EFFECT OF THE IMPACT DAMAGE TO STRENGTH OF FIBROUS COMPOSITE

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Abstract

Contact strength of the GFRC was investigated theoretically and experimentally. The sizes of contact spot and indention of spherical and cylindrical body were defined by iterations repeating the procedure of finite element analysis. The use of the general and special criteria of destruction can give the sufficient information for the approximate prediction of kind of partial destructions in a material and the sizes of a zone of damage. Results of microscopic researches of a surface of a cut in a zone of impact confirm the described shape of destruction of fiberglass at impact with rather small energy.

1. Introduction

Usually the thin-walled composite materials are used in structure with in-plate loading, mainly at tension-compression. But there are possible other, non-desirable kinds of loading in operation. One of them is impact loading. At impact in a composite there can be all probable kinds of partial destructions [1- 9]. The main features of impact loading are cross-plate direction of load, stress concentration in a small region of surface, and load dynamic action. As a result, the strongly non-uniform dynamic stress distribution occurs in a zone of impact, and many shapes of full or partial destruction are possible.

Establishing of contact loading effect to strength of a long-fiber composite is first goal of this paper. For this the experimental investigation of contact strength at different kinds of loading should be performed. The results of this test can be used for description of composite destruction at impact using different conditions.

For composite materials impact damage is one of the most dangerous. Most full all set of possible damages can be seen on an example of the sandwich panel which has two hard layers and a supporting easy core. Damages of the hard layers are: 1) cracking or crushing of a matrix; 2) breaks of the fibers; 3) delaminating. Damages of a core are: 1) crushing; 2) cracks. Besides a serious kind of damage is also the debonding. All these kinds of damages cause more or less significant change of the static strength and its life time at influence of cyclic loading.

Present paper is focused to problems of estimation of sizes of damage at low-velocity impact and its influence to the strength of composite. Complete review of these problems can find out in [1, 2]. For an estimation of the stress state at impact the velocity of impact is very important.

If the time of impact is much more than period of the lowest natural form of oscillation, the impact can accept as low-velocity. It is shown [1] that at low- velocity impact the analysis of the stress state can be carried out as the decision of a static contact problem of the theory of elasticity. It is possible to assume that such analysis suits also at medium-velocity impact, if to be limited to the analysis in a small zone with boundary conditions at its edges, corresponding not loaded condition. Using this approach elastic analysis of the stress state at impact was performed in [10-12]. The dimensionless

functions for impact force, tensor of stress, some equivalent stresses and specific energy of elastic deformation were obtained by FEA for typical anisotropic composite.
The analysis of the stress state in a zone of impact allows obtaining some qualitative judgments and quantitative estimations of character and the sizes of a zone of impact damage.
Now there are no enough reliable general dynamic criteria of destruction of composites. Therefore for reception of some representation about types and extents of areas of impact damage the static criteria are used often [1, 2, 8]. Usually the criterion based on the distortion energy is preferred. It seems that use of classical static criteria of destruction at impact should give satisfactory results for plastic materials. In this case some function of deformations, in particular, the distortion energy can define limiting impact damage. However, if the composite is brittle or contains brittle components the situation when impact damage grows as multi site damage will be typical, with formation of waves of destruction [5]. There are quickly proceeding processes or crushing of a brittle matrix, or plural breaks of brittle fibers. Thus the particles formed at crushing, will be that more finely, than above concentration specific energy of deformation.
The problem of creation of some quantitative criterion of quickly proceeding process of destruction of brittle components of a composite was discussed in article [11]. The question on the qualitative description of process of destruction and an estimation of the probable sizes of a zone of the damaged material on the basis of the elastic analysis is discussed only.
As defining characteristics of the stress state are used natural invariants of the stress state: equivalent pressure of the Tresca and Von Mizes, the hydrostatic pressure, and also specific potential energy of elastic deformation.

