Production of Aluminum Matrix Composite Material by Internal Oxidation

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Abstract. The scope of the use of aluminum-alloy-based metal-matrix composite materials has been expanding in recent years. However, the high cost of raw materials is a considerable deterrent to the widespread implementation of products made of such composites. Therefore, the ranges of the said materials commercial application are yet inadequate to their technical and operational capabilities. So, methods of making metal-matrix composite materials directly from a liquid melt are currently of interest. This paper presents the theoretical studies and the results of practical experiments for the production of metal-matrix composite material by the internal oxidation method. There are described the results of mechanical tests and the microstructure of specimens confirming theoretical assumptions in the oxidation of aluminum melt array. A comparative analysis is given for the cost of producing an alloy containing 30% of Al2O3 particles obtained by adding the Al2O3 powder and an alloy obtained by the internal oxidation of the aluminum melt. The studied technology provides for the formation of aluminum oxide directly in the aluminum melt, thus enabling to produce a composite material by a single-stage process and ensuring the process efficiency.

1. Introduction

Among other composites aluminum alloy-based metal-matrix composite materials (MMC) have gained the particular widespread use. With maintaining aluminum alloy advantages the reinforcement with dispersed particles significantly enhances mechanical and service properties scarcely affecting the density thereof [1 - 5]. The use of aluminum alloy-based MMC enables to reduce the weight of structural elements to 50% and to increase twice as much their rigidity as compared to similar metal materials (for example, steel, titanium and aluminum alloys), thus enhancing the service properties and the considerable reduction of operating costs as compared to polymer composites [6 - 10]. One of the main factors ensuring thereat the MMC strength is the particle and matrix adhesion. As noted in the relevant literature during the melt crystallization the Al2O3 particles do not act as the melt crystallization centers because of their poor wettability but their size and shape have a dominant influence on the mechanical and service properties of a finished product.

Notwithstanding such MMC advantages there should be noted their main drawbacks such as the process cycle complexity and duration and the energy to output ratio. Therefore, the scope of the MMC commercial use is yet inadequate to their technical and operational capabilities. The high cost of raw materials is a considerable deterrent to the widespread implementation of products made of MMC [11].

Therefore, methods for producing MMC directly of liquid melt are currently of interest; moreover, this is a single-stage production process, which ensures the optimum adhesion of the matrix-particle system.
Paper [12] describes a method for producing a composite material of the $\text{Al}_2\text{O}_3$ system by plastic deformation, in paper [13] a method for producing MMC saturated with aluminum nitride particles according to the reaction of $\text{Al}_2\text{O}_3 + 3\text{C} + \text{N}_2 \rightarrow \text{AlN} + 3\text{CO}$ was described, in [14] data are given about the method of producing ceramic composite $\text{Al}_2\text{O}_3 - \text{AlON} - \text{AlN}$, in [15] the process of purging the aluminum melt with water vapour to produce light deformable high-silicon multi-purpose alloys.

Statement of the Problem

For the initial calculations of the system and the successful oxidation process control the preliminary calculations were made for the oxidant warming rate areas, the assessment of the interaction area, the estimate of time to be required for the reaction completion, the hydrodynamics of the system of aluminum (solid/liquid/vapor phase) - oxygen (gas phase) - aluminum oxide (solid/liquid/vapor phase).

The oxidation of the metal melt array differs significantly from the ignition and combustion of single solid or liquid particles; their models are described in the literature [16 - 22]. The melt overheating during combustion [15] causes the boiling up of aluminum and its break through the aluminum oxide layer in the conical part above the nozzle, that is, the metal burning passes into the gas phase. This effect was previously confirmed experimentally and described in [23].

2. Theoretical Statements

In mathematical simulation the following occurrences were taken into consideration:
• conditions for the formation of bubbles, hydrodynamics of their bobbing up;  
• heat transfer from melt to gas;  
• heat release on the bubble surface.

Under the experimental stand conditions one may actually speak on the main reaction occurring during the metal melt oxidation:

$$4 \text{Al} + 3 \text{O}_2 = \text{Al}_2\text{O}_3$$

There are also possible the intermediate reactions of aluminum oxidation with obtaining $\text{AlO}$, $\text{Al}_2\text{O}$, $\text{AlO}_2$. It is also known that aluminum is oxidized during melting and this low-temperature oxide is harmful; so, metallurgists always fight therewith by melting with a shielding atmosphere, using fluxes and so on.

But it is also known that at 1100–1200°C with the $\gamma$ modification an irreversible transformation into $\alpha$-$\text{Al}_2\text{O}_3$ occurs. And during combustion the melt temperature locally increases (in a combustion area), thus, enabling to obtain $\alpha$-$\text{Al}_2\text{O}_3$, which has an advanced property package.

