THE ROLE OF MODIFIERS IN THE MODIFICATION OF ALUMINUM–SILICON CASTING ALLOYS

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Abstract. Modification of aluminum alloys is one of the most widely used methods for improving their mechanical and service properties. This paper analyzes the effect of modifiers on aluminum–silicon casting alloys. In addition, scientific research conducted to date is reviewed, and the conclusions of the respective authors are summarized.

Keywords: aluminum, silicon, modification, mechanical properties, casting alloys, modifiers.

Annotatsiya. Alyuminiy qotishmalarini modifikatsiyalash ularning mexanik va ekspluatatsion xossalarini yaxshilashning eng keng qo‘llaniladigan usullaridan biridir. Ushbu maqolada alyuminiy–kremniy quymakorlik qotishmalariga modifikatorlarning ta’siri tahlil qilingan. Shuningdek, hozirgi kungacha olib borilgan ilmiy tadqiqotlar ko‘rib chiqilib, tegishli mualliflarning xulosalari umumlashtirilgan.

Kalit so‘zlar: alyuminiy, kremniy, modifikatsiyalash, mexanik xossalar, quymakorlik qotishmalari, modifikatorlar.

Аннотация. Модифицирование алюминиевых сплавов является одним из наиболее широко применяемых методов повышения их механических и эксплуатационных свойств. В данной статье проанализировано влияние модификаторов на алюминиево-кремниевые литейные сплавы. Кроме того, рассмотрены научные исследования, выполненные на сегодняшний день, и обобщены выводы соответствующих авторов.

Ключевые слова: алюминий, кремний, модифицирование, механические свойства, литейные сплавы, модификаторы.

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INTRODUCTION

The increasing demand for aluminum–silicon alloys in mechanical engineering, the automotive industry, and other sectors has led to extensive research on these materials [1–5]. One of the approaches to improving the properties of aluminum–silicon alloys is their modification with various elements [6]. Modification is a process of artificial alteration of the structure of cast metals and alloys, characterized by a reduction in grain size as well as changes in the shape, size, and distribution of the structural constituents of the alloy. As a result of modification, the service (operational) properties of the alloy are improved; in particular, the deformability of cast products is enhanced. At present, metallurgical methods aimed at producing a fine-grained structure or modifying ingots, which are based on varying the crystallization conditions of melts, include the following:

(a) Thermal treatment of the melt, which is based on increasing the nucleation rate of crystallization centers by altering the temperature conditions during solidification;

(b) Special alloying of the melt and the introduction of modifier elements, which practically do not change the chemical composition of the alloy;

(c) Application of external force fields (such as ultrasonic treatment, electromagnetic field application, etc.) to the crystallizing system, particularly affecting the topology of the liquid–solid interface;

(d) Combined methods, involving the simultaneous action of the above-mentioned approaches.

It should be noted that two types of modification of metals and alloys are distinguished: first-type modification, in which modifiers inhibit crystal growth, and second-type modification, in which modifiers increase the number of crystallization nuclei through the use of inoculants. This paper presents a comprehensive analysis of various studies on aluminum modification carried out by researchers worldwide.

MATERIALS AND ANALYSIS

Balandin G. F. [7] proposed the following classification of modification types according to the nature of the structural changes they induce:

Table 1.

Classification of Modification Types of Aluminum Alloys.

Modification Type	Main Structural Change	Typical Casting Process	Resulting Effect
Type I	Change (refinement) of primary grain size	Ingot casting of aluminum alloys	Grain refinement, improved strength and ductility

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Type II	Change in the internal structure of primary grains	Alloying with isomorphous additives	Enhanced uniformity of microstructure
Type III	Modification (refinement) of eutectic structure	Shaped casting of Al–Si alloys (silumins)	Improved mechanical and service properties

According to another classification system, modification using surface-active additives is referred to as first-type modification, whereas modification with isomorphous additives is classified as second-type modification. It should be noted that under industrial conditions of aluminum alloy casting, grain refinement occurs during ingot casting (Type I), while refinement of the eutectic structure takes place during shaped casting of silumins (Al–Si alloys) (Type III).

The nucleation theory includes the principle of structural and dimensional correspondence, formulated by P. D. Dankov. It is known that during the crystallization of alloys, a certain degree of undercooling (1–2 °C) occurs; however, this undercooling is not observed when 0.002–0.1 wt.% Ti is added. In this case, a fine-grained structure is formed across the ingot cross-section, which is explained by the presence of nuclei such as carbides, borides, and aluminides, on which crystallization is initiated.