2. The contact strength: tests results

The glass fiber reinforced composite was selected for the experimental investigation of contact strength. It was the semi-finished product of the germane firm R&D Composite Technology: GRP sheets of E glass fabric and epoxy resin, thickness 2.5 mm, length 350 mm, width 150 mm (weight approx. 257 g), fiber bidirectional orientation 0°/90° , 43% fiber volume fraction. Standard properties of this product:
Tensile strength, MPa…….330-400

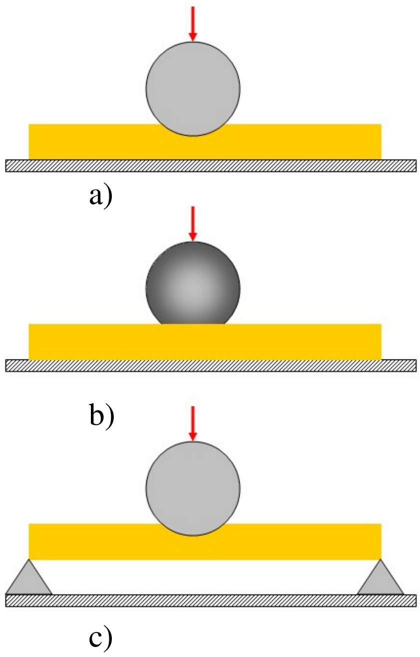


Figure 1. Contact loading of the GFR plate by cylindrical (a), spherical (b) indenter, and bending (c)

Tensile modulus, GPA…….19…21
Compressive strength, MPa…….310…440
Tensile strength obtained in special test is equal to 425 MPa.
Three versions of a contact static loading were done (Figure 1). In first two cases the 10 mm width specimen was placed to rigid (hard steel) surface and statically loaded by cylindrical (Figure 1,a) and spherical (Figure 1,b) hard steel indenter. In first case the initial theoretical contact was along a line, and in second one – in a point.
The 3, 6, 8, 10, and 45 mm diameter cylindrical indenters were applied. The full dynamic destruction of a sample with the fast flying to two bits was observed at the using of 3, 6, 8, 10 mm diameter cylindrical indenters (Figure 2) . Destruction initiation starts from the contact surface outer boundary and develops to a line on

opposite surface in the plane of symmetry.

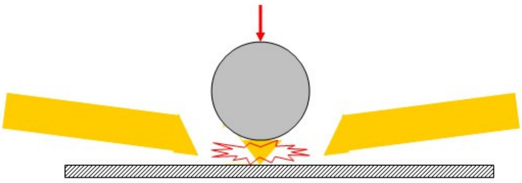


Figure 2. Typical shape of the full destruction of a sample at contact loading by a cylindrical indenter

Mainly the fast destruction develops symmetrically and, as a result, the wedge-like small peace produces (Figure 3). Maximum load (contact strength) monotonically increases with diameter increasing from 10 kN at 5mm diameter to 28 kN at 45mm diameter. At 45mm diameter the material bearing and crushing was observed with relatively slow development of the final phase of destruction.

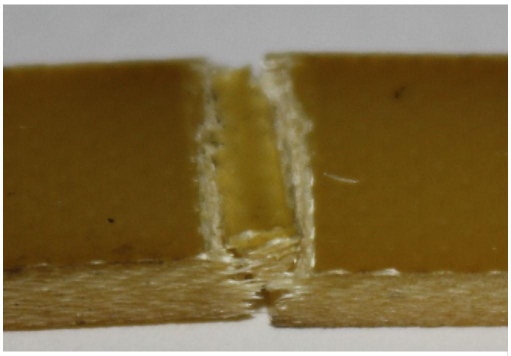


Figure 3. Composite sample destruction at contact loading by a cylindrical indenter (8mm)

At static loading by a spherical indenter the load stably increases to some maximal limit with relatively small indention, and then, the unstable slow indention process develops without of load increasing. The spherical crater through all thickness of a sample develops (Figure 4). During this process a material crushes under indenter and the low strength substance is formed. The particles size of crushed material is the smallest in a center of crater and there the material easy can be dispersed to powder (Figure 5). There is full destruction both the fibers and matrix in this zone.
Maximum load (contact strength) also depends from a diameter of indenter, and is equal to 20 kN at 5mm diameter, and 50 kN at 25mm diameter.
In the contrast with loading by a cylindrical indenter the full destruction of a sample was not be observed. Thus this case of loading can induce only partial damage.

