Structure and mechanical properties of A356-C alloys

Marina Khmeleva^{1,*}, Anton Khrustalev¹ and Alexander Vorozhtsov¹

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

Abstract. The paper deals with influence of mechanical mixing and vibration treatment on the structure and mechanical characteristics of the aluminum alloy containing ≤ 1 wt.% of nanodiamonds (A356-C). The alloy was obtained from industrial A356 Al-Si casting alloy by means of an integrated effect of mechanical mixing and vibration. It has been shown that the introduction of nanodiamond particles contributes to improving the alloy structure and increasing its mechanical tensile properties. The structure of the A356 aluminum alloy has been refined with introduction of 0.2 wt% nanodiamonds and application of vibration melt treatment. The introduction of nanodiamonds into the melt and the vibration melt treatment enable one to increase the yield strength and tensile strength of the A356 aluminum alloy without any change in ductility.

1 Introduction

Metal casting is one of the most important industrial processes offering a variety of advantages, such as the possibility to inject into a mold, the efficient use of metals, and high performance with minimal labour intensity, etc. [1]. In recent years, materials industry has caused increasing interest in aluminum alloys production. Meanwhile, Al-based and Al-Si alloys characterized by good mechanical and metallurgical properties have attracted the attention among cast alloys [2]. However, further improvement of mechanical properties for aluminum alloys is a major challenge for metallurgy.

It is known that the formation of fine-grained texture for Al-alloys is a most important condition for obtaining high-quality alloys. Many researchers and metal scientists have developed various methods to control the alloy structure and helped to implement these methods in manufacturing, thereby allowing one to influence a number of their properties [3-8]. The application of hardening non-metallic particles is an urgent issue for improving the cast alloy structure due to the grinding of structural components (α -Al solid solution, α -Al+Si eutectic phases). At present, there are quite a number of experimental data on the use of metal oxides (Al_2O_3 , TiO_2), carbides and borides for modification of the Al-Si alloy grain structure [9-13]. Carbon nanomaterials (carbon nanotubes, fullerene and shungite carbon) are also widely used for the grain structure refinement and the improvement of mechanical properties for aluminum alloys [14-15]. The injection of diamond nanoparticles (DNPs) obtained by the detonation of high explosives into aluminum matrix is of particular importance [16]. DNPs are an example of nanomaterials which production was fully deployed and commercialized [17]. The interest in nanodiamonds is caused by combining their

unique properties: high hardness and inertness of diamond nanoparticles with a high chemical activity of porous amorphous shells on their cores, their resistance to attack by corrosive media, etc. [18]. High dispersion of detonation nanodiamonds can significantly change properties of composite materials when introduced in a relatively small volume fraction [19].

Thus, it was shown that nanodiamond particles allow effectively managing aluminum alloy properties. Meanwhile, there is a fact about a possible non-uniform distribution of introduced refractory particles within the ingot structure. To address this concern, various kinds of external influences on liquid metals are used. There are a large number of studies to examine ultrasound [20, 21] and electromagnetic [22] effects on aluminum liquid metals. The vibration treatment is a method of external physical impact on liquid metals that is applied to improve their microstructure and, therefore, mechanical properties during crystallization. The vibration treatment (VT) is a cost-reserved and simple method to control the crystallization process with high performance. It also does not require high energy consumption.

A number of studies have been conducted to explore the vibration effect on alloy properties [23, 24]. It was concluded that the oscillation superposition causes the cavitation which destroys growing crystals. It was experimentally shown that the decrease in grain size provoked growth of the vibration frequency up to a certain value [25-27]. Many papers were also devoted to examining the influence of low-frequency vibrations on crystallization processes and the formation of fine-grained texture. However, issues related to the effects of vibration and modifying particles on the structure change and the improvement of mechanical properties for aluminum alloys remain unclear and require further study and discussion. It is important to investigate the integrated effect of modification and vibration on the

* Corresponding author: khmelmg@gmail.com

crystallization and mechanical properties of Al-Si alloys. At the same time, the wettability of nanoparticles will be the main factor influencing their introduction and distribution during the vibration treatment.

