MATERIALS. TECHNOLOGIES. DESIGN

УДК 621.763, 539.422.5

Effect of the matrix alloy on the fracture type and bending strength of the carbon-aluminum composites

Влияние матричного сплава на тип разрушения и прочность при изгибе углеалюминиевых композитов

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ABSTRACT

The properties of any composite material depend on a large number of factors, and the choice of a matrix alloy for the composite with a metal matrix fabrication is one of the most important. In the case of carbon-aluminum composites, the choice of alloy affects the possibility of the brittle carbides formation and the bond strength at the matrix-fiber interface, which determines the nature of fracture and the ultimate strength of the composite material.

In this work, unidirectional composite materials with matrices of aluminum alloys grades A7, AMg4 and AK12, reinforced with continuous carbon fibers, were obtained and investigated. Mechanical tests for three-point bending and microstructural studies of the composite materials fracture surfaces were carried out. It was found that aluminum alloys, which contain magnesium (AMg4) or silicon (AK12), can reduce the chemical interaction of the composite components and increase the material strength as a whole. Thus, the three-point bending strength of composites with matrices A7, AMg4, and AK12 was 288, 389, and 413 MPa, respectively. In this case, the nature of specimen fractures correlates with the obtained strength values.

KEYWORDS

Composite; carbon fiber; aluminum; bending strength.

АННОТАЦИЯ

Свойства любого композитного материала зависят от большого числа факторов, и выбор матричного сплава при изготовлении композитов с металлической матрицей является одним из важнейших. В случае углерод-алюминиевых композитов выбор сплава влияет на возможность образования хрупких карбидов и силу связи на границе матрица-волокно, которая определяет характер разрушения и конечную прочность композитного материала.

В данной работе были получены и исследованы однонаправленные композитные материалы с матрицами из алюминиевых сплавов марок А7, АМг4 и АК12, армированные непрерывными углеродными волокнами. Были проведены механические испытания на трехточечный изгиб и микроструктурные исследования поверхностей разрушения композитных материалов. Было установлено, что алюминиевые сплавы, которые имеют в своем составе магний (АМг4) или кремний (АК12), позволяют снизить химическое взаимодействие компонентов композита и повысить прочность материала в целом. Так, прочность при трехточечном изгибе композитов с матрицами А7, АМг4 и АК12 составила 288, 389 и 413 МПа соответственно. При этом характер изломов образцов коррелирует с полученными значениями прочности.

КЛЮЧЕВЫЕ СЛОВА

Композит; углеродное волокно; алюминий; прочность при изгибе.

Introduction

Fibrous composite materials are one of the most effective types of composites that are able to use the maximum strength potential of the reinforcing fiber and matrix ductility to increase the specific characteristics of the composite. Thus, due to its high specific strength, the carbon-aluminum composite can be used as a structural material in aerospace, automotive and other industrial sectors.

However, the manufacturing composites technologies with aluminum and carbon fibers require certain knowledge due to the specificity of material obtaining. Particular difficulty is the control over the components chemical interaction in the process of manufacturing an aluminum-carbon composite, which is most important when fabricating material by liquid-phase methods [1–3]. The intensity and nature of the interaction at the matrix-fiber interface are one of the main parameters that determine the final mechanical composite properties, therefore, it is necessary to understand the processes that occur at the interface in order to further optimize the technological modes of their manufacture.

One of the most informative methods for studying the interphase interaction at the matrix/fiber interface is the fractographic analysis of composite fractures, which, depending on the type of fracture, may indicate the nature of the interaction of the components.

As a rule, the strength of composites of the «aluminum – carbon fiber» type with a fiber volume fraction of 30–35% does not exceed 200–300 MPa due to an intense chemical reaction at the interface with the formation of brittle and hygroscopic aluminum carbide Al_4C_3 [4–10]. The presence of a large volume of this carbide phase, as well as the accompanying negative effects of embrittlement, affect the composite final mechanical properties.