3. Practical Studies

To practically confirm theoretical calculations, a stand was made where the studies of the aluminum array oxidation were carried out with producing a melt saturated with dispersed $\text{Al}_2\text{O}_3$ particles of various sizes. The investigations of melt were carried out in melting pots up to 150 mm deep, up to 70 mm in diameter. The photo of the installation is shown in Figure 1.

![Figure 1. Photo of the installation with heat insulation removed. The gas supply system is shown](image)
conditionally. Designations by digits are as follows: 1 - the feed point adjustment as per the height and the feed axis deviation relative to the axis of the pot "at an angle"; 2 - the feed point adjustment relative to the pot axis “as per a distance between axes”; 3 - the feed axis adjustment “as per an angle” and the feed point depth; 4 - melting pot; 5 - protective gas supply.

The availability of several degrees of freedom enables to change within a wide range the location of both the feed point in depth and at distance between axes and the feed axis relative to the melting pot axis. In this case the tangential unwinding of the melt is possible resulting in the more efficient mixing of the melt.

During experimental works primary aluminum A6 was used as a base material. The casting of the melt obtained was carried out into steel split foundry molds designed to obtain specimens according to GOST 1497-84, type IV, with a working part of 6, 10 and 20 mm in diameter.

The study of the structural phase state of obtained specimens was carried out using LOMO RV-21 and KEYENCE VHX-1000 microscopes. The specimen hardness was determined on TKS-1M, microhardness on PMT-3. The tensile strength was determined by tensile testing machine ZD 10/90. The impact strength was determined on pendulum impact machine MK-30a. All tests were performed for cast non-heat-treatable MCM.

The achieved dimensions of the solid phase under changing the size of obtained dispersed particles are ranging from 1 µm to 2 mm; the specimen microstructure is shown in Figures 2–7 [24, 25]. The measurement was performed with the aid of the software of RV-21 and KEYENCE VHX-1000 microscopes using the function of “3 points lying on a circle” and "measuring the distance between two points".

![Figure 2](image1.png)  
**Figure 2.** A microstructure of the received material, the particle size about 1 micron (x3000)

![Figure 3](image2.png)  
**Figure 3.** A microstructure of the received material, the particle size about 8 microns

![Figure 4](image3.png)  
**Figure 4.** A microstructure of the received material, the particle size about 60 microns [24]

![Figure 5](image4.png)  
**Figure 5.** Example of firm fraction of inclusions about 0.3 mm in size
The hardness of specimens with a degree of saturation up to 30% determined on TKS-1M was 50 - 75 HRF and the microhardness of the implementation phase exceeded 480 HB. The tensile strength of the aluminum A6-based alloy strengthened by Al₂O₃ particles in the cast state was 170-230 MPa while the tensile strength of the base alloy cast under similar conditions was about 80 MPa. The variation of the solid phase content and size enables to vary the material toughness within a wide range of 23 - 85 J/cm².

Figure 7 shows the structure of a fracture in a specimen with the saturation of over 50%. It is seen that the fracture occurred on the ceramic particle; it proves the high interfacial bond in the finished specimen of the metal-ceramic particle.

The stated reduction in the cost of raw materials occurs due to the refusal of powdered components. Furthermore, the hardware, the purge unit is also far cheaper than sintering, self-propagating synthesis or mechanical doping units. For comparison we give the estimation of the cost of aluminum alloy saturated with 30% Al₂O₃. (Table 1)

The aluminum oxidation is carried out by the following reaction

\[ \text{Al} (1 \text{ g}) + \text{O}_2 (0.9 \text{ g}) = \text{Al}_2\text{O}_3 (1.9 \text{ g}) \]

Table 1. Comparison of the cost of alloy containing 30% of Al₂O₃ particles and alloy produced from powdered components

| Technology of receiving alloy | Starting materials | Cost of alloy, rub/kg |
|------------------------------|--------------------|----------------------|
| With an importation of powdery Al₂O₃ | Al 0.7, O₂ 0.16      | 420                  |
| With internal oxidation      | Al₂O₃ 0.3, O₂ 0.16  | 267                  |

Note. The price of aluminum depends on the brand and a condition of delivery (100 ... 800 rub/kg); \( \text{Al}_2\text{O}_3 \) – from purity and the size of particles (450 ... 5000 rub/kg); oxygen – from purity (25 ... 150 rub/m³).

4. Conclusions

The elaborated technology for producing MMC based on the oxidation of the aluminum melt with oxygen may essentially reduce economic costs. Moreover, quite great variations of the strengthening phase and, accordingly, mechanical properties are herein possible depending on a technical task and any required operational characteristics without changing the overall design of the installation. The production cost does not depend on the size of the strengthening phase. Reinforcing particles are synthesized here directly in the melt. It enables to produce composites within one stage and to ensure the tight contact and good adhesion between the matrix and the strengthening phase.
The degree of the melt saturation with ceramic elements is regulated by the reaction duration. The conducted studies have shown the possibility for the significant variation of mechanical properties of the material.

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