Features of accounting machining process influence on fiber reinforced composites characteristics

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Abstract. The results of the experimental study of machining effect on the fiberglass specimens' tensile strength realization are presented. According to the data obtained, the size of the damaged zone, which does not carry applied loads and reduces the actual net cross-section of the specimen, has been estimated.

1. Damaged zone thickness estimation method for machined FRP composite specimens

Fibrous composite materials have a heterogeneous structure where strong and brittle fibers, which are easily damaged during machining, play a major bearing role. The damage may not be visible, but if for metals machining process leads to local hardening and microplastic deformations that have little effect on strength, then for glass and carbon plastics machining damage can have a significant negative effect [1]. Due to this fact machining on the thickness of composite plates is not allowed, and the technology and cutting modes of linear specimens have been carefully worked out.

The need to cut composite materials along curved trajectories required the acquisition and adjustment of a modern, imported CNC 6040Z milling machine, which allows you to direct the cutting tool along any trajectory, and not only straight.

1.1 Setting the task

When working out cutting modes, several questions arise: How does cutting technology affect the damage of material near the cutting line? How can we estimate the thickness of damaged layer of material that actually goes out of bearing part of specimen?

To answer these questions, at the first stage, it was decided to test strip specimens (figure 1.1) with different widths cut out using a single technology for stretching. This made it possible to estimate the width of the damaged zone - the "edge," which is formally the part of the cross section of the specimen but does not bear any load. It is considered that in a strip specimen cut from the plate with a width of \( b \) and a length of \( L \) the width of damaged zone \( \delta \) (figure 1.1) remains constant.

It should be noted that the width of the "edge" must be constant for a given size and type of cutting tool, as well as for fixed cutting modes (rotation and feed speed). Therefore, with an increase of the size of the structure (specimen width), the relative width of the damaged edge and its effect on strength should be reduced.

At the same time, changing the diameter of the cutting tool leads to change of size of the damaged zone. A larger diameter cutter will damage the specimen more heavily, while the effect of smaller
diameter cutters should not greatly affect the resulting strength values. A great result would be to get a clear dependence of size of the damaged zone on the size of the tool used which is relevant for all types of cutters.

![Figure 1.1. The damaged zone of specimen after machining process.](image)

To estimate the width of the damaged "edge" the research has been carried out at the Mechanical Engineering Research Institute of the Russian Academy of Sciences. Several series of specimens of various widths have been produced and tested with different size of tool and constant cutting modes.

1.2 Specimen fabrication and testing

Since the tests have been comparative and finding exact values of material characteristics has not been the main goal, a separate test procedure has been developed that is different from used standards. The fiberglass plate with the thickness of \( h = 2 \) mm has been made with the vacuum infusion technology. The plate has been molded from 6 layers of glass fabric with a weave type of "web" and [0/90] lay-up.

Specimens with the length of 250 mm with different widths have been cut from a plate on the CNC milling machine using a corn cutter tool (figure 1.2) with a diameter of 1 mm and 1.5 mm. Horizontal feed rate: 250 mm·min\(^{-1}\), inverter current frequency: 160 Hz. The cutting mode for all specimens has not changed.

![Figure 1.2. Corn type cutter tool.](image)

For the test implementation with 1.5 mm cutter tool 7 series of three specimens with different widths have been made: 2.5; 3; 4; 5; 7.5; 10 and 30 mm. Series number \( i = 1, 2, ..., 7 \). And with 1 mm cutter tool 5 series of three specimens have been made: 2.5; 5; 7.5; 10 and 40 mm. Series number \( j = 1, 2, ..., 5 \).

The specimens have been tensile tested on the universal electromechanical test machine INSTRON 6025 in self-tightening grips. All specimens have collapsed in the working area, which indicates the correctness of the test results.

1.3 Test results

According to the obtained experimental data, the dependence of strength of the specimen on its width has been built. Figure 1.3 shows that for 1.5 mm tool when the width of the specimen increases to 10
mm, the conditional critical stresses increase sharply, and then they go to the "plateau" with a value of about 400 MPa. This behavior of the diagram shows a strong effect of the damaged zone on the conditional strength of small-width specimens and a much smaller effect for wider ones. A similar situation can be traced for a mill with the diameter of 1 mm. Since the diameter of the cutter has decreased, the damaged zone practically does not affect the strength of the specimens at a width of 7.5 mm, while for wider specimens the strength also reaches about 400 MPa, which indicates a very little influence of the tool.