Depending on the bond strength at the interface between phases and stress concentrators, fibrous metal-matrix composites fractures (including carbon-aluminum composite) are of three main types: brittle fracture, bundle fracture and single-fiber fracture (with pulling out of fibers) [11, 12]. Composites with a brittle type of fracture are characterized by the lowest strength and undeveloped fracture surface, generally perpendicular to the direction of fibers laying [13]. A bundle fracture is the optimal type of fracture with a multilevel fracture, with a predominant pulling out of individual fiber bundles. Single pulling out of fibers from the matrix occurs if the fibers infiltration is poor or if the bonding between the fibers and the matrix is weak. Thus, by analyzing the fracture of composites, information can be obtained that facilitates the choose of a matrix alloy for obtaining maximum strength properties.

As mentioned above, increasing the strength of composites requires the formation of an optimal interphase boundary. In this case, excessive hardening of the matrix – fiber interface in the case of a brittle fiber/plastic matrix combination during intense chemical reactions can lead to embrittlement of zones around the fiber and reduce energy dissipation at the crack tip [13]. One of the simplest methods that can be used to reduce the strength of the interface is alloying the matrix with components that inhibits the formation of carbides or other undesirable phases. Zinc, magnesium and silicon can be used as such components. It was shown in [14, 15] that the listed elements can reduce the solubility of carbon in aluminum, which in turn will limit the carbon oversaturation of the regions near the fiber and the subsequent formation of aluminum carbide crystals. Japanese and Chinese researchers studied the possibility of using a matrix based on aluminum and magnesium [4, 16], and French scientists studied composites with aluminum and silicon [17], but this work compares the effect of both elements alloying an aluminum matrix on the bending strength of composites obtained under equal conditions by one method.

This article studies the effect of replacing a pure aluminum matrix in a carbon-aluminum composite with the widespread alloys AMg4 and AK12 on the three-point bending strength, as well as the nature of the fracture of composites when using the above-mentioned matrices.

1. Research methods

For the unidirectional composites fabrication, carbon fiber was used in the form of a unidirectional fabric grades UMT-49 (tensile strength 4.9 GPa), made of PAN fiber. The fiber volume fraction in all composites was set equal to 30%.

Aluminum alloys A7 (aluminum of technical purity 99.7%), AMg4 (main alloying element magnesium, 4%) and AK12 (eutectic silumin, main alloying element 11% silicon) were used as matrix alloys.

Samples of carbon-aluminum composites were obtained by a type of liquid-phase infiltration – by the the shell molding process, the essence of which is to place the composite components in a steel hermetic shell, evacuate the shell and heat until the aluminum melts, and infiltrate the fibers by the melt under the external pressure, followed by cooling. The method is described in more detail in [18, 19]. The resulting composite samples were in the form of plates with dimensions of 70×70×3 mm. Each of the resulting composite plates was divided into 5 parts for mechanical testing.

The fabrication conditions of composites with matrices A7, AMg4, and AK12 (the conventional designation of composites further like A7/Cf, AMg4/Cf and AK12/Cf, respectively) were completely identical except for the heating temperature, due to the different melting temperatures of alloys A7, AMg4 and AK12. Overheating of the alloys was about 60...70 °C above the liquidus to improve fluidity and warming up the mold.

Mechanical three-point bending tests were carried out in accordance with GOST R 56810-2015 on an AS-102 BendingTester, loading was carried out until the sample failed.

Microstructural and fractographic analyzes were carried out on a scanning electron microscope SEM, JEOL JSM 6490-LV (Japan), in the secondary electron mode at a voltage of 20 kV.

2. Results and discussion

The macrostructure of carbon-aluminum composites obtained by the shell molding process is shown in Fig. 1.

The dark, dotted, horizontally elongated shapes represent the cross-section of the bundles that make up the unidirectional carbon fiber fabric. The images below show the areas from them. Light areas – aluminum alloy. The structure shown in Fig. 1 is typical for all three composites, regardless of the matrix.

