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Heat-resistant magnesium-based alloys for aircraft casting

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The necessity of increasing the mechanical properties and heat resistance of aviation magnesium case casting is demonstrated. The choice of alloying elements to improve the installation characteristics of the Mg-Al-Zn system is justified. It was found that Ti, Zr and Hf additives in the ML5 alloy in an amount from 0.05 to 1.0 mass. % contribute to reducing the distance between the axes of the dendrites of the 2nd order up to 1.5 times and the size of the micrograin - up to 2 times.

The influence of the morphology and topology of the structural components of magnesium alloys on their properties is demonstrated. It was found that microalloying of magnesium alloys Ti, Zr and Hf in an amount from 0.05 to 0.1 mass. % increases the volume percent of intermetallic compounds, displacing them towards smaller size groups with the simultaneous formation of spherical intermetallic compounds located in the center of the grain and serving as additional crystallization centers.

It has been established that microalloying of magnesium alloys with refractory metals leads to the formation of complex intermetallic phases enriched with the corresponding alloying elements. It is shown that the optimal additives Ti, Zr and Hf in an amount from 0.05 to 0.1 mass. % help increase strength by ~ 25%, ductility by ~ 2.5 times, and heat resistance by ~ 2 times.

New heat-resistant magnesium alloys with a high complex of mechanical properties and heat resistance have been developed. An industrial testing of the production technology of castings made of improved magnesium alloy was carried out in the conditions of the enterprise JSC "Motor Sich". The use of developed magnesium alloys will improve the reliability and operation safety of aircraft engines.

Keywords: *chemical composition; alloying elements; mechanical properties; heat resistance; structure; intermetallides; magnesium; microhardness.*

The development of modern mechanical engineering requires the use of materials that can withstand high loads at elevated temperatures while reducing the weight of structures. From this point of view, magnesium-based alloys are one of the most widespread in nature [1].

Foundry magnesium alloys are one of the lightest structural materials that allow them to be used effectively in aircraft construction. Due to the fact that magnesium alloys are one and a half times lighter than aluminum alloys and four times than steel, their use, especially in shaped casting, allows achieving a weight reduction of products up to 30 % [2].

Currently, a large number of magnesium alloys have been developed and a large number of papers have been published that discuss the mechanical, physical, and special properties of magnesium alloys intended for various operating conditions. Magnesium alloys doped with aluminum and zinc (ML4, ML5, ML6) are widely used for high-strength casting, which have sufficiently high mechanical properties and low cost but have insufficient heat resistance.

Alloys of the system "magnesium-zirconium-neodymium" (ML9, ML10, ML19), which have high heat resistance, contain expensive alloying elements and it significantly increases the cost of products and reduces their competitiveness. Therefore, the development of cheap magnesium alloys with high levels of properties and heat resistance is an urgent task [3], providing reliable and safe operation of aircraft engines [4].

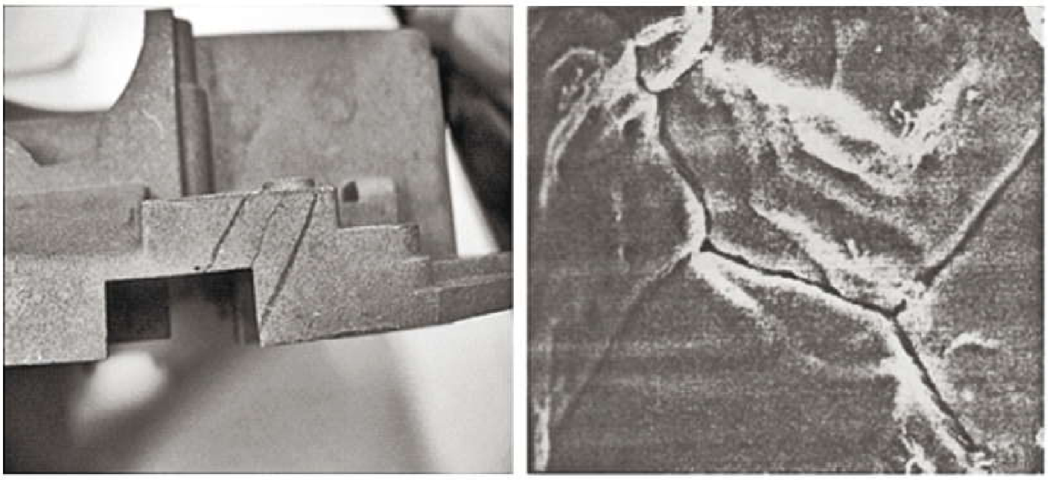
The magnesium alloy ML5 of the Mg-Al-Zn system has proven itself well to work up to 150 °C as the body parts of aviation engines manufactured by JSC “Motor Sich”. However, in some cases, when operating engines in critical conditions with large overloads, overheating of the body casting occurs, which can lead to softening of magnesium alloys.

