Investigation of structure, mechanical properties and crystallization of aluminum alloys containing aluminum oxide nanoparticles

Vladimir Valikhov¹, Nikolay Kahidze¹, Anton Khrustalyov¹, Ilya Zhukov¹, and Alexander Vorozhtsov¹

¹ National Research Tomsk State University, 36 Lenin Ave., Tomsk, Russia, 634050

Abstract. A357 and 6082 aluminum alloys strengthened by aluminum nitride nanoparticles were obtained. The process of crystallization of the A357-0.5 wt% Al₂O₃ and 6082-0.5 wt% Al₂O₃ alloys was studied under conditions of varying the cooling rate. The A357 and 6082 aluminum alloy structure and hardness were analyzed for the Al₂O₃ content from 0 to 1 wt%.

1 Introduction

Aluminum and its alloys are widely used in modern industries [1, 2] such as machine building, aerospace, shipbuilding, chemical, electrical engineering, etc. Their wide application is due to the presence of a number of properties, namely high corrosion resistance, small linear shrinkage, crack resistance, low mold shrinkage and good fluidity [3-5]. The development of nano- and microtechnologies for producing various powder materials [6-8] allows one to apply them in non-ferrous metallurgy and create metal matrix nanocomposites (MMNC) and metal matrix composites (MMC) based on traditional aluminum alloys. In this case, composite material properties will be determined by the type and amount of the particles introduced. The results obtained [9-14] allow us to assert that MMNCs based on aluminum and with nanoparticles introduced into them have higher performance characteristics, in particular, ultimate strength, yield strength, plasticity, hardness, heat resistance, etc. [15-18]. The production of MMNCs based on aluminum is possible in different ways, such as by casting (in a chill mold, sand, centrifugal, etc.), powder metallurgy methods (solid-phase sintering [19], liquid-phase sintering [20], hot pressing [21], shock-wave compaction [22]), impregnation [23], laser cultivation, etc. [24-26]. However, casting is the most universal way among the listed ones, because it has the following advantages: high productivity, simple equipment, its ability to fabricate large-volume and large-weight billets, its ability to produce complex geometric shapes, low cost of castings, etc.

Using alumina particles is of great interest as this compound remains stable over time, unlike carbides or magnesium oxides which can react with water and decompose.

When nanoparticles are introduced into the melt during casting, there exist a number of problems: agglomeration and floating to the surface because of the

poor wettability of the particle surface by the metallic melt. These can be solved in various ways, namely by introducing nanoparticles through master alloys and treating the melt by external means (mechanical mixing, electromagnetic, vibration or ultrasonic treatment). Ultrasonic treatment of the melt seems to be a promising technology for producing composite materials based on light alloys. Ultrasonic treatment contributes to the intensification of various processes in the melt due to cavitation, namely those of degassing, refining the structure (grain refinement), particle dispersion and deagglomeration and their redistribution [27-28]. In addition, when obtaining reinforced aluminum alloys, an important parameter is the cooling rate which can significantly affect the final properties of the casting. The presence of nanoparticles in the melt can significantly affect the crystallization of the melt during the cooling process [29].

The aim of the work was to obtain aluminum alloys containing alumina nanoparticles and study their structure and mechanical characteristics at various cooling rates.

2 Materials and methods

The initial materials used in this work were aluminum oxide nanopowder (<100 nm) obtained by the electric explosion of wire (EEW) technique [30], aluminum powder ASD6 (<50 µm) and aluminum alloys (6082 and A357).

2.1 Preparation of powders

For aluminum oxide nanoparticles to be introduced, a powder mixture of Al-5wt% Al₂O₃ was prepared. To provide deagglomeration and a uniform distribution of the nanoparticles in the powder mixture, stirring was carried out using stearic acid as a surfactant. 200 ml of

* Corresponding author: tofik0014@mail.ru

petroleum ether and 1.5 wt% of stearic acid were added to the powder mixture. After that, its mechanical stirring was carried out for 20 minutes. Finally, the powder mixture was air-dried and sieved.

2.2 Obtaining the master alloy

A master alloy is a metal matrix with particles and is intended to be introduced into the melt. To obtain the master alloy needed based on the previously prepared powder mixture, we applied the shock-wave compacting method. As an explosive, we used the commercial explosive Uglenit whose density is $\sim 1.2 \text{ g/cm}^3$, the detonation speed is 2300 m/s and the detonation pressure is 2 GPa. A detailed scheme of shock-wave compacting of powder mixtures is described in this paper [31].

2.3 Preparation of aluminum alloys

The 6082 and A357 aluminum alloys were melted in a graphite crucible in air with the total volume of each melt of 500 g. The ultrasonic treatment was carried out using a 5 kW water-cooled magnetostrictive converter with an operating frequency of 17.5 kHz. A conic waveguide with an operating amplitude of $\sim 30 \text{ }\mu\text{m}$ was made of niobium. Ultrasonic degassing was carried out at a melt temperature of 730°C for 1 minute. Then, the obtained master alloy (Al-5 wt% Al_2O_3) was introduced into the zone of ultrasonic cavitation in the melt directly under the waveguide. After introducing the master alloy, the melt was ultrasonically treated for another 2 minutes at a temperature of 730°C. Then, the melt was cast into a metal mold at a temperature of 710°C. The nominal content of aluminum oxide nanoparticles in the alloys was 0.5 and 1wt%. The initial alloys were obtained using the similar treatment parameters, but without introducing a master alloy.

