

To solve the task, the specimens (Fig. 1) of the same geometry but with different filling were prepared: the length of the filament embedment \( l \) was varied. The specimens were printed on the ANISOPRINT COMPOSER A3 printer using PLA plastic and carbon filament. The filament itself consists of fibers with a diameter of 6-10 µm, i.e. there can be up to 1000 fibers in a 320 µm diameter filament.

The tests were conducted on the INSTRON 34 TM electromechanical testing machine. The tests were considered to be completed after the specimen had completely lost its load carrying capacity. The principle load-displacement diagram is shown on Fig. 2.

During the loading process, displacements were recorded using the Vic 3D digital image correlation method to obtain the picture of displacements and strains in the filament embedment zone.

Fig. 6 shows the strain fields at maximum load for specimens with filament embedment at different lengths. It can be seen that the maximum strains are at some distance from the edge, which is well confirmed by the theory.
 Results and discussion

As the result of the experiments, the dependence of critical force and maximum shear (adhesive) stresses for specimens with different filament embedment lengths is shown in Table 1.

Table 1. Test results.

<table>
<thead>
<tr>
<th>l, mm</th>
<th>Max. Force, N</th>
<th>S, mm²</th>
<th>Max. Shear stress, MPa</th>
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<tr>
<td>3</td>
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<td>3.01</td>
<td>36.16</td>
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<tr>
<td>5</td>
<td>116</td>
<td>5.02</td>
<td>23.09</td>
</tr>
<tr>
<td>10</td>
<td>127</td>
<td>10.05</td>
<td>12.61</td>
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<tr>
<td>15</td>
<td>135</td>
<td>15.07</td>
<td>8.96</td>
</tr>
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<td>20</td>
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<tr>
<td>30</td>
<td>170</td>
<td>30.14</td>
<td>5.64</td>
</tr>
</tbody>
</table>

Fig. 7 shows the distribution of longitudinal strains in the specimen along the length of the embedded filament as it is pulled out, from which the critical (effective) length can be determined.
Fig. 7. Displacement of the zone of strain concentration along the length of the filament as it is pulled out in the process of loading: a – 43 N, b – 58 N, c – 76 N, d – 112 N.

6 Conclusions

It was found that the character of stress distribution during filament pulling from plastic obtained by 3D printing is the same as for traditional polymer composites. The maximum adhesion stresses for carbon filament-plastic PLA materials are at 36 MPa. The effective filament length for the investigated materials is equal to 20 mm. The effective length of the filament must necessarily depend on its diameter. Since 3D printers have the ability to widely vary printing parameters, including fiber diameter, it is necessary to conduct similar studies for all sizes of filaments used.

References

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