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DEVISING RESOURCE-SAVING TECHNOLOGIES FOR THE PRODUCTION OF CASTING FROM MAGNESIUM ALLOYS USING WASTE OF METALLURGICAL ENTERPRISES

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Based on the study of the chemical composition and analysis of the physicochemical properties of waste from a number of metallurgical enterprises in the Zaporizhzhya region, the possibility of using waste as charge materials for the production of magnesium-based alloys has been established.

The possibility of using solid salt chlorinator melt (SCM) from ZTMC as a flux in the smelting of magnesium alloy instead of the flux VI-2 has been studied; its effect on the structure and mechanical properties of casting was investigated. The technological possibility of using these chloride wastes in the smelting of the ML5 alloy is shown. It was established that the use of SCM as a flux in the smelting of magnesium alloy contributes to the grinding of the structure and improvement of the mechanical properties of the metal of experimental smelting.

The possibility of modification of foundry magnesium alloy with graphite powder (GP), which is the waste from JSC «Ukrgrafit», is investigated. It is shown that the optimal GP additive in the volume of 0.05...0.3 % contributes to the grinding of metal grain and increases its strength characteristics due to additional strengthening of both solid solution and eutectoid. It is established that carbon changes the parameters of eutectic transformation, as a result of which, with an increase in its concentration in the alloy, the volume of eutectoid of type δ+γ (Mg_4Al_3) decreases markedly.

Testing the proposed waste for the smelting of the M5 alloy showed that no changes in melting technology are required while the environmental safety of the devised technological process meets the established standards; their quality was improved while increasing the strength limit by 25 %, and plasticity by 30 %.

At the same time, the use of waste in the smelting of magnesium alloys can reduce costs in its production, and improve the environmental situation due to the fact that waste is not disposed of at landfills but reused in metallurgical industries

Keywords: magnesium alloy, salt chlorinator melt, flux, modification, graphite powder, microstructure

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1. Introduction

Industrial waste causes great harm to the environment, occupies huge areas, and increases the cost of finished products of enterprises due to the significant costs of their disposal and transportation.

The situation regarding the processing of industrial waste remains unsatisfactory. The largest volume of waste is produced by the mining and metallurgical industry. At metallurgical enterprises, billions of tons of waste have accumulated in dumps and sludge storage facilities. Further accumulation of them threatens with environmental disasters not only in the areas where metallurgical enterprises are located but also in entire regions.

The main types of man-made waste are slags, sludges, dust, and scale. Some of them are not used in industry, so they have to be disposed of, spending huge amounts of money and occupying large areas of landfills for their burial. Others are only partially used in industry, being promising materials that make it possible to increase production efficiency and reduce the cost of production. At the same time, such waste, which is technogenic deposits of valuable secondary raw materials, can meet the needs of industrial production in expensive and scarce products.

Hundreds of millions of tons of toxic waste have accumulated in the world, with industry and mining waste accounting for 98 % of the total waste turnover. Therefore, the processing and use of waste from metallurgical and machine-building enterprises for the needs of mechanical engineering are very relevant and promising. At the same time, the study, development, and adjustment of technological processes to produce casting using waste as charge materials require further research. Addressing this issue is associated with the need to develop new resource-saving technologies for the production of casting using Ukrainian charge materials, including waste from metallurgical enterprises, as well as foundry waste.

2. Literature review and problem statement

At machine-building enterprises, in the production of various articles, great importance is paid to improving the properties of the alloys from which they are made [1]. Improving the structure and improving the properties of various alloys [2] are studied at different stages of their production, ranging from charge preparation to heat treatment [3, 4], so the influence of technological modes at all stages of casting production is very important [5].

A promising direction for improving the properties of magnesium-based alloys is to control structure formation processes to increase their physical, mechanical, and special characteristics by optimizing their composition, refining [6], and modification. However, the use of certain technologies in the production of magnesium casting does not make it possible to achieve a significant improvement in the specified characteristics. The use of a set of technologies under consideration for these purposes will lead to a significant improvement in the structure of alloys and, as a result, their mechanical and special properties [7, 8]. The quality of the alloy is mainly determined by the technology of its smelting and refining [9]. However, changing the technological parameters alone cannot provide a significant improvement in its properties. An additional combination of alloying and modification makes it possible to change the degree of granularity of the structure and improve the set of properties of the alloy [10, 11]. However, the relationship between the integrated use of all these factors from the point of view of not only structure formation and properties but also resource-saving has not been studied. At the same time, a very important factor is the reduction in the cost of articles, which is possible through the use of resource-saving technologies in their production. The technologies used today in the production of magnesium castings involve the use of valuable imported charge materials and carry the risk of instability in the work of enterprises. There are also no technological solutions for the use of metallurgical waste to obtain high-quality casting from magnesium alloys with an increased set of mechanical and special properties.