The aim of this research was to determine the effect of DNPs and the vibration treatment on the structure and mechanical properties of the A356 aluminum alloy.

2 Materials and methods

The A356 aluminum alloy (Al-Si system, GOST RF 1583-93 Russia) based on the Al-Si system was used as a matrix alloy. The DNP (Fig.1) obtained by detonation synthesis was used for alloy hardening [28, 29]. To improve the wettability of DNPs, they were premixed with micro-sized aluminum powder and the resulting mixture was wrapped with aluminum foil.

Fig. 1. SEM image of nanodiamond powder ("FSPC "Altai", Russia).

The A356 alloy was placed in a crucible located in an enclosed-type furnace at 800 °C. Then, using a gripper we removed the crucible from the furnace and poured the liquid metal at 700 °C in a preheated chill mold with a cylindrical cavity (diameter of 30 mm and a height of 110 mm) which was located on a vibrating table. The vibration frequency was 60 Hz, the amplitude was 0.53 mm (a schematic representation of the process is shown in Fig. 2).

Fig. 2. Schematic representation of the vibration effect on the melt.

Another experiment was carried out to evaluate the integrated effect of nanoparticle modification and vibration. A rod-shaped container with DNPs was heated in the furnace at 200 °C. The special mixing device (the device consisted of several perforated disks with openings and pins made of commercially pure titanium; the rotational speed was 1500 rpm) was used to

provide a uniform distribution of DNPs within the melt volume. The mixing device was completely immersed in the molten metal. Then a container with DNPs was fed into the mixing zone for 30 sec mixing with the subsequent casting at 250 °C into the steel chill mold located on the vibrating table (Fig.2. The content of DNPs in the alloy was 0.2 and 1 wt%.

The structure of obtained materials was studied by an optic microscope Olympus GX71 (Olympus, Japan). The microstructure was achieved by mechanical polishing and electrochemical oxidation with 5% fluoroboric acid at the voltage of 20 V and current of 1 A. An universal testing machine Instron 3369 (Instron, USA) was used for mechanical tensile testing of the alloys. The density of the alloy samples was determined by a hydrostatic weighing method using the following formula:

$$\rho = \frac{m}{V}$$

where m was the sample mass, V – the sample volume, calculated as the difference between its mass in air and in water.

The tensile test samples were in a shape of flat blades with a useful cross section of 1×6 mm and a length of 35 mm. The strain rate was 0.001 s⁻¹, while the test temperature was 23 °C. Three samples were tested for each alloy.

3 Results and discussion

Fig. 3 shows optical images of the initial A356 alloy surface and that of A356 alloys with DNPs (0.2 wt% and 1 wt%) in two modes: before and after the vibration effect.

Fig. 3. Optical images of the surface of alloys: A356 (a), A356_VT (b), A356+0.2wt%C (c), A356+0.2wt%C_VT (d), A356+1wt%C (e), A356+1wt%C_VT (f).

The samples with DNPs and without the vibration treatment was not observed a decrease in average grain size (460 μm for the A356 alloy + 0.2 wt%C; 429 μm for the A356 alloy + 1 wt%C, Fig. 3a, 3c, 3e) compared to the initial A356 alloy (423 μm). However, the combined effect of the DNPs injection and vibration treatment on the melt during the crystallization process greatly affected the size and structure of the grains. The average grain size decreased goes down from 449 μm (the A356 alloy after vibration, Fig.3b) to 176 μm (the A356 alloy + 0.2 wt%C after vibration, Fig.3d) and to 386 μm (the A356 alloy + 1 wt%C after vibration, Fig.3f). Drop in grain size may be associated with the formation of new crystallization centres and a significant containment of the crystal growth due to their destruction under the oscillatory effect arising during the vibration treatment of the melt. The 0.2 wt% DNPs injection provided a greater number of crystallization centers after the vibration effect. The 1 wt% DNPs injection led to agglomerate into larger micron particles and this does not allow to use them effectively as modifiers. The DNPs content of 0.2 wt% cannot be considered limiting as there are intermediate values up to 1 wt% that require further research. The density of all alloys did not change and was about 2.6 g/cm^3 .

