Aluminum alloy matrix composite wire reinforced by continuous carbon fibers

S N Galyshev¹, A I Gomzin², R F Gallyamova², A Yu Nazarov³, E L Vardanyan³, U Sh Shayakhmetov⁴ and F F Musin⁵

¹Institute of Solid State Physics of RAS, Chernogolovka, Moscow distr., Russia
²Department of Material Science and Metal Physics, Ufa State Aviation Technical University, Ufa, Russia
³Mechanical Design Technology, Ufa State Aviation Technical University, Ufa, Russia
⁴Department of Engineering Physics and Materials Physics, Bashkir State University, Ufa, Russia
⁵Ufa Chemistry Institute of RAS, Ufa, Russia

andre-gomzi@yandex.ru

Abstract. In this study, samples of composite wire with a matrix of aluminum alloy, reinforced with continuous carbon fibers were obtained by the method of liquid-phase infiltration with ultrasonic treatment. Mechanical tests for three-point bending were carried out and the structure of the composite was studied. The qualitative relationship between the strength of the CF/Al composite and the relief of the fracture surface is shown.

1. Introduction

Fabrication of metal matrix composites reinforced with carbon fiber is primarily complicated by the fact that carbon materials are practically not wetted physically by liquid metals [1], as a result the negative capillary effect prevents the spontaneous impregnation of carbon fiber by melt. The solution to this problem is to apply external pressure to the molten metal that compensates for the capillary effect [2]. However, the processes (liquid stamping, die casting, etc.) that implement this solution, in most cases, imply long-term contact (at least 60 seconds) of the melt with carbon fiber. This leads to the second technological problem of metal matrix composites at the interface of the matrix/fiber. As a rule, this is the cause of the destruction or complete transformation of the fiber in the molten metal, as in the case with carbon/titanium composites, the technology of which remains at the development stage today. It should be noted that the formation of carbidizes at the interface of the matrix/fiber in most cases plays a negative role, deteriorating the mechanical properties of the composite with a metal matrix.

An alternative to the aforementioned technological methods is the use of ultrasonic treatment of melt in the process of carbon fiber infiltration. Under the influence of ultrasonic vibrations in the matrix melt acoustic cavitation occurs. This phenomenon is the formation and collapse of cavitation bubbles, which locally causes a significant increase in pressure in the metal melt (up to several GPa [3]), which in turn compensates for the capillary effect and contributes to the infiltration [4].
In this paper, a scheme has been implemented for obtaining composite wire by pulling a bundle of carbon fibers through an AMg6 aluminum alloy melt subjected to ultrasonic processing. This method has several advantages, firstly, during its exploitation, the contact time of liquid aluminum with carbon fiber is only a few seconds. Secondly, the method allows to obtain a composite wire of any length, which can be used as a finished product, for example, as the basis of a conductive core for high-voltage power lines. Another application of the composite wire with a metal matrix is its use for building composites with a hierarchical structure, where the reinforcing component is composite wire, and as a matrix, metal or alloy.

2. Experimental materials and methods

2.1. Materials

In this work, AMg6 alloy as a matrix material was used. The chemical composition of the alloy is presented in Table 1. The choice of matrix alloy is due to the presence of magnesium, which suppresses the formation of aluminum carbide at the matrix melt / carbon fiber interface [5, 6].

Table 1. Chemical composition of AMg6, %

| Al   | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Be  | Ti   | Other |
|------|-----|-----|-----|-----|-----|-----|-----|------|-------|
| ≥91,1| 0,4 | 0,4 | 0,1 | 0,6 | 6,3 | 0,2 | 0,005| 0,06 | 0,1   |

PAN-based carbon fiber in the form of a bundle of UMT49 and UMT430 grades was selected as a reinforcing component, the strength and modulus of elasticity of which are 4.9 GPa, 260 GPa and 4.5 GPa, 430 GPa, respectively (UMATEX Group, Russia).