Metallurgical enterprises in the Zaporizhzhia region have a large volume of recyclable waste. The analysis of these wastes showed that a certain proportion of them can be used as charge materials in the production of magnesium castings to produce implants.

During the processing of titanium-containing concentrates at GP «Zaporizhzhia Titanium-Magnesium Plant», a significant volume of chlorine-containing waste is formed, some of which can be partially used in the national economy while others have not yet found application. Thus, during the chlorination of titanium slags in the production of titanium tetrachloride, a spent salt chlorinator melt (SCM) is formed, the production volume of which is up to 12 thousand tons per year. The spent SCM has the following physical and mechanical properties: density, 2000...2300 kg/m^3; bulk weight, 980...1100 kg/m^3; average melting point, 910 °C; the heat of melting, 420...440 J/deg; compressive strength, up to 20.3 MPa; bending strength, up to 0.71 MPa. This material is disposed of in trenches equipped with a lime «cushion», which makes it possible to restrain the spread of chlorides in the soil. The company spends hundreds of thousands of hryvnias on waste disposal and maintenance of landfills for their burial. At the same time, the chemical composition of SCM is close in chemical composition to the flux VI-2, which is used in the smelting of magnesium alloys. Chemical composition of the flux VI-2, wt%: 38...46 $MgCl_2$, 32...43 KCl, 10...11 $CaCl_2$, 5...9 $BaCl_2$, 3...5 CaF_2. Chemical composition of SCM flux, wt%: 15...20 $MgCl_2$, 24...28 KCl, 2...4 $CaCl_2$, 7...10 $TiCl_4$, 19...21 $FeCl_3$, 8...10 $AlCl_3$, 5...9 $CrCl_3$, 8...10 NaCl.

Therefore, it is interesting to study the possibility of replacing the expensive VI-2 flux, which has imported components, with waste from the production of ZTMK during the smelting of magnesium alloys.

One of the promising areas for improving the quality and properties of magnesium casting is its modification [12, 13].

The main requirements for modifiers of magnesium alloys are the ability to form insoluble crystallization centers, a stable modification effect, low cost, and non-scarcity. The most suitable for these conditions is carbon [14, 15], the main advantage in the use of which is its ability not to contaminate the metal with oxide inclusions and reaction products in contact with melt [16, 17]. Therefore, it is interesting to devise technology for modifying magnesium melts with carbon, providing these requirements.

In the production of graphite electrodes at JSC «Ukrgrafit» (Zaporizhzhia, Ukraine), various carbon-containing waste is generated in the form of chips and powders of various fractional compositions, which are advisable to use for modifying magnesium alloys.

Analysis of such carbon-containing waste showed that the graphitized powder (GP) from the electrode machining shop is more suitable in chemical and granulometric composition for modifying magnesium alloys. It is finely dispersed and has the highest carbon content, low ash content and the yield of volatile substances. GP is formed in the graphitizing and shaped compartments and is retained by the electrostatic precipitators UVP 16 SK and UVP 12 SK during the purification of the gas-air mixture formed during the processing of graphite articles. GP has the following characteristics: mass fraction of carbon, not less than 98.5 %; ash content, not more than 1.0 %; the mass fraction of sulfur, not more than 0.1 %; volatile matter yield, not more than 1.5 %; bulk density, 0.57 g/cm^3. Sieving GP showed that it is based on particles of 0.071 mm or less, which is the most acceptable in its characteristics and can be used to modify magnesium alloys.

Thus, a significant factor in the production of casting from magnesium alloys is the use of resource-saving technologies, which makes it possible to reduce the cost of casting and make its production more competitive. The solution to this problem is possible through the use of waste from metallurgical enterprises. Its use as charge materials that do not contain valuable imported components in their composition and meet the requirements of regulatory and technical documentation at the level of physical, mechanical, and special properties, in the production of responsible magnesium casting.