To estimate the width of the damaged zone, we use simple formulas for conditional and real ("true") strength.

Conditional strength (critical load to full cross section):

\[
\sigma_{i,j}^{\text{eff}} = \frac{F_{i,j}}{b_{i,j} \cdot h}
\]  

Real strength from test (load to unknown net cross section):

\[
\sigma_{i,j}^{\text{real}} = \frac{F_{i,j}}{b_{i,j}' \cdot h}
\]  

where \(b_{i,j}' = b_{i,j} - 2\delta\) — is the effective (actually resisting applied force) width.

For approximate calculations, the maximum value of the conditional strength of this material can be used as the real ("true") strength. On the basis of the diagram (figure 1.3), the "true" strength has been taken as the value of the conditional strength obtained on specimens with the width of 30 mm since at this width the damaged zone no longer has a significant impact on the implementation of the strength.

\[\text{Figure 1.3. Conditional strength on specimen width dependence. 1 – 1 mm cutter tool; 2 – 1.5 mm cutter tool.}\]
Changing $\sigma_{i,j}^{\text{opt}}$ to $\sigma^* = \sigma_7^{\text{eff}} = \sigma_5^{\text{eff}} = 402 \text{MPa}$ in (2) (indexes «7» and «5» mean the width of specimens $b_7 = 30 \text{ mm}$ and $b_5 = 40 \text{ mm}$) we estimate from the experimental values of the critical load $F_{i,j}$ the width of the damage zone $\delta$, which turns out to be slightly different for specimens of different widths:

$$\sigma^* = \frac{F_{i,j}}{b_{i,j} \cdot h} \quad (3)$$

$$\delta = \frac{1}{2} \left( b_{i,j} - \frac{F_{i,j}}{\sigma^* \cdot h} \right) \quad (4)$$

The results of the evaluation according to the formula (4) of the size of the "edge" for specimens of different widths ($i = 1...5$ and $j=1...3$), taking into account the spread, are given in figure 1.4. The initial assumption that the width of the damaged zone should not depend on the width of the specimen was not confirmed, instead, the results showed a linear dependence. The main reason for this can be the effect on the strength of the specimen of a much larger number of factors in addition to the type and size of the tool, as well as machining modes. In this regard, it is difficult to talk about an accurate determination of the size of the damaged zone. However, the average value has been used for practical evaluation of the effect of machining on the strength of the material in both series. As shown in figure 1.4, for a 1.5 mm diameter cutter, the delta is 0.24 mm and for a 1 mm cutter 0.17 mm, which in both cases is about a sixth of the tool diameter.

![Figure 1.4. Damaged zone size estimation. 1 – 1 mm cutter tool; 2 – 1.5 mm cutter tool; 3 – average for series 1; 4 – average for series 2.](image-url)
1.4 Results of chapter 1

1. The showed method can become the basis for estimating the effective width of the damaged zone when cutting composite parts. For the given data, $\delta_{1.5} \approx 0.24$ mm and $\delta_1 \approx 0.17$ mm, which is about a sixth part of the diameter of the cutting tool.

2. Strictly speaking, obtained values correspond only to the tool size and type used in the experiments at the selected horizontal feed rate and rotation speed. When changing the tool type and cutting modes, the effective width of the damage zone may be different.

3. The nominal size of the damaged zone is small and can be ignored for big parts, but making small parts from fibrous composites, the effect of damaged zone should be taken into account.

2. The scale effect of strength in composite specimens with hole

Strength properties of structural elements made of polymer fibrous composites are closely associated with the scale effect. It is well known that multiple scaling of a structural element or a specimen leads to reduction in limit stresses. Because of this feature of composite materials scale modeling and the creation of small-sized models of composite structures for testing are very difficult.