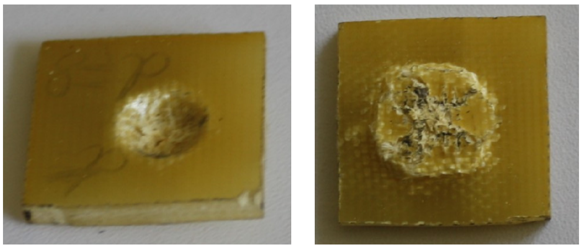


Figure 4. Both sides of a sample with contact destruction at loading by a spherical indenter (8mm)

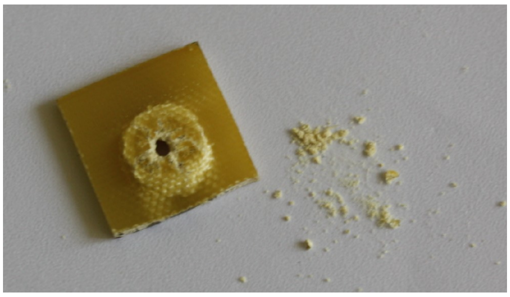


Figure 5. Full destruction of the fibers and matrix in the center of a crater

If the contact loading is combined with bending (Figure 1,c), then the effect of contact damage is not significant. There is observed the destruction typical for bending and independent from the type of an indenter (Figure 6). The strength at bending for this composite is on 30-40% more than tensile strength.

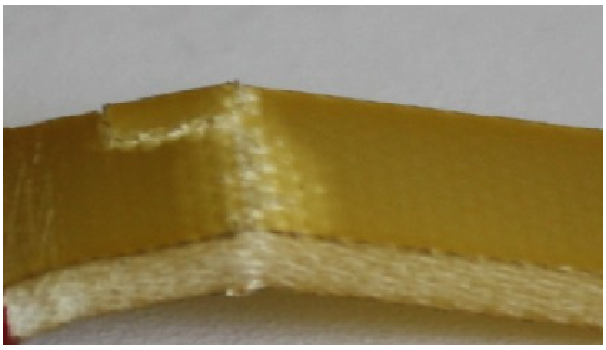


Figure 6. The shape of destruction at bending

3. Finite element analysis of the contact problem

Two kinds of contact problem of a composite plate were analyzed.

3.1. Rotation-symmetrical contact: description of a problem

The round plate in radius R and by thickness t from a transversal-isotropic material with elastic constants E_r, E_t, E_z, υ, G is considered. The plane of isotropy coincides with a median plane of a plate. Some absolutely rigid body with weight m makes direct impact (perpendicularly surfaces of the plate) with a velocity V at the moment of a contact. It is supposed that the external surface of hard impactor is spherical with radius R_m and is absolutely smooth (as well as a surface of a plate). It is supposed the low-velocity impact is realized. Two types of axis-symmetric boundary conditions are considered:

1) Rotation-symmetrical loading. Vertical displacements on the bottom smooth surface of a plate are excluded (Figure 7)

The boundary conditions

$$\begin{cases} \sigma_n = \sigma_z = 0 \\ \tau_{rz} = 0 \end{cases}, \text{ if } r \geq R_c \text{, and } z=0 \qquad (1)$$

$$\begin{cases} u_n = u_z = f(r) \\ \tau_{rz} = 0 \end{cases}, \text{ if } r \leq R_c \text{, and } z=0 \qquad (2)$$

$$\begin{cases} u_n = u_z = 0 \\ \tau_{rz} = 0 \end{cases}, \text{ if } z=t \qquad (3)$$

where R_c is radius of a contact zone, t is a plate thickness,

$$f(r) = w_0 + w - R_m\left(1 - \sqrt{1 - \left(\frac{r}{R_m}\right)^2}\right), \qquad (4)$$

w is the size of indention to a plate, w_0 is a difference between the full displacement of a indenter center and the size of indention to a plate.