3. The aim and objectives of the study

The purpose of this study is to devise resource-saving technologies in the production of high-quality casting with increased mechanical properties. This will reduce the cost of components and make the production of machines and mechanisms more competitive. In addition, the studies carried out are of great environmental importance since they make it possible to use the waste of metallurgical enterprises instead of recycling it in landfills and to obtain significant material and environmental effects.

To accomplish the aim, the following tasks have been set:

– to establish the effect of solid salt chlorinator melt for refining the ML5 alloy on the structure and mechanical properties of the alloy;

– to establish the effect of graphite powder for modification of the ML5 alloy on the structure and mechanical properties of the alloy.

4. The study materials and methods

The object of this study is a magnesium alloy.

The magnesium alloy ML5 was smelted in the induction crucible furnace IPM-500 (Ukraine). Refining of the melt was carried out in gas dispensing furnaces. As a flux, VI-2 and SCM were used in various ratios, which were previously crushed to a fraction of 0.01...2.0 mm and calcined at a temperature of 150 °C. After refining and settling the finished melt, it was modified. The main requirements for modifiers of magnesium alloys of the Mg-Al-Zn system are the ability to form insoluble crystallization centers, a stable modification effect, low cost, and non-scarcity. The most suitable for these conditions is carbon, the main advantage in the use of which is its ability not to contaminate the metal with oxide inclusions and reaction products in contact with the melt. Given that carbon is insoluble in magnesium and its particles can be additional centers of crystallization, the ML5 alloy smelted using GP waste of industrial production of JSC «Ukrgrafit» as a modifier was investigated. The effect of increasing GP additives (0.05 %, 0.1 %, 0.3 %, 0.5 %, 1.0 % wt.) on the structure formation and properties of the ML5 alloy were studied. To this end, increasing additives of waste from JSC «Ukrgrafit» (Ukraine) in the form of graphite powder were introduced into the liquid metal; standard samples ($T_{filling}$=750 °C) were thoroughly mixed and poured for mechanical tests into a sandy-clay mold. The samples underwent heat treatment in Bellevue and PAP-4M furnaces according to the T6 mode. T6: heating up to 415±5 °C; settling 15 h; cooling in air and aging at 200±5 °C; settling, 8 h; cooling in air.

The temporary tensile resistance (σ_B) and the relative elongation (δ) of samples with a working diameter of 12 mm were determined on a P5 break machine at room temperature according to DSTU ISO 6892-1: 2019.

The microstructure of the castings was studied by light microscopy (Neophot 32) on heat-treated samples after etching with a reagent consisting of 1 % nitric acid, 20 % acetic acid, 19 % distilled water, 60 % ethylene glycol. The microhardness of the structural components of the alloy was determined on a microhardness meter of the company «Buehler» (Germany) at a load of 0.1 N. Phase analysis of the structural components of magnesium alloys was studied on an electron microscope – a microanalyzer with the energy-dispersive setup REMMA 202M and REM 16I.

The chemical composition of the alloy of various technological modes met the requirements of GOST 2856-79 and, in terms of the content of the main elements, was approximately at the same level: 7.8...8.9 % Al; 0.4...0.7 % Zn; 0.35...0.50 % Mn; Mg is the rest.

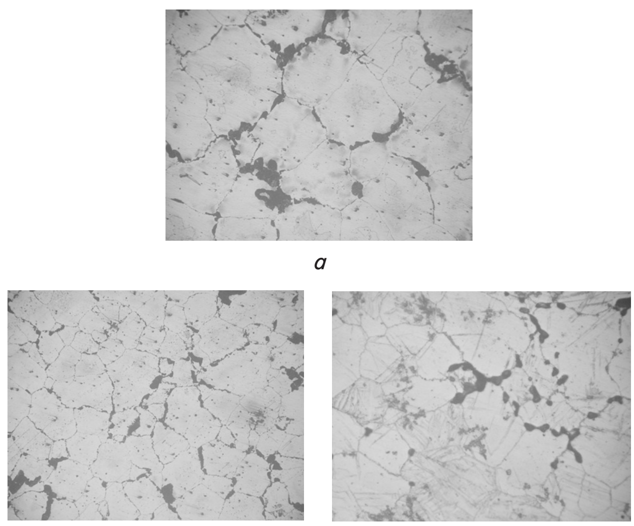
5. Results of studying the microstructure and mechanical properties of magnesium alloy obtained using metallurgical waste

5. 1. Investigation of the effect of solid salt chlorinator melt for refining the ML5 alloy on the structure and mechanical properties of the alloy

The macrostructure of the samples of all variants of experimental melting was dense, homogeneous without shrinkage loosening, captivity, gas pores, and other defects.