To investigate the influence of the cooling rate on the structure and properties of the aluminum alloys containing alumina nanoparticles, wedge-shaped castings were made, at the base of which a smaller cooling rate was realized, while a higher cooling rate was at the top.

2.4 Research methods

Obtaining the samples of composite materials was followed by the preparation of metallographic sections to study the composite microstructures. The specimens prepared were chemically etched in a solution of picric acid to reveal the grain boundaries of the resulting material. Analysis of the structure of the samples was carried out using an Olympus GX71 optical microscope. To calculate the average grain size, the random secant method was used.

3 Results and discussion

3.1 Microstructure of the 6082- Al_2O_3 alloy

Figure 1 shows the optical microstructure images of the 6082-0.5 wt% Al_2O_3 composite in various sections of the wedge-shaped specimen.

Fig. 1. A composite microstructure 6082-0.5 wt% Al_2O_3 in various sections

It can be seen that with decreasing the size of the casting section (an increase in the cooling rate), the grain size decreases from 200 to 100 μm , that can be directly related to the change in the cooling parameters in different zones of the wedge-shaped casting. At the same time, the alumina nanoparticles are likely to have little effect on the crystallization of the 6082 aluminum alloy. The average dendritic cell size of the 6082 alloy is reduced from 42 to 13 μm .

Figure 2 shows the structure and the grain size distribution for the 6082 aluminum alloys before (Figure 2a) and after introducing nanoparticles (Figures 2b, c).

According to the obtained images the average grain size of the aluminum alloy with 0.5 wt% of the nanoparticles introduced increases from 155 to 240 μm and slightly changes from 240 to 220 μm after increasing the content of alumina (up to 1wt%). The negative effect of nanoparticles can be due to their agglomeration during the production process. Agglomeration and the inability to break such agglomerates with ultrasound lead to a decrease in the efficiency of ultrasonic treatment of the aluminum matrix.

Fig. 2. A microstructure and histograms of alloys 6082 (a), 6082-0.5 wt% Al_2O_3 (b), 6082-1 wt% Al_2O_3 (c).

3.2 Hardness of 6082- Al_2O_3

Table 1 shows the results of the microhardness measurements (HV) for the composites obtained.

Table 1. Hardness of 6082 alloy and the alloys obtained on its basis.

Alloy	HV _{min}	HV _{max}	HV _{average}
6082	53	84	67
6082-0.5wt% Al_2O_3	63	71	65
6082-1wt% Al_2O_3	58	75	68

It can be seen that the introduction of aluminum oxide nanoparticles does not change the 6082 alloy hardness. At the same time, the results of the microhardness measurements for the initial alloy have a wide range of values, which decreases with the introduction of nanoparticles. This may be due to hardening of the aluminum substrate, but the hardness of the alloy surface areas containing intermetallics [32] is higher and the total contribution of nanoparticles to hardening is negligible.

3.3 Microstructure of the A357- Al_2O_3 alloy

Figure 3 shows the optical microstructure images of the A357-0.5 wt% Al_2O_3 composite in various sections of the wedge-shaped specimen.

Fig. 3. A357-0.5wt% composite microstructure in various sections.

It can be seen that the average size remains practically unchanged, that indicates an insignificant effect of the cooling rate and the presence of nanoparticles on the alloy structure. Meanwhile, the cooling rate significantly affects the average dendritic cell size of the A357 alloy, which is reduced from 152 to 45 μm .

3.4 Hardness of A357- Al_2O_3 .

Table 2 illustrates some change in the hardness of the resulting alloys.

Table 2. Hardness of A357 alloy and the alloys obtained on its basis

Alloy	HV _{min}	HV _{max}	HV _{average}
A357	76	86	80
A357-0.5wt% Al_2O_3	69	87	76
A357-1wt% Al_2O_3	76	86	80

Figure 4 shows the microstructure and the grain size distribution in the A357-0.5 wt% Al_2O_3 (Figure 4a) and A357-1wt% Al_2O_3 (Figure 4b) aluminum alloys.

Fig. 4. Microstructure and histograms of A357-0.5wt% Al₂O₃ (a) alloys and A357-1wt% Al₂O₃(b).

It can be seen that introducing the nanoparticles does not affect the hardness of the A357 aluminum alloy, that may be due to the fact that the process of obtaining such a composite needs their proper introduction and distribution, so the method applied requires further analysis and optimization.

4 Conclusion

The cooling rate of the 6082 aluminum alloy has been revealed to directly affect its grain size.

The introduction of more than 0.5 wt% of aluminum oxide nanoparticles has been found to lead to negative consequences for the microstructure of the 6082 alloy (an increase in the average grain size of the alloy was from 155 μm to 220-240 μm).

The change in the cooling rate and the introduction of aluminum oxide nanoparticles into the A357 alloy have been shown to slightly affect the change in the average grain size of the alloy.

Also, it has been found that the introduction of aluminum oxide nanoparticles does not significantly affect the hardness of the aluminum alloys.

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