All others surfaces are free from external load and constrains.

2) Rotation-symmetrical bending.

In this case there are the same boundary conditions (1) and (2), but additionally

$$u_r = u_z = 0 \text{, if } r = R \qquad (5)$$

All others surfaces are free from external load and constrains.

In the first case the impact refers to compressing, and in the second – bending.

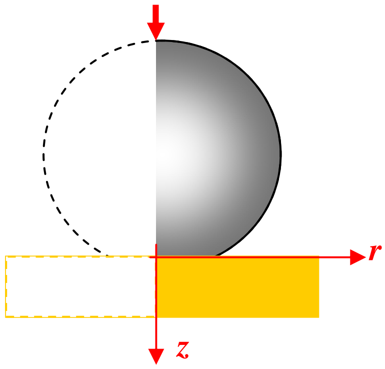


Figure 7. The scheme of contact loading by a spherical indenter

3.2. Plane strain contact: description of a problem

The infinite length plate of half width l and thickness t with the same elastic properties is considered.. Some absolutely rigid R_m radius cylinder contacts with a plate (it may be the low velocity impact) Two types of boundary conditions are considered:

1) The plate is supported by a bottom smooth rigid surface (Figure 8).

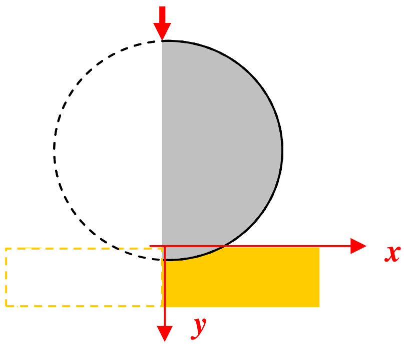


Figure 8. The scheme of contact loading by a spherical

The boundary conditions

$$\begin{cases} \sigma_n = \sigma_y = 0 \\ \tau_{xy} = 0 \end{cases}, \text{ if } x \ge x_c, \text{ and } y=0 \qquad (6)$$

$$\begin{cases} u_n = u_y = f(x) \\ \tau_{xy} = 0 \end{cases}, \text{ if } x \le x_c, \text{ and } y=0 \qquad (7)$$

$$\begin{cases} u_n = u_y = 0 \\ \tau_{xy} = 0 \end{cases}, \text{ if } y=t \qquad (8)$$

where x_c is half width of a contact zone, t is a plate thickness,

$$f(x) = w_0 + w - R_m\left(1-\sqrt{1-\left(\frac{x}{R_m}\right)^2}\right), \qquad (9)$$

w is the size of indention to a plate, w_0 is a difference between the full displacement of a indenter center and the size of indention to a plate.

All others surfaces are free from external load and constrains.

2) The plate is fixed along lateral sides.

In this case there are the same boundary conditions (6) and (7), but additionally

$$u_x = u_y = 0, \text{ if } y = \pm l \qquad (10)$$

All others surfaces are free from external load and constrains.

3.3. Some results of the FEA

The procedure of stress analysis is different from generally accepted. The size w of indention is controlled, but the common normal force on surface of contact is not known. Therefore, the iteration method was used.

1st step: At initial iteration the indention parameter w must be accepted.

2nd step: It uniquely defines the size of contact zone.

