Structure and characteristics of a thin-layer "aluminum - carbon nanotubes" sandwich structure

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Abstract. The study describes a way to produce thin-layer sandwich structures containing layers of aluminum foil and an interlayer filler of carbon nanotubes (CNTs). To obtain a homogeneous structure of the composite, induction heat treatment was used combined with a device providing primary compression of the assembly. To determine the functional characteristics of sandwich structures, the homogeneity of their microstructure and surface conductivity were studied. It was found that the use of CNTs allowed increasing the surface conductivity by a factor of 8.3–9.5 compared to the sandwich structure without filler.

1. Introduction

It is known that carbon nanotubes (CNTs) are a promising and available material that has a unique combination of strength and the ability to control physical properties such as electrical conductivity. This type of filler is widely used in the manufacture of composites. For example, CNTs are used to improve the strength of aluminum; however, the limited ductility of high-strength aluminum matrix composites still remains a critical issue [1]. The elongation of Al/CNT composite (with small volume fraction of 1.3 %) sintered at 900 K is enhanced by 82 % compared to that sintered at 800 K, while an increment of 18 % in yield strength (from 127 MPa to 150 MPa) is achieved, as well as 14 % in ultimate tensile strength (from 186 MPa to 212 MPa).

To obtain layers containing CNTs, various types of solvents are used, e.g. the m-cresol (3-methylphenol, CH₃C₆H₄(OH)) weak organic acid [2]. Composites with CNTs have higher mechanical properties and the ability to pre-form compared to the initial material [3]. An important fact is that the amount of filler providing a noticeable strengthening effect is at a low level – not more than 0.5–5 wt. %.

Powder metallurgy, e.g. cold pressing of powder with nanosized particles, is used for the production of Al/CNT nanocomposite (0.5 wt.%) [4]. This material has the stable coefficient of thermal expansion (CTE) in the temperature range of 25–250 °C, which decreases by about 75–85 % compared to that of the aluminum. Aluminum-based composites containing MW-CNTs are produced by a powder metallurgy route involving a ball-milling technique [5]. The composite with individually dispersed nanotubes shows an increased strength with unchanged electrical and thermal conductivities. However, the composite with a network structure of MWCNTs reveals much enhanced electrical conductivity of about 33×10⁷ S/m and thermal conductivity of 172 W/m×K (for aluminum – electrical conductivity of 3.77×10⁷ S/m and thermal conductivity of 237 W/m×K).
The combined use of CNTs and graphene nanoplatelets (GNPs) synergistically reduced the carbon fiber reinforced plastics surface resistivity by 4 times and increased the thermal conductivity by more than 7 times, thus creating possibilities for the replacement of metallic mesh structures for electromagnetic interference shielding and lightning strike protection [6].

CNTs are many times stronger and lighter than metals (magnesium, aluminum, titanium, iron, copper, etc.), and they appear to be a good candidate for reinforcing them [7]. The integration of CNTs into a metal matrix depends on dispersion uniformity. In this case the composite material properties are a function of the uniformity of CNTs dispersion, interfacial bonding, weight percent of fillers, and the geometric parameters of the matrix itself.

2. Methodology
The samples were pressed and thermally treated layers of aluminum foil (thickness of 12.9–13.0 μm, Fe impurity of 0.5–1 wt.%) (figure 1,a). The sandwich structure had from 16 to 64 layers, which was associated with the peculiarities of the formation of test samples. The interlayer filler was applied by staining with a colloidal solution containing carbon nanotubes (5 mg CNTs in 100 ml m-cresol). Homogenization of the solution was performed using ultrasonic treatment. Further the solution was applied on the aluminum foil by staining followed by drying at 50–60 °C (figure 1,b).

![Figure 1](image)

**Figure 1.** Aluminum foil (a); an applied layer of CNTs (b); the process of IHT at the sintering temperature (c).

The induction treatment of sandwich structures was conducted using a special device that provided primary compression of the assembly. The treatment temperature of the layered assemblies lied in the range of (0.9–0.95)×T_m with a process duration within 0.5–1 min (figure 1,c).

When studying the structure of the resulting aluminum foil sandwich, methods of optical and scanning electron microscopy (SEM) were used. Mechanical tests were performed to establish tensile strength and the clamps with soft inserts were used to fix the samples.

Surface electrical resistance was measured by the four-probe method using a picoammeter ("Keithley 6485", Textronix, US) and a DC voltage source ("Agilet 6614C", US). Surface resistance tests were performed in accordance with ASTM D4496–87 standard.
3. Results
During induction treatment of the formed assembly, there was a thermal effect on the system containing a special clamping device (figure 2,a). As the temperature grew, the plasticity of the heated material increased as well, and in a number of cases, partial melting was observed. The pressure in the system decreased and a homogeneous structure was formed; however, during mechanical tests (bending), defects appeared, in particular delamination occurred (figure 2,b).

The internal structure of the sandwiches was layered and there were joint areas between the layers (figure 3,a). In the enlarged parts, changes in the directional structure of the deformed metal were observed, which was associated with the temperature effect as a result of IHT (figure 3,b). A sandwich structure sample having 32 aluminum layers without any melt regions on the lateral surface was characterized by increased strength (about 25–28 %) and high plasticity. The thickness of the resulting composite was at the level of 0.89–0.93 of the theoretical value.

In the presence of CNTs filler, the joint areas were retained; however, a fibrous structure was observed between the layers (figure 3,c). The strength of the resulting structure was increased on average by 10–12 % whereas the ductility was unchanged. Thus, CNTs formed fibrous structures between the layers of aluminum foil (figure 3,d).

When studying the functional characteristics of the resulting samples, it was also found that the use of CNTs allowed increasing the surface conductivity by a factor of 8.3–9.5 compared to the sandwich structure without filler. This may be due to the influence of CNTs on the integral value of the conductivity of a thin-layer system containing a strengthened aluminum alloy (Fe content of 0.5–1 wt.%).

4. Conclusions
The possibility of creating a homogeneous "Al – CNTs" sandwich structure with increased strength was shown in the study. The use of CNTs filler allowed increasing the surface conductivity by a factor of not less than 8, which can find application in the creation of electromechanical systems.
Figure 3. Fracture surface of the aluminum sandwich (a); an enlarged fragment of the layered structure (b); an area of the interaction between CNTs and the aluminum foil (c); an enlarged fragment showing accumulation of fibers of CNTs (d).

Acknowledgments
The research was supported by the Ministry of Education and Science of the Russian Federation and German Academic Exchange Service (DAAD) in the framework of the program "Mikhail Lomonosov" (Agreement No. 075-03-2021-304/3 from 21.05.2021; Project Executor Fomin A.A.).

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