Aviation engines, which have passed the guaranteed service life, undergo maintenance, at which they are disassembled and the quality indicators of individual parts and components are evaluated. However, on the surface of cast parts made of ML5 magnesium alloy and having a complex configuration, some inconsistencies with the requirements of the regulatory and technical documentation can be detected: painting, chipping, wear and cracks (Fig. 1 a). In this case, cracks with traces of corrosion were most often observed. The macrostructure of such cracks had a folded multifocal relief, often with the melting of grain boundaries (Fig. 1 b). The surface of the cracks was covered with a dense layer of oxides, and the crack itself could develop both along the grain and along its boundaries.

Analyzes of the chemical composition and mechanical properties of samples of the investigated metal, cut from cast parts, showed that they meet the requirements of regulatory and technical documentation. The bulk of the cracks considered occurred in the case of over-warranty period of operation engines and with large overloads in critical modes. Thus, the standard magnesium alloy ML5, meeting the requirements of regulatory and technical documentation and providing guaranteed service life of the units, does not always provide the necessary properties of the products when operating aircraft engines with high overloads in critical modes and requires increasing their heat resistance.

It is known that the heat resistance of cast alloys is provided by two factors [5]:

1. The introduction into the alloy of alloying elements, which form during crystallization and recrystallization refractory phases in the form of



a b

Fig. 1. Surface crack on the housing cover of ML5 alloy (a, × 0.5) and metal microstructure with the melting of grain boundaries (b, × 300).

mesh secretions or in the form of a solid frame between the branches of the dendrites.

2. By doping the main component with the elements included in the solid solution [6]. In this case, the alloying components must have a melting point higher than the base of the alloy.

The analysis of the state diagrams of various alloying elements with magnesium showed that with the increase of the melting temperature of the studied elements, the state diagrams were transformed from eutectic to a peritectic one. At the same time, as the melting temperature of the alloying element increased, the melting temperature of the intermediate phases also increased, providing a heterogeneous structure that was resistant to the effects of elevated temperatures.

In this regard, it is of practical interest to study the effect of refractory elements (Ti, Zr, Hf) on the heat resistance of magnesium alloy ML5. These metals have atomic radii and electronegativity close to magnesium [6] and can therefore form solid solutions and phases, reinforcing the metal matrix. The melting point of the alloying elements under study significantly exceeds the melting temperature of the alloy, which should ensure the thermal stability of the formed phases and increase the heat resistance of the magnesium alloy as a whole.

The effect of the above elements on the structure formation, mechanical properties and long-term strength at elevated temperatures of ML5 magnesium alloy castings were investigated.

The magnesium alloy ML5 was smelted in an induction crucible furnace type IPM-500 by standard technology. The refining of the melt was carried out in a dispensing furnace, from which the melt was taken portion wise and the increasing additives of aluminum, Ti, Zr and Hf ligatures were introduced.

Standard specimens for mechanical testing were poured into a sandy-clay form. The samples were heat treated in Bellevue and PAP-4M T6 furnaces: heating to 415 ± 5 °C, holding for 15 h, cooling in air and aging at 200 ± 5 °C, holding for 8h, cooling in air.

The tensile strength (σv) and elongation (δ) of samples with a working diameter of 12 mm were determined on a tensile testing machine P5 at room temperature. Long lasting strength(τ^{80}_{150})was determined on an INSTRUN installation with elongated rods for attaching samples; upon reaching 150 °C, a load was applied (σ = 80 MPa) and the time was recorded until complete destruction.

