Regulation of carbon plastic properties upon impact by hybridization of the reinforcing fibers

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Abstract. Regulation of carbon fiber reinforced plastic (CFRP) properties and failure mode upon low-velocity impact by hybridization of the reinforcing fibers is discussed. Effect of the ratio of carbon fiber (CF) and plasma-activated ultra-high molecular weight polyethylene (UHMWPE) fiber contained in a hybrid fiber on the ultimate tensile strength and impact properties of the hybrid composite material (HCM) has been investigated by impact break (IB) method. It was found out that at the ratio of CF:UHMWPE-fiber = 20:80, the carbon and UHMWPE-fibers in HCM are no longer deformed and broken down simultaneously. At first carbon and then UHMWPE-fiber are broken down. At this ratio the HCM values of ultimate tensile strength and specific absorbed-in-fracture energy were increased by the factors of 1.65 (from 594 to 986 MPa) and 1.98 (from 47 to 89 J/cm²), respectively. The detected effect of the delay in the destruction of HCM can be used to create aircraft and other impact-resistant structures.

1. Introduction

To conquer living spaces humanity should create new materials working both on Earth and Space. The present time carbon fiber reinforced plastics (CFRP) are widely used in the production of the large aerospace composite structures due to the high specific properties of carbon fibers. The growth of the business of high-performance composite structures may be linked to the growth of the demand for carbon fiber [1]. Modern carbon fibers have become stiff and the resulting composites based on them are very stiff but would the composite materials (CM) be tough and impact-resistant?

Most important in using of CFRP in structures subjected to impact loads are the level and the mechanism of energy absorption at various velocities and impact properties of material. Because carbon fibers and CFRP are brittle materials they challenge users, which is associated with the loss of their high properties and the risk of destruction upon impact.

The velocity of loading strongly affects the mechanical properties of CFRP. Especially large change in the CM properties occurs in the transition from static to dynamic loading conditions because CFRP are strictly anisotropic composite materials. This is very important for aircraft and other impact-resistant structures.

What does it mean anisotropic CM? Strength and stiffness of CM are provided by the reinforcing fibers or fabrics and the integrity and environmental resistance of the CM are contributed by the
matrix. The matrix transfers the load on the reinforcing fibers, redistributes the stresses between them and consolidates the monolithic material. The time of these processes is drastically reduced to 1-2 ms upon impact. This limits the stress relaxation and energy dissipation at break of the fibers. That is why impact is an unsafe load type because it is catastrophic quickly reduced the high-performance characteristics of CM [2].

The ways to increase the fracture toughness and impact-resistant of CFRP are based on the hybridization of the materials [3]. In order to create a hybrid composite material (HCM) with increased resistance to impact one should alternate layers of fabrics from carbon and ultra-high molecular weight polyethylene (UHMWPE) fibers [4]. It is also possible to create HCM to apply hybrid fabrics woven from glass, carbon and UHMWPE fibers [5].

The disadvantage of these methods and materials is the small effect of hybridization due to the difference in the modulus and the deformation capacity of carbon and UHMWPE-fibers, which is ~1.77% and 3.6-3.8%, respectively, as well as a large distance between fibers of different types in layered woven and non-woven HCM. When these materials are loaded, carbon fibers are first destroyed and then UHMWPE-fibers destroyed. Fibers of various types in such HCM do not work together and poorly transfer the load to each other at all stages of deformation.

For the rational use the fiber properties from materials of different chemical nature, it is necessary to have them as closer as possible to each other. It is possible when combining different fibers in one hybrid fiber. Such hybridization of the fibers is one of the effective ways of improving the energy absorption capability of anisotropic CM. The properties of the hybrid fiber can be controlled by adjusting the content of its fibers [6].

A special method for investigation of the properties of anisotropic fiber-reinforced composite materials by means of shock tests of CM sample (in the form of a single bundle of filaments micro-composite) with the help of pendulum impact testing machine has been developed. The method is called “Impact Break” (IB). The IB method is perspective for determination of the CM properties such as the longitudinal and relative deformation, specific absorbed-in-fracture energy, ultimate tensile strength, shear strength of the fiber to the matrix et al. properties upon impact. The IB method allows one to predict of CM properties upon impact and their use in structures [6-11].

The objective of this research is to study the effect of the ratio of carbon and UHMWPE-fibers in hybrid fiber on the properties and failure mechanisms of anisotropic HCM reinforced with hybrid fiber upon low-velocity impact by IB testing.

2. Experiment

As reinforcement, we used hybrid fiber which involved two types of the fibers: high-strength high-modulus brittle carbon fiber (CF) trademark Tenax®-J HTA40 E13 3K 200 tex (Japan) and UHMWPE-fiber trademark D800 Pegasus® (China).

The carbon fiber had a tensile strength of 4.18 GPa, an elastic modulus of 236 GPa, a density of 1.76 g/cm³, an elongation at break of 1.77%. There were 3000 filaments in a single bundle of carbon fiber. The UHMWPE-fiber had a tensile strength of 2.48 GPa, an elastic modulus of 85 GPa, a density of 0.97 g/cm³, an elongation at break of 4%. There were ~1000 filaments in a single bundle of UHMWPE-fiber.