The microstructure of the studied samples consisted of a δ-solid solution of aluminum, zinc, and manganese in magnesium with clear grain boundaries, eutectics δ+γ (Mg_4Al_3), and finely dispersed hardening intermetallic γ (Mg_4Al_3)-phase. The eutectics were concentrated along the boundaries of grains, the intermetallic phase was distinguished in the form of particles of globular shape mainly in the center of the grains.

An increase in the share of SCM in the total volume of flux contributed to a decrease in the size of micro grains (Fig. 1). At the same time, the size of the structural components and the size of the micro grain decreased by ~1.5 times while the microhardness of the structural components of the alloy increased (Table 1).

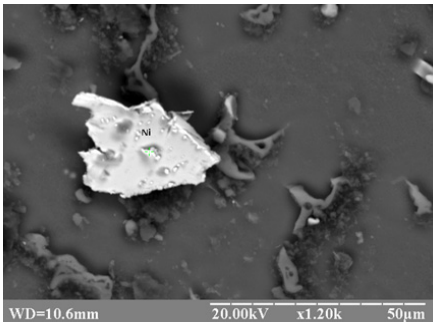


a, *b*, *c*

Fig. 1. Microstructure of the ML5 alloy samples smelted with various fluxes ×200: *a* – VI-2 (100 %); *b* – VI-2 (50 %)+salt chlorinator melt (50 %); *c* – salt chlorinator melt (100 %)

Micro-X-ray spectral analysis of the ML5 alloy obtained using SCM (Fig. 2) showed that the intermetallic phase contained molybdenum, niobium, tungsten, and yttrium.

The mechanical properties of heat-treated samples in the ML5 alloy of experimental melting using SCM had a higher level of both strength and plastic characteristics of the metal (Table 2). This was facilitated by microalloying and modification of the metal with SCM components.



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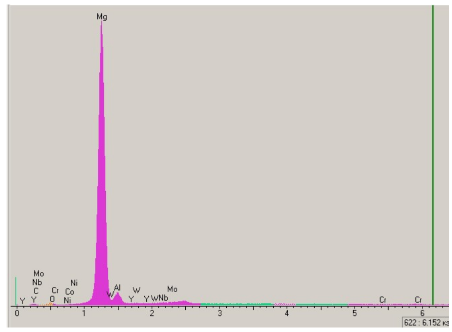


b

Section	Mg	Al	O	Mo	Nb	W	Y	Impurity
Y	78.00	13.20	3.89	2.79	0.30	1.41	0.37	0.04

c

Fig. 2. The results of micro-X-ray spectral analysis of intermetallic in the alloy ML5, melted using a salt chlorinator: *a* — the site of analysis; *b* — spectrogram of the analyzed site; *c* — chemical composition of the site (wt.%)

Table 1

Characteristics of structural components in heat-treated samples from the ML5 alloy with various refining technologies

Refining technology option	Dimensions of structural components, µm		Microhardness, HV, MPa	
	eutectic	micro grain	matrix	eutectic
VI-2 (100 %)	190	210	827.5	1,065.3
VI-2 (50 %)+ +SCM (50 %)	155	145	1,018.4	1,320.5
SCM (100 %)	150	140	1,090.3	1,435.4

Table 2

Average mechanical properties of samples from the ML5 alloy with various refining technologies

Refining technology option	Mechanical properties		
	σ_B, MPa	δ, %	HB
VI-2 (100 %)	230	3.4	105
VI-2 (50 %)+SCM (50 %)	243	3.7	112
SCM (100 %)	270	4.8	120

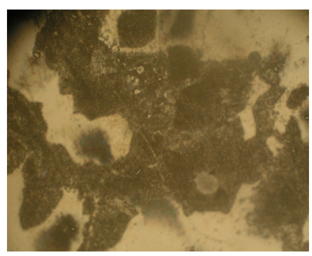
Castings made under industrial conditions from the ML5 alloy using SCM as a flux had a homogeneous finely dispersed structure and a high set of mechanical properties that exceeded the requirements of regulatory and technical documentation. At the same time, the use of SCM makes it possible to save up to 400 kg of the VI-2 flux per ton of usable and significantly reduce the cost of magnesium alloy.