The microstructure of the castings was studied by light microscopy (Neophot 32). The microhardness of the structural components of the alloy was determined on a Buehler microhardness meter at a load of 0.1 N.

We studied the effect of the contents of Ti, Zr and Hf (within 0.05 … 1.0 % each) on the structure and properties of the ML5 alloy. The chemical composition of the ML5 alloy of the studied variants met the requirements of GOST 2856-79 and was approximately at the same level in terms of the content of the main elements (8.4 % Al, 0.30 % Mn, 0.32 % Zn, 0.014 % Fe, 0.005 % Cu, 0.030 % Si).

A macrographic study of fractures of samples of an ML5 alloy with titanium, zirconium and hafnium showed that these elements were crushed by macrograin. The microstructure of the standard composition ML5 alloy was a δ solid solution with a $\delta + \gamma$ type eutectic located at the grain boundaries and individual γ phase intermetallic compounds (Fig. 2 a). With an increase in the content of Ti, Zr, and Hf in the alloy, the amount of eutectic, the size of the structural components (Fig. 2, b-d), and the distances between the axes of the second-order dendrites decreased (Table). The effect of these elements on the microhardness of the matrix increased from titanium to zirconium and hafnium.

Analysis of the distribution of intermetallic compounds by size groups showed that lamellar intermetallic compounds predominated in the standard ML5 alloy, most of which were in the size group 4 … 15 μm. Spherical intermetallics are mainly represented by a size group of 2.0 … 7.9 microns. The studied alloying elements in the alloy ground the intermetallic phase (up to 2.0 … 11.5 microns for spherical and < 2.0 … 7.9 microns for lamellar). With an increase in the content of the studied elements, the volume percentage of intermetallic compounds with sizes less than 2 μm increased and decreased for large intermetallic compounds (> 11.6 μm).

The content of Ti, Zr and Hf in the range of 0.05 … 0.1 % increased the ductility of the ML5 alloy due to grain refinement. However, when their content in the alloy was up to 1.0%, this indicator decreased due to the formation of an excess amount of the intermetallic phase embrittling the metal. Titanium, zirconium and hafnium increased the tensile strength and heat resistance of the alloy. The effectiveness of their influence on the properties of the alloy increased from titanium to zirconium and hafnium and increased with an increase in their content.