For effective action, these additions must be stable in the aluminum melt at high temperatures (the melting point of the additive must be higher than that of aluminum), exhibit structural and dimensional compatibility with the aluminum lattice, and form strong adsorption bonds with the atoms of the modified melt [8]. The criterion for such interactions is the surface tension at the melt–solid particle interface. Moreover, the higher the surface tension value, the poorer the wetting of the particle and the lower the probability of its participation as a crystallization nucleus.

Researchers I. P. Volchok, A. A. Mityaev, and R. A. Frolov from Zaporizhzhia National Technical University proposed improving the quality of aluminum alloys through the application of complex (combined) treatment. Their studies were carried out on AK7ch and A356.2 aluminum alloys. The authors proposed a combined treatment of aluminum alloys involving refining and modification [9]. Analysis of the obtained data shows that fine-grained casting and the amount of modifiers (additives) exhibit a strong correlation with the mechanical properties of the alloy, namely the ultimate tensile strength σ_{β}, elongation δ, and hardness HRB.

G. T. Abdel-Jaber investigated the effect of silicon content (3–15 wt.%) in Al–Si alloys on solidification behavior, castability, and mechanical properties. It

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was found that an increase in silicon content led to an increase in solidification time, while the liquidus temperature decreased proportionally with increasing silicon content, reaching a reduction of up to 12%. When the silicon content increased from 3% to 8%, a slight increase in tensile strength was observed, which is attributed to the eutectic composition and the presence of primary silicon in hypoeutectic alloys.

With further increase in silicon content, tensile strength gradually increased and reached its maximum at a silicon content of 12%. The minimum tensile strength was observed for a mold thickness of 10 mm, whereas the maximum value was obtained at a mold thickness of 30 mm. This behavior may be associated with the effect of the solidification rate. It was also established that increasing the silicon content resulted in an increase in hardness, which reached its maximum value of 70 MPa at 12% Si. Thereafter, hardness decreased, reaching 60 MPa at 15% Si. This trend is related to changes in the eutectic composition with increasing silicon content as well as the formation of post-eutectic primary silicon.

In addition, it was determined that mold thickness has no pronounced effect on hardness, and that a fully eutectic composition is achieved only when the structure is sufficiently modified and uniformly distributed. The coefficient of friction and wear rate of Al–Si casting alloys were also studied. It was observed that weight loss decreased with increasing silicon content up to 10%, after which a slight increase occurred. The highest weight loss was recorded for castings produced in molds with a thickness of 10 mm, whereas castings produced in 30 mm thick molds exhibited lower weight loss due to the cooling effect and the presence of hard Al_2Si particles [10].

DISCUSSION OF RESULTS

At present, none of the existing modification theories provides a comprehensive explanation of the nucleation phenomena observed in practice. The mechanism of grain refinement is explained primarily by the introduction of modifier particles into the melt, which act as nucleation sites in liquid aluminum, as well as by the addition of other elements that control the grain growth rate in aluminum. Thus, grain refinement should be divided into two separate tasks: first, providing nucleation sites on which aluminum dendrites initially form, and second, controlling the growth rate of these dendrites once they reach a critical size (in this case, the critical size is defined as the size at which the dendrite becomes thermodynamically stable) [11].

At present, grain refinement in aluminum alloy ingots produced by the semi-continuous casting process is mainly achieved using rod-type modifying master alloys based on the Al–Ti–B and Al–Ti–C systems of foreign manufacture.

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However, as industrial experience shows, the use of these master alloys does not always make it possible to obtain a fine-grained and homogeneous structure throughout the entire volume of the ingot. The reasons lie both in the quality of the master alloys themselves and in the technology used for their introduction into the melt.

CONCLUSIONS

Future studies should focus on optimizing the type and concentration of modifiers used for aluminum–silicon alloys to achieve stable and reproducible microstructural refinement. Particular attention should be paid to a systematic comparison of in-furnace and out-of-furnace modification methods, including their influence on nucleation behavior, grain growth kinetics, and eutectic morphology. In addition, the combined effects of thermal conditions, modifier addition techniques, and holding time in induction furnaces require further investigation. Advanced characterization methods, such as quantitative metallography and in situ thermal analysis, should be employed to establish clear correlations between processing parameters, microstructure evolution, and mechanical and tribological properties. Such studies will contribute to the development of more efficient and controllable modification technologies for aluminum–silicon casting alloys.

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