2.2. The fabrication method

Samples of the composite wire were obtained by drawing carbon fibers through a molten aluminum alloy using a method described in the paper [7]. During the process of drawing, ultrasonic processing of the melt was performed (Figure 1). The fiber was passed through a 5 mm diameter hole in an ultrasonic niobium alloy horn, the lower part of which was immersed into the melt. The input power of the ultrasound unit was 1000 watts. The melt temperature was 800 °C.

![Figure 1. Scheme of composite wire fabrication](image)

2.3. Bending tests and SEM

Mechanical tests for three-point bending were carried out according to the scheme close to GOST R 56810-2015. The cross-sectional shape of the wire was taken as an ellipse, the maximum strength values were obtained by the following equation (for ellipsoidal cylinders):
where \( F \) is the maximum load preceding failure, \( a \) is the major axis of the ellipse in the cross section of the sample, \( b \) is the minor axis of the ellipse in the cross section of the sample, \( L \) is the distance between the supports; \( L \) is 15 mm.

The microstructure analysis of the CF/Al composite specimens was conducted using scanning electron microscopy (JSM-6490LV, JEOL, Japan). The material was shot in the mode of secondary electrons with an accelerating voltage of 20 kV at magnification up to 500 times.

3. Results and discussion

As a result of experiments on the carbon fibers drawing through an AMg6 melt, samples of CF/Al composite wire were obtained. All obtained samples had a similar specific structure (Figure 2a). One must note that the carbon fiber bundle is completely infiltrated with aluminum alloy. The fibers in the volume have nonequilibrium distribution, in the central part the volume fraction of fiber in the composite was approximately 60%, the average volume fraction of fiber over the whole cross-section was about 30%.

The bending strength of the obtained samples of CF/Al composite wire ranged from 315 to 1445 MPa. The surface relief of the tested samples fractures correlates with the value of their strength (Figure 3). Samples with greater strength have a more rough fracture surface, which indicates a high level of crack energy dissipation. This character of destruction is more typical for the composites of the ceramic/ceramic system type with “weak” matrix/fibers interfaces [8], however, similar situation was observed in the CF/Al composite [9]. It should be noted that for maximum strength of the CF/Al composite, the matrix/fiber interface must not be “weak” - it has to be at the optimal level.

The fracture surface of the weakest specimen, on the contrary, is practically flat, which indicates easy crack propagation. The authors of [10, 11] showed that the observed phenomenon is associated with the formation of aluminum carbide \( \text{Al}_4\text{C}_3 \) at the matrix/fiber interface. The causes of the different types of composite failure will be considered in further studies.

The composite having the maximum strength (1446 MPa) was reinforced with high-modulus UMT450 fiber, while the remaining samples of composites whose strength did not exceed 625 MPa were reinforced with standard UMT49 fiber. Despite the fact that the high modulus fiber has lower strength compared to the standard (4.2 GPa and 4.9 GPa, respectively), the composite reinforced with UMT450 fiber has maximum strength.
Most likely, this is due to the orientation of atomic planes of carbon, which are the structural elements of fiber surface layer that were known as the basic structural units (BSU) [12]. High modulus fiber is produced under conditions, which are different from conventional low modulus fiber. It can be assumed that the resulting high-modulus fiber surface is different from the surface of conventional fiber in a greater orientation of BSU along the fiber, whereas in a standard fiber they are less oriented. This means that the edges of unoriented BSU come to the surface of the fiber, thus creating on the surface areas with a higher reactivity, where later the formation of the first aluminum carbide crystals occurs, which affects the crack propagation [8].

**Figure 3.** Results of mechanical testing of composite specimens and corresponding images of fracture surfaces

4. Conclusion
Aluminum alloy composite wires reinforced by continuous carbon fiber were fabricated using the liquid-phase infiltration method with ultrasonic treatment. The maximum strength of the composite on a three-point bending amounted to 1446 MPa.

The relationship between the strength of the CF/Al composite and the relief of the destruction surface is established. The flat fracture surface indicates more easily propagated crack, resulting in a low strength of the composite.

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