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Study of damage accumulation mechanisms in reinforced aluminum-boron-steel composites during thermal cycling

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The internal friction method has been used to study the damage accumulation under thermal cycling of an aluminum-boron-steel composite material produced by hot pressing technique. The steel has been introduced into the material in the form of knitted nets containing different amounts of wires in the bundle. The main mechanism of damage accumulation in the material has been shown to be of binding break-off nature at the aluminum-steel interfaces.

Методом внутреннего трения изучается природа накопления повреждений при термоциклировании композиционного материала алюминий-бор-сталь, изготовленного методом горячего прессования. Сталь входит в материал в виде трикотажной сетки с различным содержанием проволок в жгуте. Показано, что основным механизмом накопления повреждений в таком композите является нарушение связи на границе алюминий-сталь.

In boron fiber reinforced aluminum-based composite materials, phase interfaces between are of great significance and produce a considerable effect on the composite properties. Interfaces provide a matrix-fiber binding for the load transfer and distribution among the components. The interface state is associated with such crucial problems of composite materials (CM) as physico-mechanical and physico-chemical compatibility of components. In this work, the problems of physico-mechanical compatibility of components in aluminum-boron and aluminum-boron-steel net CM are studied basing on the investigation of their elastic and non-elastic properties by the internal friction (IF) method. The IF method has been selected due to its high response to structural transformations and the opportunity to perform the non-destructive study on an actual material.

In reinforced composite materials with distinct phase interfaces, the damage accumulation may occur due to the action of various mechanisms of matrix straining and failure, boundary effects, fiber rupture, etc. The sequence of each mechanism involvement in the process depends on many factors, e.g. on the CM composition and manufacturing technology. The material loading conditions play also an important role. It is known that the damages accumulate in a CM due to internal stresses of thermal nature during the CM thermal cycling [1, 2]. Since the structures made of CM often operate under varying temperatures, the study of CM damage degree during thermal cycling is of practical importance. Moreover, the study data can be useful for understanding of the material damage behavior under mechanical loading.

This work is aimed at investigation of the damage accumulation mechanisms in aluminum-boron CM and hybrid aluminum-boron-steel net CM under thermal cycling. The net had a knitted structure of "Lastic 1+1" type produced by a bundle of X18H10T stainless steel wires of 32 μm in diameter. The CM preforms consisted of one-way single layers of boron fibers of

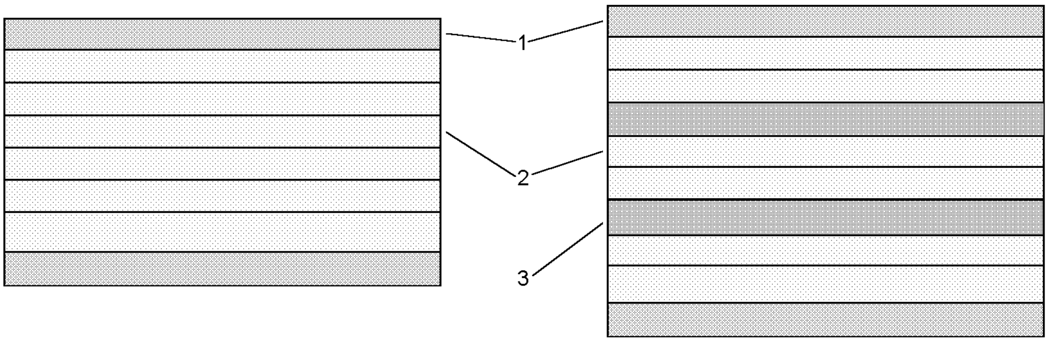

Fig. 1. The layout of stacks as preforms for CM: Al foil (*1*), Al–B monolayer (*2*), steel net (*3*).

140 μm in diameter, average strength of 2800 MPa, plasma-covered with aluminum alloy, AD1. The layout of pre-forms or stacks is shown in Fig. 1. The boron fibers volume fraction was 43 % and the steel one, 10 %. The number of wires in the bundle in knitted nets used 3 and 5. The CM stack-like preforms as prepared were compacted by diffusion welding [3]. Specimens for high-frequency testing were 120 mm in length, 10 mm in width with a thickness of near 1 mm. The IF and elastic modules in CM were measured on a unit realizing the Foerster method [4]. The method is based on excitation of bending oscillations in a specimen by means of conventional electromagnetic converters. The thermal cycling was conducted within 20 to 600°C range at heating and cooling at the 10 deg/min rate. The frequency of specimen bending oscillations was 700 Hz and the amplitude of relative strain was 10^{-7}.

The testing results are presented in Fig. 2. The figure shows that the temperature dependences of internal friction, $Q^{-1}(T)$, do not coincidence at heating and cooling for all the specimens investigated, meanwhile, for the aluminum-boron-steel CM, the dependence data revealed a characteristic hysteresis evidencing an accumulation of damages in the material [2]. Damages in the CM may accumulate due to various processes induced by internal stresses, such as plastic deformation of the matrix, binding break at interfaces, etc. The IF hysteresis loop size, in our opinion, must depend on the interface binding behavior and on the annealing depth in the CM during the thermal cycling, since the annealing reduces structural defects in CM. Thus, if the main mechanism of damage accumulation, which governs the IF hysteresis, is associated with the interfaces, a decrease of the IF background after the thermal cycling as a result of annealing of structural defects may prevail over its increase due to generation of structural defects under the action of internal stresses in case of a rather good boundary bindings. It is just the case in the aluminum-boron composite (Fig. 2a), where there is no hysteresis even at the thermal cycle upper temperature of 400°C and above. The results show the technology chosen for making CM provides a sufficiently sound binding at the matrix-boron fiber interface exhibiting no noticeable change