5. 2. Investigation of the effect of graphite powder for modification of the ML5 alloy on the structure and mechanical properties of the alloy

Metallographic studies of the ML5 alloy, cast according to standard technology, established that its main structural components were: δ-solid solution, eutectics of the type δ+γ (Mg_4Al_3), and intermetallic γ (Mg_4Al_3). The eutectic phase was concentrated on the grain boundaries, the intermetallic phase γ stood out mainly in the form of particles of globular shape.

In the structure of the studied alloys, after heat treatment according to the standard T6 mode, the release of eutectoid δ+γ (Mg_4Al_3), which has the form of alternating plates, as well as boundary secretions of Mg_4Al_3 in the form of degenerate eutectics (Fig. 3, *a*), was observed. In the process of heat treatment, the chemical heterogeneity of the alloy decreased, and the grain boundaries became clearer.

Modification of the alloy with graphite powder in the volume of 0.05 % contributed to a decrease in the size and amount of eutectoid secretions (Fig. 3, *b*). A further increase in the GP additives in the melt enhanced the grinding effect (Fig. 3, *c*–*e*). At the same time, the size of the [δ+γ (Mg_4Al_3)]-phase and the size of the micro grain decreased by ~1.5 times (Table 3).



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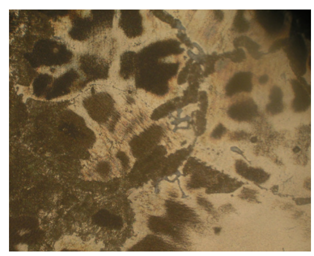

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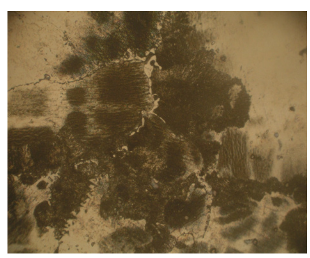

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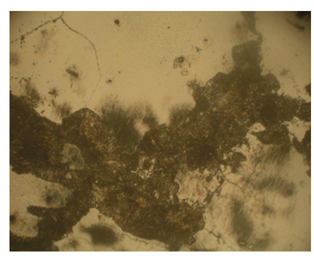

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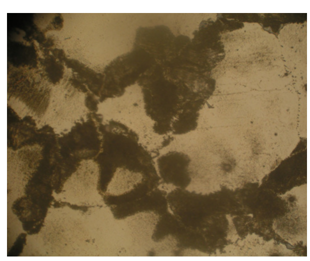

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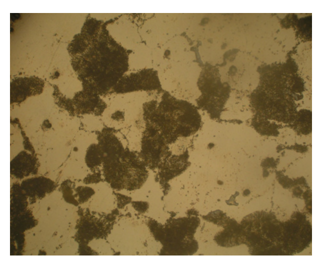


f

Fig. 3. Microstructure of the ML5 alloy after heat treatment, ×500: *a* — initial alloy; *b* — additive 0.05 % C; *c* — additive 0.1 % C; *d* — additive 0.3 % C; *e* — additive 0.5 % C; *f* — additive 1.0 % C

Table 3

Dimensions of structural components and their microhardness in samples from the ML5 alloy after heat treatment

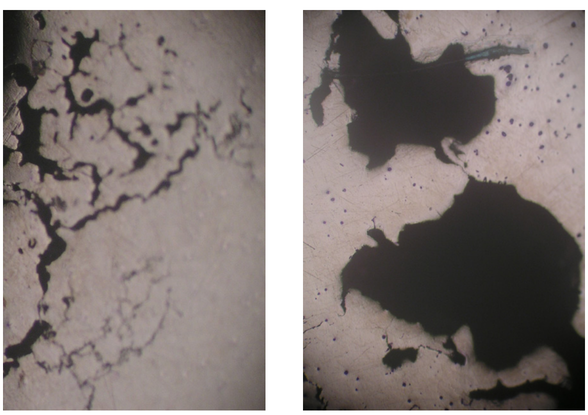
Additive modifier (C), wt%	Dimensions of structural components, μm		Microhardness, HV, MPa	
	eutectoid δ+γ (Mg_4Al_3)	Micro-grain size according to GOST 21073.1-75	matrix	eutectoid δ+γ (Mg_4Al_3)
without modification	60...320	150...260	761.8...894.1	1,017.3...1,114.1
0.05	60...250	90...200	973.5...1,064.0	1,287.5...1,354.4
0.1	60...240	80...200	1,017.3...1,064.0	1,287.5...1,504.7
0.3	50...220	70...200	1,017.3...1,167.8	1,287.5...1,504.7
0.5	50...200	70...210	1,064.0...1,167.8	1,354.4...1,681.6
1.0	50...180	60...200	1,064.0...1,167.8	1,354.4...1,782.0