From (4)

$$f(r_c) - w_0 = w - R_m\left(1-\sqrt{1-\left(\frac{r_c}{R_m}\right)^2}\right) = 0$$

$$\Rightarrow r_c = R_m\sqrt{1-\left(1-\frac{w}{R_m}\right)^2} = 0$$

From (9)

$$f(x_c) - w_0 = w - R_m\left(1-\sqrt{1-\left(\frac{x_c}{R_m}\right)^2}\right) = 0$$

$$\Rightarrow x_c = R_m\sqrt{1-\left(1-\frac{w}{R_m}\right)^2} = 0$$

3rd step: For first iteration of the shift parameter w_0 should be solved the contact problem by FEM and defined distribution of the normal contact stress.

4th step: The conditions

$$\sigma_n = 0, \text{ if } r=R_c \text{ or } x=R_c \qquad (11)$$

must be checked.

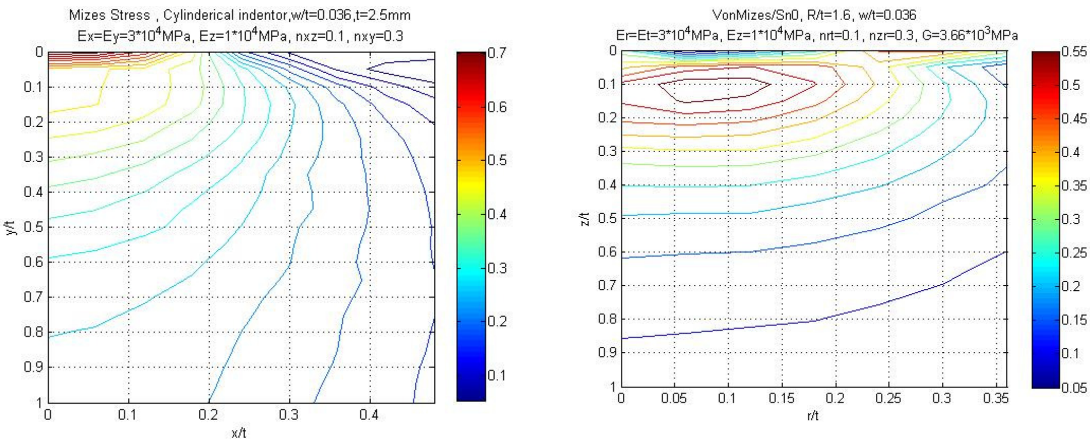
If $\sigma_n \ne 0$, the shift parameter w_0 must be corrected and started next iteration beginning from 3rd step.

Dimensional analysis allows planning rationally, in particular, numerical experiment by the FEM.

Following values of constants of the elasticity, corresponding one of the widespread types of fiberglass are accepted:

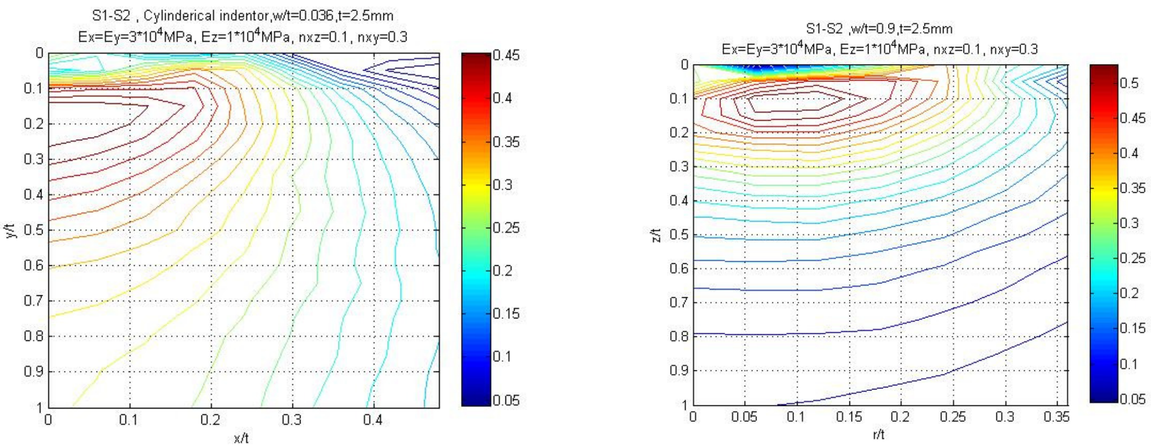
$$E_r = E_t = 3\cdot 10^4\text{MPa},\ E_z = 10^4\text{MPa},\ \upsilon_{rz} = 0.1,\ G_{rz} = 3.66\cdot 10^3\text{MPa},$$