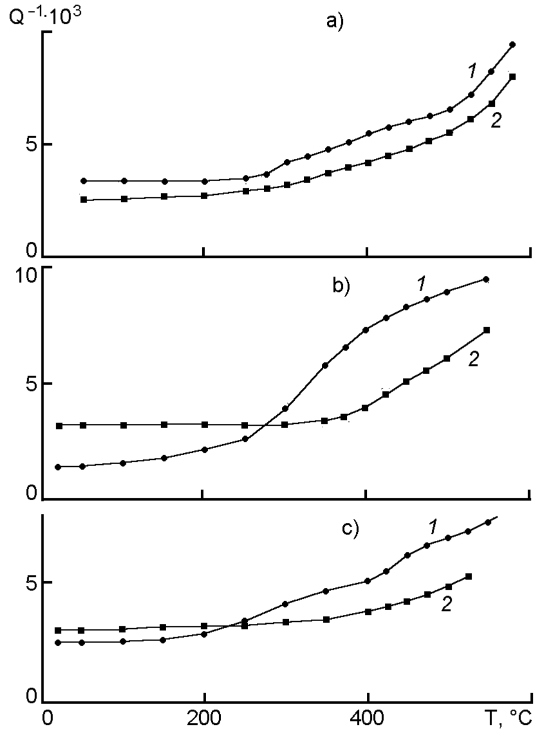

Fig. 2. Temperature dependence of internal friction coefficient in composites at heating (*1*) and cooling (*2*): Al–B (a); Al–B-steel, three-wire bundle net (b); Al–B-steel, five-wire bundle net (c).

under the thermal cycling conditions, i.e. 20–600–20°C.

Steel nets, when introduced into the composite, result first in formation of a new type of internal interfaces (aluminum-steel) with the strength different in general from that of aluminum-boron interfaces and, second, in a new pattern of internal stress distribution in CM. Therefore, the emergence of hysteresis in the case of aluminum-boron-steel net CM is thought to be due to generation of structural defects at the aluminum-steel interfaces (Figs. 2a, 2b). Since the thermal expansion coefficient of X18H10T steel has an intermediate value between those of boron and aluminum, the new type interfaces shall be in a rather less stressed state under thermal cycling conditions used than the aluminum-boron interfaces. Nevertheless, these thermal cycling conditions result in binding breaking at aluminum-steel interfaces. A stronger binding is obviously formed between the matrix and boron fibers as compared to matrix-steel net interface when the CM is manufactured using the above-mentioned technology. The fracture surface of the aluminum-boron-steel CM is presented in Fig. 3.

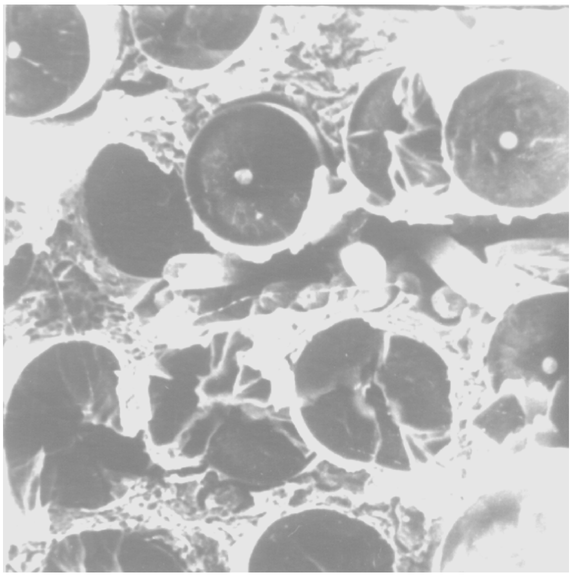

Fig. 3. Fracture surface of aluminum-boron-steel CM.

Comparison of hysteresis loop size for a CM containing various steel nets shows that the matrix-to-net binding is influenced by the number of steel wires in the net bundle. A larger amount of wires in a bundle produces a stronger binding at the aluminum-steel interface. This is manifested by a smaller hysteresis loop size. Such results can be explained as follows. Due to plastic strain which occurs during the diffusion welding when preparing a CM, the matrix surrounds more tightly a bundle of greater size and the aluminum-steel interaction covers a greater area. This results in a high binding strength at corresponding interfaces.

In conclusion, it has been shown using the IF method that the damage accumulation occurs at the aluminum-steel net interface in CM during the thermal cycling due to binding breaking. It has been found also that the diffusion welding of such CM results in a stronger binding at the aluminum-boron interface rather than at aluminum-steel one, furthermore, the binding strength at the aluminum-steel interface increases with number of wires in the steel net bundle. As the results of this work testify, knitted steel nets introduced in the aluminum-boron CM must result in an improvement of its damping and fatigue properties due to accumulation of damages at the aluminum-steel net interfaces, thus providing an expansion of its application field as construction bodies for new equipment.

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Вивчення механізмів накопичення пошкоджень в армованих композитах алюміній-бор-сталь при термоциклюванні

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Методом внутрішнього тертя вивчається природа накопичення пошкоджень при термоциклюванні композиційного матеріалу алюміній-бор-сталь, виготовленого способом гарячого пресування. Сталь входить в матеріал у вигляді трикотажної сітки з різним вмістом дротиків у джгуті. Показано, що основним механізмом накопичення пошкоджень в цьому композиті є порушення зв'язку на межі алюміній-сталь.