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A method for introduction of Al_2O_3 nanofiber into aluminum alloy

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Abstract. Experimental samples of aluminum matrix composites (AMCs) reinforced with Al_2O_3 nanofibers were obtained. In order to increase the wettability in liquid phase combination conditions, it is proposed to use copper powder as a carrier of nanofiber. When studying the structure of the samples, a modifying effect of the introduction of reinforcement, demonstrated by grinding the grain, was revealed.

1. Introduction

The development of modern science and technology requires the optimization of technical characteristics of machines and mechanisms, which can be provided on condition that new materials are created and fully utilized [1,2]. Current researches have proved that aluminum matrix composites (AMCs) are very promising new generation materials, and AMCs have aroused considerable interest among researchers. AMCs combine the best properties of their two constituents, such as ductility and toughness of the aluminum matrix, high modulus and strength of the reinforcements [3]. Important AMCs applications in the ground transportation (auto and rail), thermal management, aerospace, industrial, recreational and infra-structure industries have been enabled by functional properties that include high structural efficiency, excellent wear resistance, and attractive thermal and electrical characteristics [4,5]. AMCs can reduce the curb weight of vehicles, thereby improving fuel efficiency [6]. 10% reduction in the weight of cars and light-duty trucks can reduce CO_2 emissions by 72 million metric tons. A market report from Technavio Research in 2017 says that the global metal matrix composites market size is projected to reach 10.8 kilotons by 2021, growing at a CAGR of over 6% during the forecast period. According to market report from Grand View Research, the largest product segment was the aluminum-based metal matrix. It accounted for 30% of the demand. The need for lightweight and high tensile strength parts are the driving factors for the demand of aluminum to soar [7]. The North America market is expected to remain the largest market for 2022 (figure 1).

So far, various efforts have been made to exploit aluminum matrix composites with different reinforcement materials. In particular, since nanosized materials own a series of excellent performances, many studies have been done to develop AMCs with nanosized reinforcements (CNTs, graphene, SiC nanoparticles, Al_2O_3 nanoparticles, etc.) [3,8,9]. On the other hand, a few results have been reported on alumina nanofibers reinforced aluminum matrix composites.

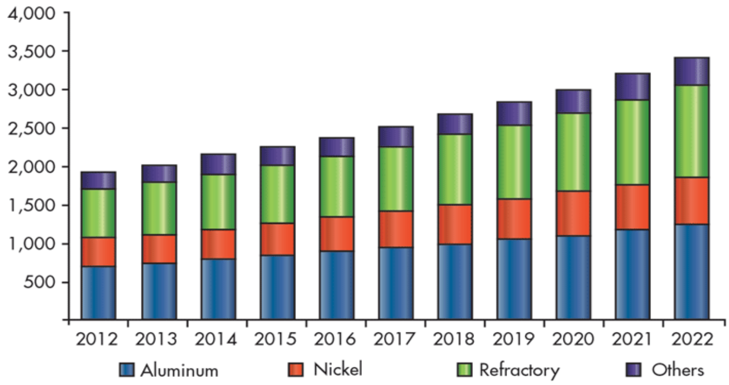


Figure 1. North America metal matrix composite market volume by product, 2012-2020 (Tons) [7]

Alumina nanofiber is one of the most important ceramic nanomaterials, which finds applications in many areas such as high-temperature insulation, reinforcement components, microelectronics and optics, fire protection and catalysis [10,11]. Alumina nanofibers (Al_2O_3-NFs) have very high elastic modulus and high tensile strength. Compared to other nanosized reinforcement materials, aluminum oxide nanofibers have high temperature properties. Therefore, they are suitable as reinforcement materials of large scale aluminum matrix composites.

There are various methods to synthesize AMCs [2,3,12]. Generally, these methods are classified into: solid state processing, liquid state processing and vapour deposition [12]. In liquid state methods, the aluminum matrix is in the state of iquid. As a useful method of liquid state processing to produce AMCs, casting is a more industrial compatible technique to produce composites in large scales [13].

However, the fabrication of composites with uniformly distributed Al_2O_3 nanofibers by casting is very difficult. The problem is that, due to the physicochemical features, the aluminum matrix and alumina nanofibers reinforcement are quite difficult to connect. Nanomaterials with a large specific area (up to 1000 m^2/g) usually tend to easily agglomerate due to the presence of van der Waals forces. In addition, a significant difference in surface tension and density between nanosized reinforcements and matrices complicates the connection. Thus, the main technological problems of introducing discrete Al_2O_3 nanofibers into aluminum alloys are to overcome the surface tension forces and ensure homogeneity of their distribution.

The analysis of the special literature showed that an effective way to improve wettability is alloying the matrix alloy and applying special coatings to the reinforcing phase. The hypothesis of the experimental part of the studies is the use of copper as a component that ensures an improvement in wettability [14,15]. Copper is proposed to be introduced in the form of powder, which simultaneously acts as a carrier of nanofibers.