Some results of calculations partly presented below are obtained for both versions of loading (Figures 9-11). The ratio of each parameter to pressure in center of contact surface is shown.



a) b)

Figure 9. Mizes stress distribution in zone of the plate contact with a cylindrical (a) and spherical indenter (b)



a) b)

Figure 10. The difference of the first and second principal stress distribution in zone of the plate contact with a cylindrical (a) and spherical indenter (b)

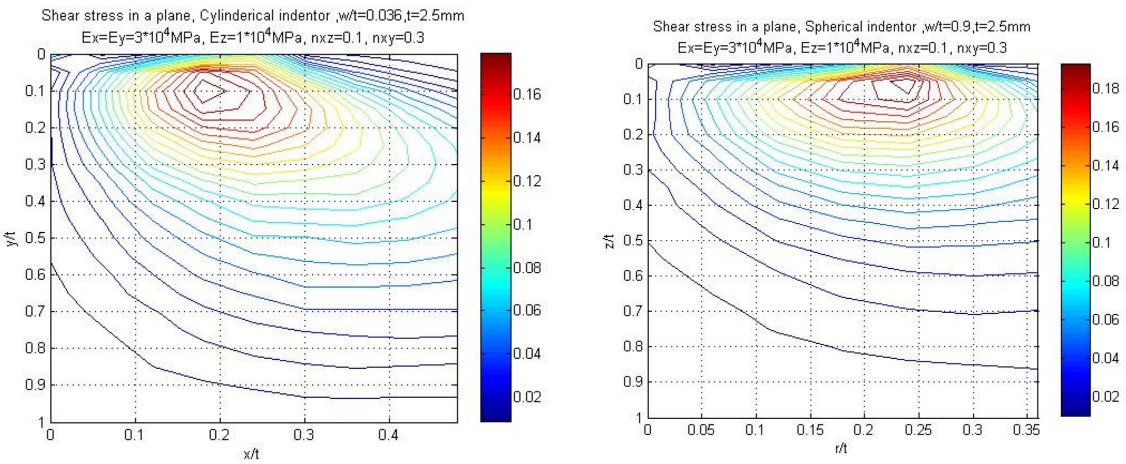


Figure 11. Shear stress in a plate distribution in zone of the plate contact with a cylindrical (a) and spherical indenter (b)

The Figures 12 and 13 show distribution of some relative parameters of stress state on contact surface.

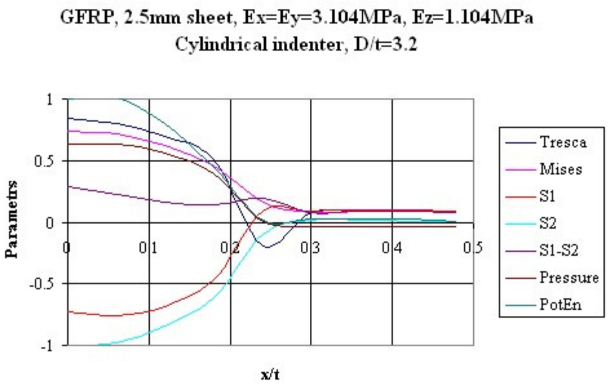


Figure 12. Relative parameters of stress state distribution on contact surface (cylindrical indenter)