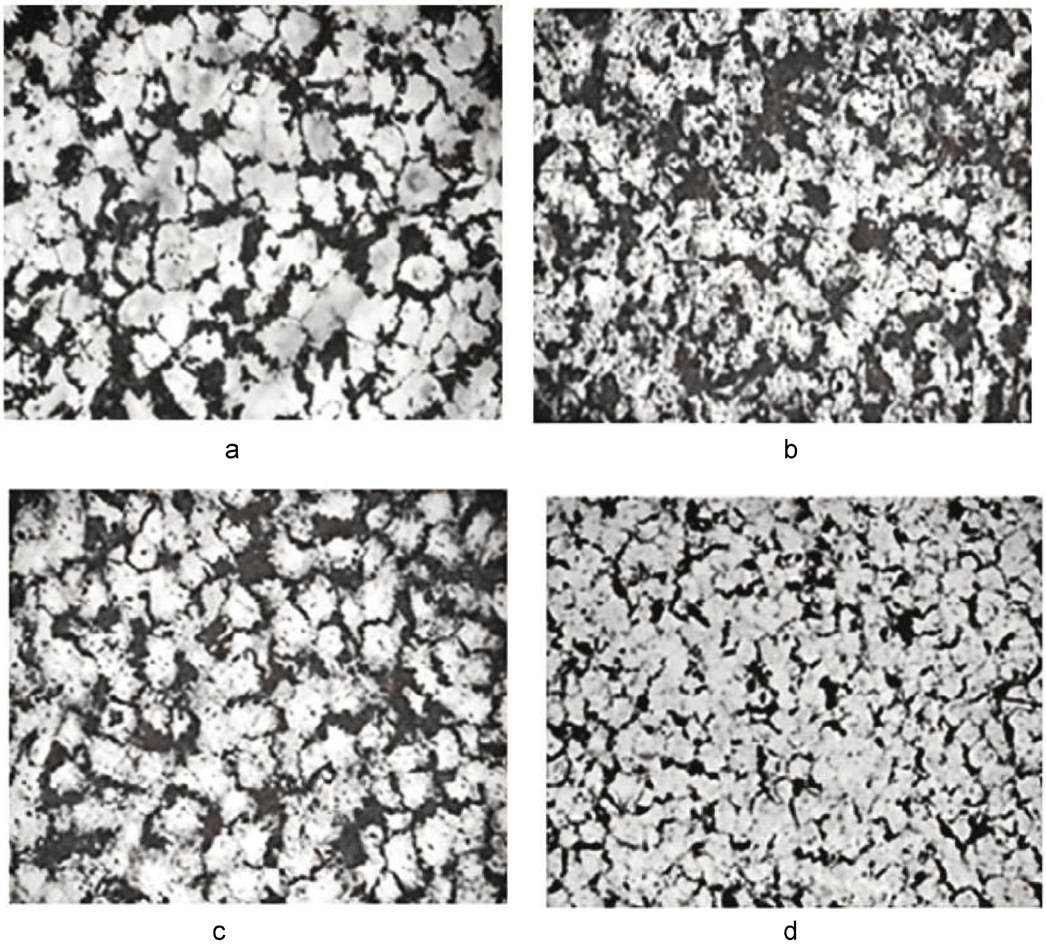


Fig. 2. Microstructure of samples from alloy ML5 with additives: a – standard alloy, b – 0.1 % Ti, c – 0.1 % Zr, d – 0.1 % Hf, ×100.

X-ray microanalysis of the phases of the ML5 alloy with titanium, zirconium and hafnium showed the presence of these elements in the composition of intermetallic compounds. The studied elements contributed to the grinding of the intermetallic phase. Moreover, its volume percentage increased with increasing concentration of the studied elements in the alloy (Table). The content of elements in the range of 0.05 ... 0.1 % intensively increased the volume percentage of spherical intermetallic compounds with a slight increase in plate. A further increase in the concentration of elements insignificantly increased the volume percentage of spherical intermetallic compounds inside the grain and intensely lamellar ones.

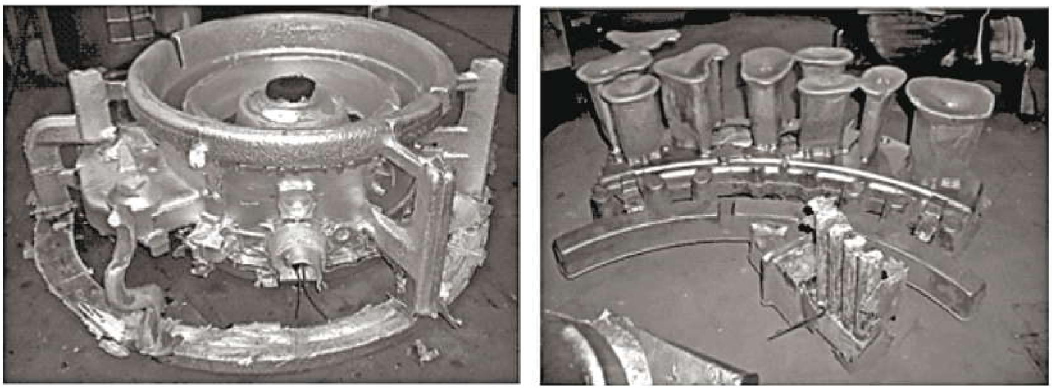
Thus, Ti, Zr, and Hf additives crushed the structure of the ML5 alloy, increasing the volume percent of small intermetallic compounds, and increased the strength, ductility, and heat resistance of the alloy.