2. Experimental procedure

2.1: Materials

In the current research, AK6 aluminum alloy was chosen as the matrix alloy. The chemical composition of AK6 aluminum alloy according to GOST 4784-97 [16] is shown in Table 1. Table 2 shows the properties of AK6 aluminum alloy.

Table 1. Chemical composition of AK6 aluminum alloy (wt.%).

Composition	Al	Cu	Si	Fe	Mn	Mg	Zn	Ti	Ni
wt.%	93.3-96.7	1.8-2.6	0.7-1.2	<0.7	0.4-0.8	0.4-0.8	<0.3	<0.1	<0.1

Table 2. Properties of AK6 aluminum alloy.

Material	Density (g/cm^3)	Vickers Hardness (MPa)	Young's modulus (GPa)	Tensile strength (MPa)
AK6	2.75	95-100	72	400

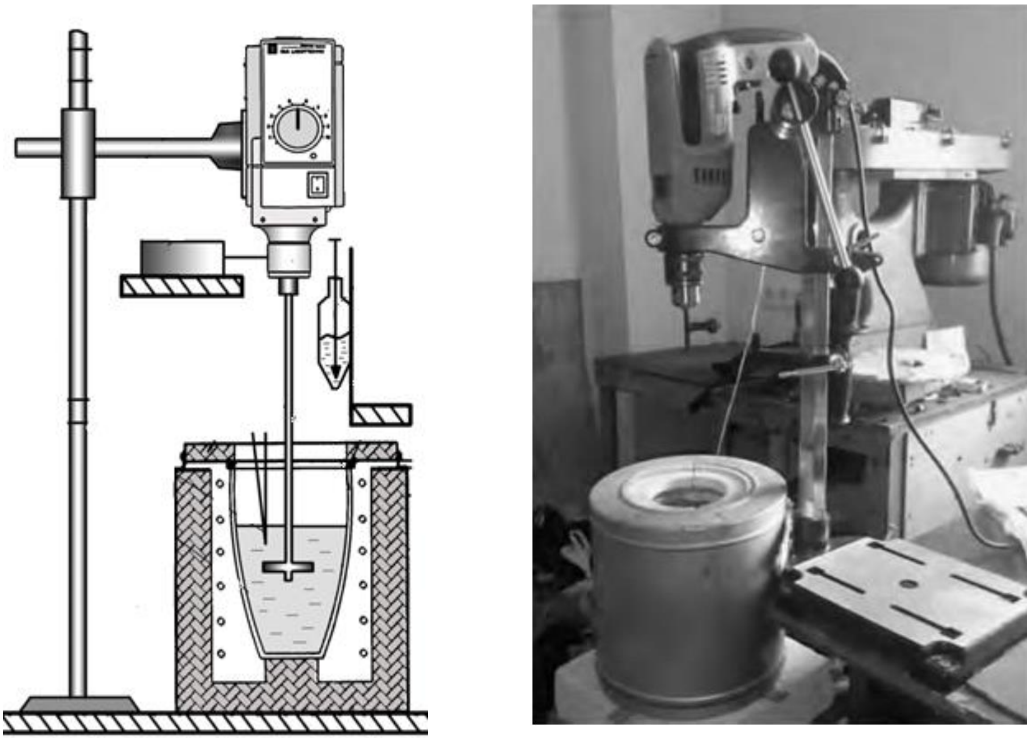
Discontinuous nanosized alumina fibers were used as the modifying additive. "Nafen" brand Al_2O_3-NFs with an average diameter of 10-20 nm and an average length>100 nm were offered by ANF Technology Ltd (Estonia). The properties of Al_2O_3-NFs were shown in Table 3.

Table 3. Properties of Al_2O_3 nanofibers.

Material	Density (g/cm^3)	Thermal resistance (°C)	Young's modulus (GPa)	Tensile strength (GPa)
Al_2O_3-NFs	3.98	1200	400	12

2.2: Fabrication of composites

To combine the matrix alloy with discrete Al_2O_3 nanofibers placed on copper powder, a casting method of mechanical stirring was used. As illustrated in figure 2, the introduction of Al_2O_3 nanofibers into the aluminum melt was carried out at a temperature of 800°C with constant stirring at a rate of 600 rpm for 10 min. Figure 3 shows the agitated Al_2O_3 nanofibers/Al composites.



a b

Figure 2. Schematic diagram (a) and experiment device (b) of the liquid process for composite manufacturing by mechanical stirring

Figure 3. Al_2O_3 nanofibers/Al composite

2.3: Composite characterizations

The macrostructure of the aluminum alloy and the as-fabricated composites was characterized by Optical Microscopy (Neophot 21), and the microstructure of the aluminum alloy and the as-fabricated composites was characterized by Optical Microscopy (Olympus GX51).