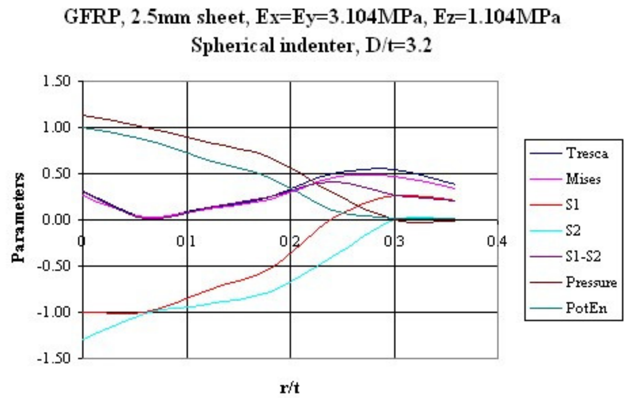


Figure 13. Relative parameters of stress state distribution on contact surface (cylindrical indenter)

3.4. Discussion: Stress state and possible damages

Results of test and numerical analysis allow to note two significant features of contact destruction of a composite.

There is high level of in-plate shear stress at both versions of contact loading (Figures 11). The maximum of shear stress is located at rather small depth under contact surface. Because usually interlayer shear strength is small, the delaminating is very probable damage of this kind composite at the contact loading.

The stress state near boundary of contact surface defines the initiation of composite destruction at loading by cylindrical indenter (Figure 12). The difference between first and second principal stress is the most probable cause of destruction. The stress state at loading by spherical indenter is significantly other: high level of the mean direct stress (pressure) defines the mentioned mode of destruction (compare Figure 12 and 13).

It can note other features of stress state and destruction.

The level of the maximal direct stress on the surface of contact (is more exact, in its center) has the greater value at rather small depth of penetration ***w/t***. It is sown, that already at ***w/t=0.025*** the maximal pressure exceeds tensile strength of material.

Equivalent stresses by classical criteria (for example Von Mizes) are essentially non-uniformly distributed in a zone of impact, and differ for two kinds of loading (Figure 9). The maximum for plain strain is located in center of contact surface, and in some depth under contact surface at rotation-symmetrical loading. That the maximum of this stress is no more than 0.6 from the maximal pressure.

4. Microscopic structure of a composite in zone of impact damage

Figure 14 shows the general view of a surface of the sample in a zone of impact damage with energy of an impactor 13.05 Joules. Impact was made by an impactor with a steel tip of the spherical form in diameter of 6 mm. It was as a result formed the crater of a small depth. This fact, and also change of a shade of a surface in a zone of impact testifies to irreversible changes of a material. The sections 1 and 2 in which the sample was cut and prepared for micro investigation of structure of a surface are marked on the Figure 14.

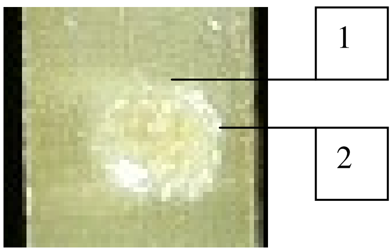


Figure 14. Surface of a sample with impact damage (13.08 J)

Section 1 is located on boundary of a impacted zone, and section 2 is located more close to the center of this zone. The analysis of a surface of cross-sections has allowed establishing some features of partial destructions of components of the composite at impact. The picture of a surface of the section 1 is shown in Figure 15.

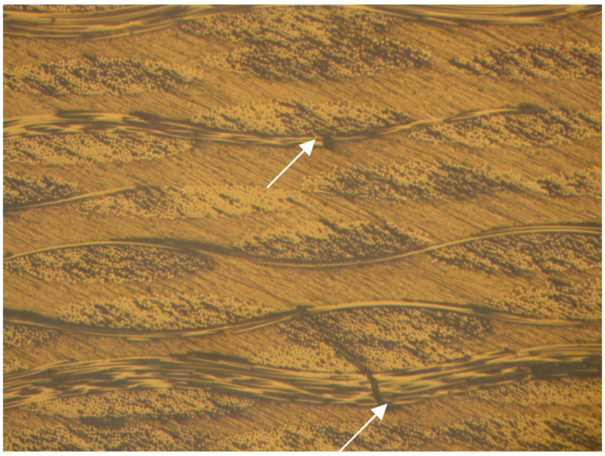


Figure 15. Section 1: Fibers destructions in cross layers are indicated by arrows (x120)