To increase the shear strength at the fiber/matrix interface UHMWPE-fiber was activated by non-equilibrium low-temperature radio-frequency (RF) propane-plasma at the reduced pressure from 1.33 up to 660 Pa [12,13]. The RF-plasma thermal component was cut to a minimum due to low density of ion current \( j_i = 0.5-1 \) A/m² [13]. It was found out that RF-plasma treatment of UHMWPE-fiber increased the interfacial shear strength of hybrid fiber to the matrix by the factor of ~2 [14].

An HT2 epoxy resin Poxy-Systems® (trademark R&G, Germany) with HT2 as a curing agent and with diethylene glycol (DEG) up to 37% as plasticizing agent served as the flexible matrix (FM). Processing time of the matrix was 45 minutes. Mixing ratio was 100:48 parts by weight of resin to hardener. We used next curing mode: at room temperature for 24 h.
To obtain hybrid fiber, we introduced plasma-activated UHMWPE-fiber into carbon fiber in the amount of 20, 50 and 80% by volume and twisted together with multiplication factor of twisting of at least in approximately 33 twists by meter.

Impact tests were carried out by IB method with the help of transversal impact on the impact pendulum-type testing machine Roell Amsler RKP-450 with computer-controlled and continuous recording of dynamic curve load–deformation, in this case load — flexure (bending). The impact velocity was 5.25 m/s. The shape of impactor head was with radius \( R = 3 \) mm.

The failure mechanisms and mechanical properties of HCM upon impact may be studied using an IB-sample. It can be defined as a single bundle of filaments micro-composite, subjected to impact [9]. The IB-samples were obtained by longitudinal hand lay-up of hybrid fiber and impregnated with the matrix, and cured. The samples contained 50% of the matrix and 50% of the hybrid fiber by volume.

The sample in the form of a rod has the following dimensions: length of the working part of the sample \( L = 68 \) mm, length of the sample fixation in the testing machine \( l = 24 \) mm, diameter of the hybrid sample \( d = 2.3 \) mm. Five IB samples of each HCM were tested at room temperature upon impact. The strength and energy criteria of the HCM were obtained from the experimental load–flexure curves. Experimental results are shown in the table and the figure 1.

Impact is applied in the middle of the sample across the fibers. Due to the transversal impact the sample is stretched and bended by an amount \( \Delta \) above which the fibers are broken at the bending location. When the sample of CM was broken and the fibers were destroyed, their ends remained fixed in the CM. The scheme of IB-sample and distribution of the forces upon impact are given in [9].

The IB test allows one to analyze mechanisms of CM loading and failure and to determine the following CM properties: \( v \) — the loading velocity; \( P \) — the loading force; \( P' \) — the tensile and breakdown force simultaneously; \( X \) — the longitudinal deformation; \( \varepsilon \) — the relative deformation; \( \Delta \) — the transverse deformation of the sample at the load location; \( \sigma \) — the ultimate tensile strength; \( W \) — absorbed-in-fracture energy; \( \alpha \) — specific absorbed-in-fracture energy; \( \tau \) — the shear strength of the fiber to the matrix; \( K_f \) — coefficient of strength implementation et al. All formulas are given in [2,9].

### 3. Results and discussion

The properties of brittle CFRP are sharply reduced under impact loading conditions [10,11]. CFRP has a brittle-fragmentation fracture due to its brittleness. The results of the experiments showed that introduction of 20% of UHMWPE-fibers into the hybrid fiber was increased the strength \( \sigma \) and specific absorbed-in-fracture energy \( \alpha \) of HCM by the factors of \( \sim1.31 \) from 594 to 779 MPa and 1.29 from 47 to 61 J/cm\(^2\), respectively (curve 3, figure 1 and Table 1).

#### Table 1. Effect of the ratio of carbon fibers Tenax® and plasma-activated UHMWPE-fibers D800 in hybrid fiber on the properties and failure mode of HCM upon impact

| Properties of HCM | The ratio of carbon fiber (CF) and UHMWPE-fibers in HCM CF:UHMWPE-fiber, % |
|-------------------|--------------------------------------------------------------------------|
|                   | 20:80                      | 50:50                      | 80:20                      | 100:0                      |
| \( \alpha \), J/cm\(^2\) | 89                         | 84                         | 61                         | 47                         |
| \( \sigma \), MPa  | 986                        | 836                        | 779                        | 594                        |
| \( \varepsilon \), % | 2.1                        | 2.1                        | 1.65                       | 1.4                        |
| \( \tau \), MPa   | 24                         | —                          | —                          | —                          |
| \( \rho \), g/cm\(^3\) | 1.13                      | 1.33                      | 1.61                       | 1.77                       |
| Failure mode      | Shear                      | Shear                      | Break                      | Break                      |
At the ratio of CF:UHMWPE-fiber = 50:50, the HCM values of $\sigma$ and $\alpha$ are increased by the factors of 1.40 from 594 to 836 MPa and 1.78 from 47 to 84 J/cm$^2$, respectively (curve 2, figure 1 and Table). At the values of $\varepsilon$ up to 1.65%, the main contribution to the strength of the HCM is made due to a rigid CF. An increase D800 fiber content into hybrid fiber up to 50% is caused a change the failure mechanism of the HCM from break to shear. The relative deformation becomes constant $\varepsilon = 2.1\%$.