3. Results and discussion

3.1 Comparative analysis of the macrostructure

The results of comparative studies of experimental initial and filled samples, carried out on the Neophot 21 microscope with an attachment for macroscopic studies with zoom of 20x, are shown in Figure 4. It indicates that the addition of Al_2O_3 nanofibers has reduced the grain size of aluminum matrix. Besides, the porosities are visible in the composite, which could be attributed to gas entrapment during the stirring.

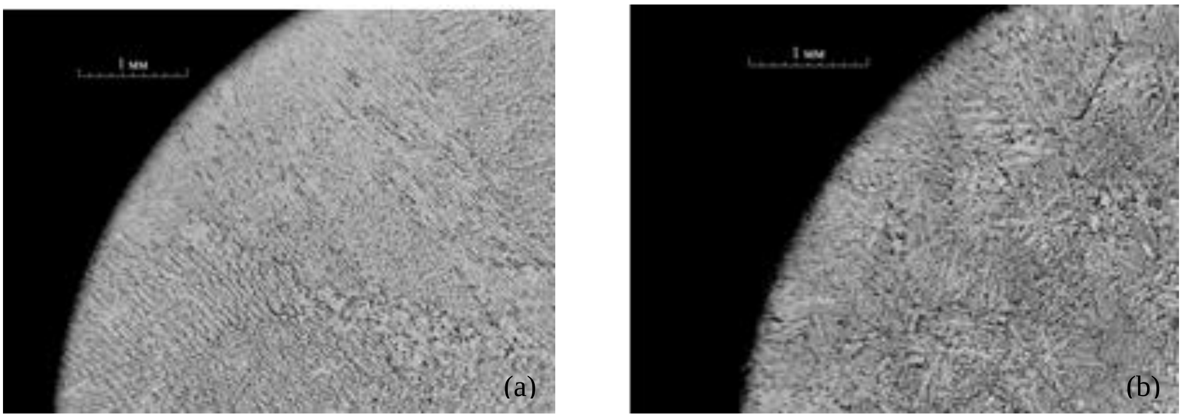


Figure 4. Optical macrostructures of cast materials: (a) AK6 alloy matrix; (b) Al_2O_3 nanofibers/Al composite

3.2 Comparative analysis of the microstructure

The results of comparative studies of the microstructure performed on the Olympus GX51 microscope after etching in 0.5 % aqueous HF solution with zoom of 100x and 500x are shown in figure 5.

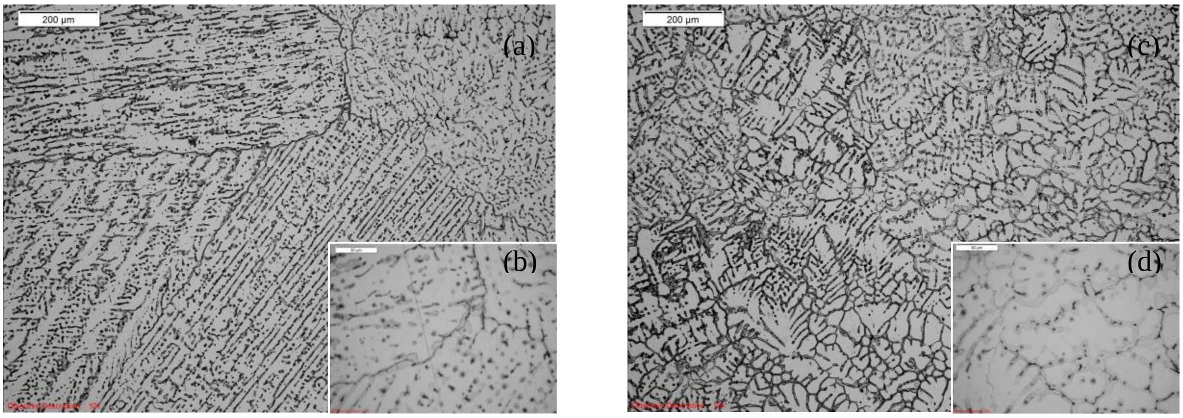


Figure 5. Optical microstructures of cast materials: (a,b) AK6 alloy matrix; (c,d) Al_2O_3 nanofibers/Al composite

Analysis of the structure at various magnifications, demonstrated the presence of a modifying effect, expressed in the grinding of structural components. So, if the average grain size is taken as the quantitative index, then the average grain area, estimated by the method of GOST 5639-82 [16], is equal to 1.1 mm^2 and 0.015 mm^2 for the initial and modified samples, respectively.

4. Conclusion

Based on the present study, the following conclusions can be drawn:

(1) As a result of the work, by mechanical mixing, samples of a composite material with a filler in the form of a thin-discrete alumina with a diameter of 10-20 nm were obtained.

(2) In the course of the study, the effect of introduction of nanofibers on structure refinement is established.

Thus, the analysis of the results of the study showed the presence of a modifying effect in aluminum alloy from the introduction of Al_2O_3 nanofibers .

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