The article is devoted to the analysis of dependence of the size of specimen on the scale effect rate. The presence of stress concentrators in composite parts, such as holes, increases the scale effect - the larger the specimen with the hole, the more bearing fibers are turned off in cross section. It is therefore obvious that in anisotropic fibrous composites the constant ratio $d/b$ (figure 2.1) will not guarantee the same strength in specimens of different size precisely due to the scale effect. In order to verify this assumption, the experimental part of the work has been built. The research has been carried out at the Mechanical Engineering Research Institute of the Russian Academy of Sciences.

![Figure 2.1](image1.png)

**Figure 2.1.** Composite specimen with hole during the tensile test.

![Figure 2.2](image2.png)

**Figure 2.2.** Vacuum infusion principle diagram. 1 - vacuum pump, 2 - resin trap, 3 - composite bag, 4 - degassed binder, 5 - vacuum pipeline.

2.1 Specimen fabrication and testing

The specimens with length of 250 mm and different widths have been produced for tests (table 2.1). The ratio $d/b = 0.1$ has been constant for all dimensions. Holes have been drilled.
Table 2.1. Specimen size and hole diameter.

| Specimen width (mm) | Hole diameter (mm) |
|---------------------|-------------------|
| 5                   | 0.5               |
| 10                  | 1                 |
| 15                  | 1.5               |
| 20                  | 2                 |
| 25                  | 2.5               |
| 30                  | 3                 |

Strip specimens have been cut from a 2.5 mm thick fiberglass plate produced by vacuum infusion method (figure 2.2). The plate consisted of 8 layers of fabric with [0/90] lay-up.

Strip specimens with and without holes have been tensile tested on the universal electromechanical test machine INSTRON 6025 machine in self-tightening grips. All specimens failed in the working area so the test results are correct. The results obtained for the hole specimens have been compared with the results obtained on the reference specimens without holes.

2.2 Processing of test results
As it was expected, specimens with holes showed lower net stress limits than solid specimens (figure 2.3). Moreover, with the increase of the size (width) of specimen, the hole effect is more noticeable, which means the smallest limit stresses has been shown by the widest specimens with big holes.

The strength reduction factor based on the obtained data has been calculated for each width value:

\[
K_{\sigma} = \frac{\sigma^*_0}{\sigma^*_n}
\]

where \(\sigma^*_0, \sigma^*_n\) – stress limits of solid specimen and similar specimen with hole. After that, the dependence of the coefficient on the width of the specimen has been built (figure 2.4).

![Figure 2.3. Specimen stress limit on width dependence. 1 – specimens without hole; 2 – specimens with hole](image-url)
It is also interesting to note that limit stresses increase with increasing width of solid specimens. Most likely, this is due to the effect of damage from the tool during the machining process of specimens, which was described in chapter 1. At the same time, the results and their graphical representation are slightly different from those shown in figures 1.3 and 1.4. As noted in chapter 1, the size of the damaged zone and therefore its effect on the strength of the specimen are individual for each type of tool and processing modes. In this experiment the specimens have been cut on a vertical milling machine using a disk cutter made of fast-cutting steel, but the trend of strength increasing with the increase of specimen width is still relevant.

2.3 Results of chapter 2
1. Definitely the stress concentration factor for composite specimens with holes with the same ratio of hole diameter to width is not a constant so traditional equations for isotropic materials are not suitable.
2. As the diameter of the hole and the width of the specimen increase, the strength reduction factor (effective stress concentration factor) increases. The larger specimens are most affected by the hole.
3. Analyzing the slope of the strength reduction curve (figure 2.4) for wide specimens the authors should say that there should be a plateau which the strength of specimens with holes is approaching. The test results suggest that the maximum reduction in strength for wide specimens of orthogonal fiber-reinforced composites at the ratio of d/b=0.1 would be about 50%.

3. Conclusion
This paper presents data from the experimental study of the effect of various types of machining on the strength of parts (specimens) made of fibrous polymer composite materials: the results clearly describe the phenomenon of strength reduction in composite specimens with drilled holes and in milled specimens. Thus, the strength of the composite parts, in addition to the accuracy of the process of creating the material, is also affected by the machining process, which is undesirable, however, often mandatory when moulding products.
References

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