The additive in the melt of the carbon-containing modifier in the volume of 0.05...0.3 % contributed to an increase in both the strength and plastic characteristics of the metal. A further increase in the volume of GP additive led to a slight decrease in the mechanical characteristics of the alloy.

It was found that the microhardness of eutectoid secretions of the cast alloy was ~1.5 times higher than the values of the matrix δ-solid solution.

In the heat-treated alloy, an increase in the microhardness of its structural components was observed. At the same time, the ratio of microhardness values of the matrix to eutectoid was approximately 1:1.5.

During the macro fractographic analysis of samples destroyed during the test with an additive of more than 0.3 % GP, defects were found in the fractures, the size and number of which increased with an increase in the carbon content in the alloy. Microstructural analysis of the studied defects showed that they were coarse loose flopping and film contamination (Fig. 4).



a *b*

Fig. 4. Defects in samples with graphite powder additive 1.0 %, ×100: *a* – captives; *b* – porosity

The mechanical properties of the ML5 alloy modified with GP had a higher level compared to the original metal (Table 4).

Table 4

Mechanical properties*) of samples made of the ML5 alloy

Additive modifier (C), wt%	Mechanical properties			
	without heat treatment		after heat treatment	
	σ_B, MPa	δ, %	σ_B, MPa	δ, %
without modification	142	1.8	198	2.7
0.05	167	4.8	230	5.0
0.1	173	3.0	221	4.8
0.3	172	3.3	230	3.5
0.5	176	2.5	223	4.6
1.0	155	2.5	211	3.6

*Note: *) – mean values*

6. Discussion of results of the use of waste from metallurgical enterprises for the smelting of the ML5 alloy

When smelting magnesium alloys, complex processes of interaction occur between the charge materials and alloying components of the alloy, fluxes, protective media, and modifiers. Therefore, the role of technological modes in the melting and pouring of magnesium alloys is crucial.

The refining of magnesium alloys is carried out with the help of fluxes, which are various mixtures of chloride and fluoride salts. Their action is due to the envelopment of the removed particles with melted chloride salts. At the same time, the flux wettability of the melt must be minimal in order to ensure its complete separation from the liquid alloy during crystallization, which determines the quality of the cast metal and the set of its properties.

Analysis of the chemical composition and physical and mechanical properties of SCM from ZTMK showed that it is close in its characteristics to the flux VI-2, standardly used in the smelting of magnesium-based alloys. At the same time, these wastes contain in their composition a number of scarce and expensive metals that can affect the quality and mechanical properties of magnesium casting. The experiments conducted showed that the composition of the flux does not affect the technological process of smelting, ensuring the environmental safety of production.

X-ray micro spectral analysis of the ML5 alloy obtained with the use of SCM revealed (Fig. 2) that the intermetallic phase contained molybdenum, niobium, tungsten, and yttrium. At the same time, its melting temperature increased, which allowed these SCM components to separate from the liquid melt at the beginning of the crystallization process and create additional crystallization centers. This contributed to additional grain refinement by ~1.5 times (Table 1) and led to an increase in the mechanical properties of the alloy. At the same time, there is an increase in the microhardness of the metal matrix and the eutectic component of the alloy by 30...40 % due to their hardening by SCM components. The mechanical properties of heat-treated samples made of a magnesium alloy of experimental melts using SCM had a higher level (Table 2). Microalloying the structural components of the alloy leads to distortion of their crystalline lattice and, accordingly, strengthening of the alloy as a whole, while the strength characteristics of the alloy have increased by ~20 %. And the formation of additional crystallization centers contributed to additional grinding of grain and, accordingly, an increase in plasticity to ~40 % (Table 2). Thus, the possibility of using SCM as a flux in the smelting of secondary magnesium alloy has been established, which will significantly reduce the cost of its production.