![Strain diagram](image)

**Figure 1.** Strain diagram (load vs flexure) upon impact for HCM reinforced with hybrid fiber consisting of carbon fiber (CF) Tenax® and plasma-activated UHMWPE-fiber D800 in the following ratio (CF:UHMWPE): 1 — 20:80; 2 — 50:50; 3 — 80:20; 4 — 100:0.

At the ratio of CF:UHMWPE-fiber = 20:80, the carbon and UHMWPE-fibers in HCM are no longer deformed and broken down simultaneously (curve 1, figure 1 and Table). At first carbon and then UHMWPE-fiber are broken down. It was observed the effect of the delay of destruction of HCM reinforced with hybrid fiber made from carbon and UHMWPE-fibers is ascertained. At this ratio the HCM values of $\sigma$ and $\alpha$ were increased by the factors of 1.65 (from 594 to 986 MPa) and 1.98 (from 47 to 89 J/cm$^2$), respectively.

4. **Conclusion**

The effect of the ratio of UHMWPE-fiber and carbon fiber contained in a hybrid fiber on the energy criteria and failure mechanisms of the HCM has been determined experimentally by IB-method. On the basis of the investigation carried out we can conclude that hybridization of carbon and UHMWPE-fibers into a joint hybrid fiber makes it possible to obtain HCM with higher impact properties and greater resistance to the loads. By changing the composition of the hybrid fiber, one can control the failure mode and basic properties of the HCM such as ultimate tensile strength, shear strength, specific absorbed-in-fracture energy et al. The effect of the delay in the destruction of HCM based on hybrid fiber consisted of carbon and UHMWPE-fibers can be used to create aircraft and other impact-
resistant structures. The concepts developed in this study on the possibility of using hybrid fiber in producing of HCM can be extend to other fibers such as polyvinyl fluoride (PVF), polyethylene terephthalate (PET), polyethylene naphthalate (PEN), poly(p-phenylene-2,6-benzobisoxazole (PBO) et al. for creating new types of materials with high physicomechanical indices.

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References
[1] Kelly A 2008 J. Mater. Sci. 43 6578
[2] Korneeva N V, Kudinov V V, Krylov I K and Mamonov V I 2018 J. Phys. Conf. Series 1134 012028
[3] Safri S N A, Sultan M T H, Yidris N and Mustapha F 2014 A review Int. J. Eng. Sci. 3 50
[4] Li Y, Xian X J, Choy C L, Meili G and Zhang Z 1999 Compos. Sci. Technol. 59 13
[5] Marissen R 2002 Proc. Conf. ECCM-10 (Brugge, Belgium, June 3-7) CD-ROM 184
[6] Kudinov V V, Krylov I K, Mamonov V I and Korneeva N V 2016 Fizika i Khimiya Obrabotki Materialov (Physics and Chemistry of Materials Treatment) (1) 64 (In Russ)
[7] Kudinov V V, Krylov I K, Korneeva N V and Mamonov V I 2014 Fizika i Khimiya Obrabotki Materialov (Physics and Chemistry of Materials Treatment) (6) 63 (In Russ)
[8] Kudinov V V and Korneeva N V 2016 AIP Conf. Proc. (Ischia, Italy, June 19-23) 1736 (1) 020178
[9] Korneeva N V, Kudinov V V, Krylov I K and Mamonov V I 2017 Polym. Eng. Sci. 57(7) 693
[10] Kudinov V V, Krylov I K, Mamonov V I and Korneeva N V 2018 Fizika i Khimiya Obrabotki Materialov (Physics and Chemistry of Materials Treatment) (1) 42 (In Russ)
[11] Kudinov V V, Krylov I K, Mamonov V I and Korneeva N V 2018 Fizika i Khimiya Obrabotki Materialov (Physics and Chemistry of Materials Treatment) (3) 66 (In Russ)
[12] Kudinov V V, Korneeva N V 2012 Proc. Conf. ECCM-12 (Biarritz, France, 29 Aug – 1 Sep) CD-ROM 341
[13] Sergeeva E A, Korneeva N V, Zenitova L A and Abdullin I Sh 2011 Modification of Synthetic Fibrous Materials and Manufactured Products with the Help of Non-Equilibrium Low-Temperature Plasma. Part 2. Properties, structure, technologies (Kazan: Kazan State Technological University Press) (In Russ)
[14] Garifullin A R, Abdullin I Sh, Korneeva N V and Kudinov V V 2015 Design. Mater. Technol. 5(40) 9