Fig. 4. Mechanical properties (engineering curves) of A356 alloy and A356-based composite alloys before and after the vibration effect.

Table 1. Properties of A356 alloy and A356-based composites containing diamond particles before and after the vibration effect.

Alloy	YS, $\sigma_{0.2}$ MPa	UTS, σ_B MPa	ϵ , %	d, μm	ρ , g/cm^3
A356	33	143	4	423	2.56
A356+0.2 wt%C	142	199	2	460	2.54
A356+1 wt%C	150	204	2.4	429	2.57
A356 VT	74	183	4	449	2.55
A356+0.2 wt%C VT	155	273	4	176	2.58
A356+1 wt%C VT	169	282	3.5	386	2.6

Mechanical tensile testing (Fig. 4) showed that there was an increase in the yield strength from 33 to 142 MPa for A356 alloy + 0.2 wt%C compared to 150 MPa for A356 alloy + 1 wt%C; the tensile strength from 143 to 199 and 204 MPa for (A356 alloy, respectively, with 0.2 and 1 wt% of C followed by insignificant reduction in plasticity compared to the initial A356 alloy. The ductility of aluminum alloy with the introduction of 0.2 wt% DNPs reduced from 4% to 2%. Increasing the amount of DNPs in the alloy up to 1 wt% did not significantly affect the ductility, that was 2.4%.

It can be observed (fig.4) that the vibration treatment of the A356 melt helps to improve tensile test outcomes: the yield strength from 33 to 74 MPa and the tensile strength from 143 to 183 MPa while maintaining the plasticity, in comparison with the initial A356 alloy. The injection of 0.2wt% DNPs with subsequent vibration treatment of the melt allows increasing the yield strength from 74 to 155 MPa and the tensile strength from 183 to 273 MPa while maintaining the plasticity (4%) compared to the A356 alloy after vibration. A further increase in DNPs concentration to 1wt% demonstrates high mechanical properties of the alloy: there is an increase in the yield strength from 74 to 169 MPa and the tensile strength from 183 to 282 MPa.

Table 1 presents the mechanical and structural properties of the A356 alloy and A356-based composites containing diamond particles before and after the vibration effect.

The increase in A356 alloys with DNPs strength properties compared to the initial A356 alloy may be related to the presence of structure heterogeneities that significantly affect the ultimate mechanical properties of the materials. In work [30] the vibration treatment of an aluminum alloy containing particles was used, which allowed improving the structure and mechanical properties without reducing its ductility. The mechanical properties are formed mostly due to the contribution of three mechanisms resulting from the presence of diamond particles in the structure of composites. The first mechanism is the load transfer from the particle to the matrix. This mechanism was due to the influence of hardening particles on composite properties [11]. Under specified conditions nanoparticles can change the direction of growth of the defect by orienting it from the boundary into the grain volume. The implementation of the second mechanism (the Hall-Petch law) [11] seems to become possible due to a dramatic decrease in the grain size for composites (A356+0.2 wt%C) from 423 to 176 μm after the vibration effect, in comparison with the initial alloy. The second mechanism is typical for the alloys containing 0.2 wt% of DNPs with a significant modifying effect. The third mechanism is the Orowan one, where non-cut nanoparticles can prevent dislocations from moving. As a result, the dislocation line bends and forms an Orowan ring around the particle.

4 Conclusions

We have shown the integrated positive effect of DNPs introduction and vibration treatment on A356 alloys and

A356-based composites. It has been concluded that the composites containing 0.2...1 wt% of DNPs are characterized by lower grain sizes in comparison with the initial alloy due to the formation of new crystallization centers and a significant containment of crystal growth during the vibration effect on the melt.

Low additives of DNPs jointly with vibration treatment (0.2 wt%) improves mechanical properties of Al alloys. The composite mechanical properties significantly increase due to the influence of at least three mechanisms: the load transfer from the particle to the matrix, the Hall-Petch law and the Orowan mechanism.

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