The fracture surface analysis can provide a large amount of information about the processes occurring at the interface during the manufacture of a composite material. Based on the fracture pattern, it is possible to estimate the interaction intensity, the bond strength at the interface, and other parameters.

A composite with a pure aluminum matrix, as noted, has low strength and brittle fracture (Fig. 2, *a*). The figure shows that the fracture surface is brittle and almost flat. This type of fracture corresponds to the low strength of the composites, as a result of high adhesion, fiber degradation and stress concentration at the sites of carbide formation between the fiber and the matrix, crack energy dissipation practically does not occur [12, 20], the function of the so-called «mechanical safety device» does not work. The crack propagates freely, passing from the fiber to the fiber practically only in one plane – i.e. a flat crack is formed [17].

This pattern is observed mainly in areas with high fiber density. However, as the crack reaches a sufficiently large area of the matrix free of fibers, the crack propagation slows down, because in this section of the composite, the crack energy is spent on plastic deformations in front of the crack tip.

In the case of the AMg4/Cf composite, the fracture surface becomes more pronounced (Fig. 2, *b*), which indicates changes at the matrix – fiber interface. A multilevel surface indicates a change in the nature of crack propagation in the material, due to a decrease in the number of defects and concentrators on carbon fibers. As a result, the crack propagation work and strength of the composite as a whole increase.

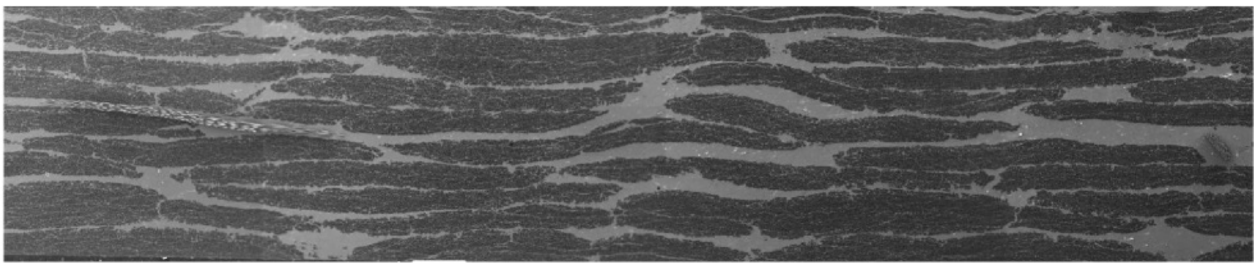
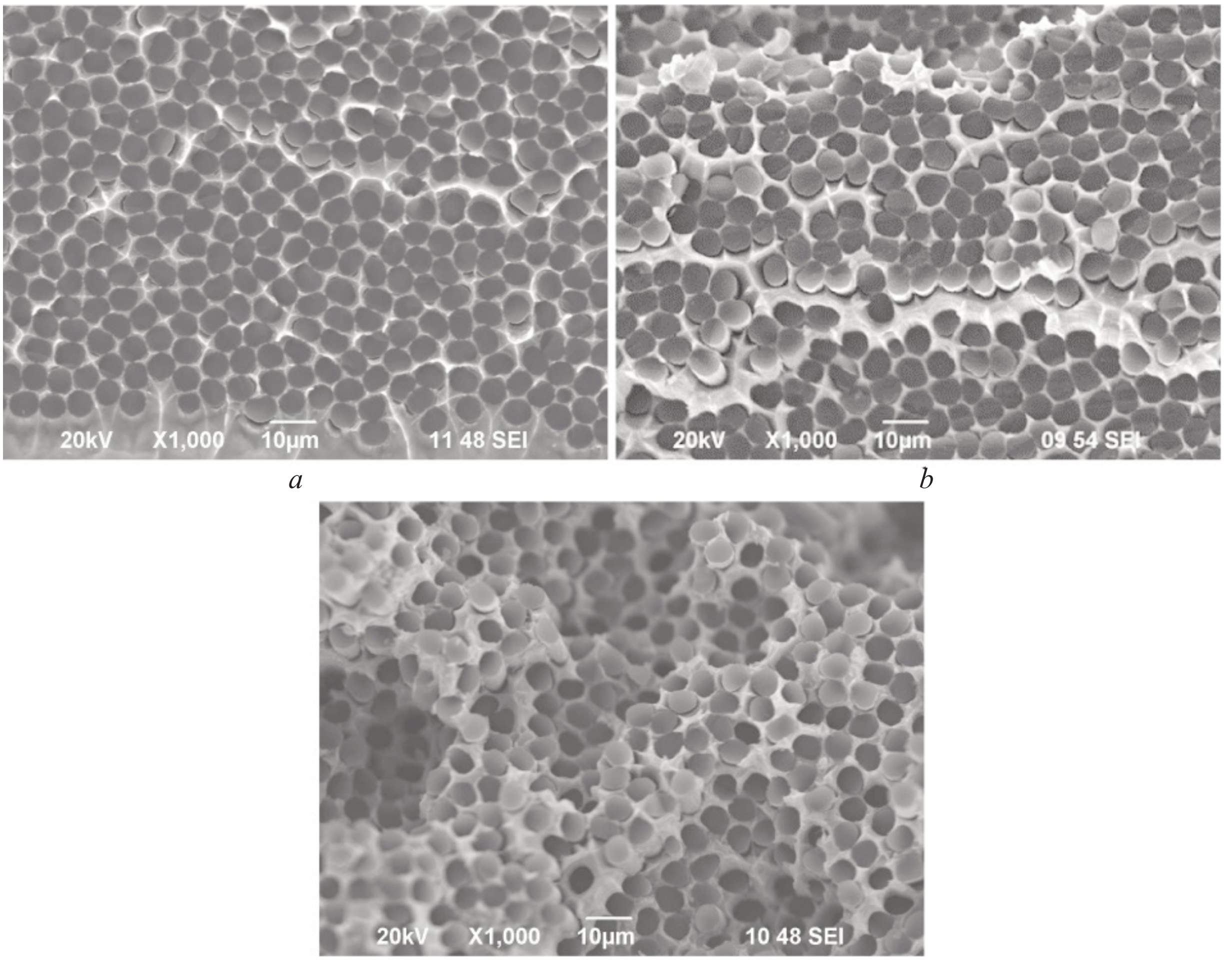