Based on the research conducted at the Zaporizhzhya Polytechnic University, a series of new heat-resistant alloys of the Mg-Al-Zn system, Characteristics of the structural components of the alloy ML5 with Ti, Zr and Hf

Element	Content,% calc.	Micro grain size, μm	The distance between the axes of the dendrites of the 2nd order, μm	Microhardness of the matrix, HV, MPa		
				before heat treatment	after heat treatment	after τ^{80}_{150}
standard		140	21	1115,9	1256,5	1286,5
Ti	0,05	120	18	1120,2	1265,6	1281,1
	0,1	100	16	1127,8	1270,7	1288,1
	1	100	16	1135,5	1283,3	1292,9
Zr	0,05	105	17	1166,8	1235,3	1278,8
	0,1	100	16	1198,3	1265,6	1305,5
	1	70	16	1215,4	1297,9	1324,2
Hf	0,05	110	17	1188,9	1256,6	1318,9
	0,1	100	16	1233,5	1294,4	1346,6
	1	70	15	1270,4	1321,1	1387,7
Note: the table shows average values.						

additionally alloyed with Ti, Zr and Hf, was developed [7 … 10]. Industrial testing of the technology for the production of new alloys was carried out in the conditions of the company JSC "Motor Sich" - castings "drive box housing" and "fuel pump housing" were made from improved alloys (Fig. 3). After heat treatment under T6 mode, samples were made from castings for metallographic analysis and mechanical tests.

The use of improved magnesium alloys for the manufacture of body casting can improve the reliability and safety of aircraft engines.



a b

Fig. 3. Castings made of improved magnesium alloys: a – "fuel pump housing", b – "drive box housing".

The alloying of the ML5 alloy with refractory metals contributes to the refinement of structural components, an increase in their microhardness, and an increase in the volume percent of intermetallic compounds that have a complex composition and are enriched with the corresponding alloying elements.

Experienced castings made from improved magnesium alloys had a uniform and fine-grained structure without any defects, and the mechanical properties and heat resistance significantly exceeded the level of standard alloys. At the same time, their strength increased by 25 %, ductility by 2.5 times, and heat resistance by 2 times.

Titanium, zirconium and hafnium in an amount of from 0.05 to 0.10 % mass. significantly increase the strength, ductility and heat resistance of a magnesium alloy.

The elements considered are promising alloying components for the development of new magnesium alloys when operating at elevated temperatures.

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Жароміцні сплави на основі магнію для авіаційного лиття

Анотація

Показана необхідність підвищення механічних властивостей і жароміцності корпусного магнієвого лиття авіаційного призначення. Обгрунтований вибір легуючих елементів для поліпшення характеристик сплаву системи Mg – Al – Zn. Встановлено, що присадки Ti, Zr і Hf в сплав МЛ5 в кількості від 0,05 до 1,0 мас. % сприяють зменшенню відстані між осями дендриту 2 порядку до 1,5 разів і розміру мікрозерна - до 2 разів.

Показано впливи морфології і топології структурних складових магнієвих сплавів на їх властивості. Встановлено, що мікролегування магнієвих сплавів Ti, Zr і Hf в кількості від 0,05 до 0,1 мас. % збільшує об'ємний відсоток интерметалідів, зміщуючи їх у бік менших розмірних груп при одночасному утворенні сферичних интерметалідів, що розташовані в центрі зерна і слугують додатковими центрами кристалізації.

Встановлено, що мікролегування магнієвих сплавів тугоплавкими металами приводить до утворення комплексних інтерметалідних фаз, збагачених відповідними легуючими елементами. Показано, що оптимальні присадки Ti, Zr і Hf в кількості від 0,05 до 0,1 мас. % сприяють підвищенню міцності на ~ 25 %, пластичності в ~ 2,5 рази, а жароміцності в ~ 2 рази.

Розроблені нові жароміцні магнієві сплави, що мають високий комплекс механічних властивостей і жароміцності. Проведено промислове випробування технології виробництва відливань з поліпшеного магнієвого сплаву в умовах підприємства АТ "Мотор Сич". Застосування розроблених магнієвих сплавів дозволить підвищити надійність роботи і безпеку експлуатації авіаційних двигунів.

Ключові слова: хімічний склад, легувальні елементи, механічні властивості, жароміцність, структура, інтерметаліди, магній, мікротвердість.