Unlike the VI-2 flux traditionally used in production, which provides refining of the melt from harmful impurities, the use of SCM provides its additional modification. This is made possible by the formation of refractory intermetallics, which are additional centers of crystallization.

Metallographic analysis of the prototypes modified with GP established a noticeable grinding of the alloy grain. Grain grinding occurs due to the fact that the injected graphite powder does not dissolve in the magnesium melt, so its particles are additional centers of crystallization. At the same time, with a carbon content of more than 0.3 % in the alloy, defects appeared in the castings, the size and number of which increased with the increase in the carbon content in the metal. The microstructure of such defects consisted of micro-loosening and film contamination (Fig. 4). These surface films have been identified by metallographic methods as MgO and Mg(OH) compounds. An increase in the number of such defects led to a drop in the strength and plastic characteristics of the alloy. It is known [15] that increasing the thickness of such a film improves the anti-corrosion properties of the alloy during operation.

Modification of the GP alloy contributed to a decrease in the size and amount of eutectic secretions. It was found that the microhardness of eutectic secretions in the alloy before heat treatment was ~2.5 times higher than the values of the matrix solid solution. After the heat treatment of samples, the microhardness of the matrix increased (Table 3) while the eutectics (δ+γ) decreased, which indicates an increase in the uniformity of the heat-treated alloy. The increase in the carbon content in the alloy contributed to an increase in the microhardness of the matrix and eutectics. At the same time, it was found that carbon inhibits eutectic conversion, as a result of which, with an increase in its concentration in the alloy, the amount of eutectoid of type δ+γ (Mg_4Al_3) decreases markedly. The effect of the carbon content in the ML5 alloy on the characteristics of its structural components was linearly dependent. With an increase in the carbon content, the eutectic index, the average grain size decreased, the specific surface area of the grain boundaries increased, and the volume percentage of the γ phase increased. The addition of GP to the melt contributed to an increase in the strength of the metal with a slight decrease in ductility (Table 4).

Heat treatment contributed to an increase in the homogeneity of the alloy due to the redistribution of elements between the axes and interaxial spaces of dendrites, which, in turn, led to an equalization of the properties along the cross-section of the casting.

The use of dispersed graphite powders to modify magnesium alloys is a promising technology for improving their properties. Thus, as a modifier for magnesium alloys, it is advisable to use the waste from PJSC «Ukrgrafit», which makes it possible to improve the quality of castings and reduce the cost of casting.

Our results on the development of resource-saving technologies for the production of magnesium alloys with increased properties using the waste of enterprises are very relevant. This will reduce the cost of components and make the production of machines and mechanisms more competitive. In addition, the studies carried out are of great environmental importance since they make it possible to use the waste of metallurgical enterprises instead of recycling it in landfills and to obtain significant material and environmental effects.

The optimal additive in the melt of a carbon-containing modifier is 0.05...0.3 % while increasing the strength of the ML5 alloy by ~15 %, and its plasticity by almost 2 times.

The application of the devised technologies using the waste of metallurgical enterprises can be promising for the production of other non-ferrous alloys and requires additional research. At the same time, it is necessary to take into consideration the need for additional preparation of production (grinding, sieving, calcination).

7. Conclusions

1. Based on the analysis of the physicochemical properties of the waste of metallurgical enterprises, the possibility of using chloride waste of SCM from ZTMK as charge materials for the production of magnesium-based alloys has been established. Their use does not require any additional changes in the technological process of smelting and obtaining magnesium alloy while environmental safety meets the established standards. The positive effect of SCM from ZTMK in the smelting of the ML5 alloy on the granularity of the structure and the indicators of the mechanical properties of the metal was established. It is shown that the components of the SCM flux contribute to the grinding of the structural components of the alloy and its micro grain by ~1.5 times due to the modification of the metal. At the same time, the strength of the experimental alloy ML5 increased by ~20 % and the ductility to ~40 %.

2. The possibility of improving the casting of magnesium alloys by modifying it with graphite powder, which is a waste product of the production from AT «Ukrgrafit», has been investigated. The optimal additive in the melt of the carbon-containing modifier in the volume of 0.05...0.3 % contributed to a significant grinding of micro grains and provided an increase in the strength of the ML5 alloy by ~15 %, and its plasticity by almost 2 times.

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