Cracks of rupture in a matrix practically are not present. There are the ruptures of bunches of the across-directed fibers. The surface density of such ruptures is rather insignificant. Independent micro cracks in a matrix in this section have not been found out. There are the attributes of weak cracking of the matrix in zones of rupture of fibers. It allows assuming, that the fibers in this section are more subject to partial destruction in comparison with a matrix for the given composite.

The picture of a surface of the section 2 is shown in Figure 16. In this section it is observed

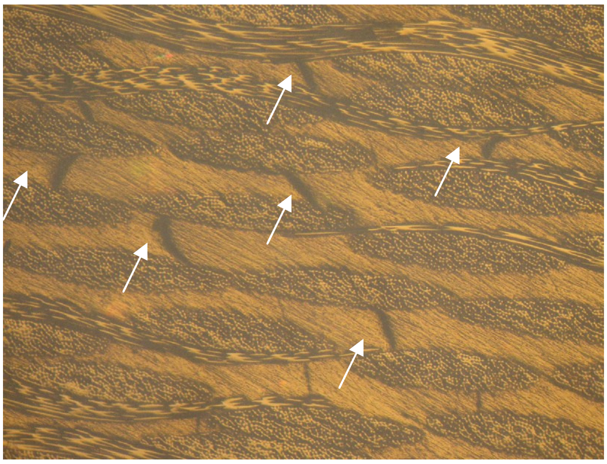


Figure 16. Section 2: The largest cracks in epoxy matrix are indicated by arrows (x120)

intensive cracking of a matrix. It is possible to see also the ruptures of the across-directed fibers. However, there are no facts to accept that their density is much more than in section 1.

The fact of the presence of delaminating "fiber-matrix" cannot be unequivocally concluded by results of the direct analysis. However, character of micro cracks in a matrix and ruptures of fibers allows supposing that such damages also appear in a composite at impact.

5. Discussion and conclusions

There is high level of in-plate shear stress at both versions of contact loading. The maximum of shear stress is located at rather small depth under contact surface. Because usually interlayer shear strength is small, the delaminating is very probable damage of this kind composite at the contact loading.

The stress state near boundary of contact surface defines the initiation of composite destruction at loading by cylindrical indenter. The difference between first and second principal stress is the most probable cause of destruction. The stress state at loading by spherical indenter is significantly other: high level of the mean direct stress (pressure) defines the mentioned mode of destruction.

In earlier executed research [11] the finite-element analysis of the stress state was executed for a thin sheet of a long fiber composite at impact. Conclusion on effect of stresses localness has been done. On the one hand, it is in the full consent with the classical theory of impact, and on the other hand, is the precondition for the decision of the important question on the sizes of a zone of the destruction formed at impact. It is shown, that irrespective of used criterion of destruction, the sizes of a zone in which the level of criterion much more than limiting value, are comparable to the sizes of a contact zone. Outside of this zone the level of stresses intensively falls up to safe size. Thus, destruction of a material should concentrate mainly in the specified zone. Thus the density of potential energy of elastic deformation much more exceeds a level necessary for realization of one-surface destruction. Therefore next conclusion can be done: if the composite contains brittle components, the process of multiple destructions should be proceeded in a zone of impact. In a limit it should be the crushing with sharply non-uniform size of particles. They should be finer in zones of higher concentration of energy of deformation.

Results of microscopic researches of a surface of a cut in a zone of impact confirm the described character of destruction of fiberglass at impact with rather small energy. Really, the density of microcracks in epoxy matrix sharply decreases on edge of a zone of destruction. Interestingly the density of break of fibers within the limits of the same zone varies significantly less.

6. Acknowledgement

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