Fig. 1. Panoramic view of the carbon-aluminum composite cross section

Рис. 1. Панорама углеалюминиевого композита в поперечном сечении



a *b* *c*

Fig. 2. Fracture surfaces of carbon-aluminum composites: *a – A7/Cf; b – AMг4/Cf; c – AK12/Cf*

Рис. 2. Поверхности разрушения углеалюминиевых композитов: *a – A7/Cf; b – AMг4/Cf; c – AK12/Cf*

The AK12/Cf composite has an even more developed fracture surface (Fig. 2, *c*). Also in the picture you can see fibers sticking out from the matrix separately. These signs indicate an even greater decrease in the chemical interaction of the fiber and matrix and an increase in the crack propagation work. The strength of the composite also increases, which will be discussed below.

Due to the different intensity of chemical interaction and, as a consequence, differences in the nature of the destruction of composites, their strengths are different. Thus, the three-point bending strength of the A7/Cf, AMg4/Cf, and AK12/Cf composites was 288, 389, and 413 MPa, respectively. Thereby, replacing the A7 aluminum matrix with the AK12 silumin matrix led to an increase in the average bending strength of the composite by 40%.

Conclusion

The fracture patterns of composites with A7, AMg4, and AK12 matrices differ significantly due to different degrees of chemical interaction at the matrix-fiber interface. Carbon-aluminum with a matrix of pure aluminum has a brittle fracture nature and the lowest three-point bending strength of 288 MPa. Alloys with additions of magnesium and silicon react less intensively with carbon fibers, due to which the type of fracture changes – the fracture surface becomes multilevel, and the strength increases to 389 and 413 MPa, respectively.

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