Features of the structure of metal composite alloy obtained by electric slag remelting with controlled magneto-hydrodynamic action

Evgenii N. Kuzmichev[1*], *Pavel S.* Gordienko[2], *Evgenii A.* Drozdov[1] , *Evgenii A.* Kirichenko[3]

[1]Far Eastern State Transport University (FESTU), 680000, Khabarovsk, Russia
[2]Institute of Chemistry, Far Eastern Branch of the Russian Academy of Sciences; Vladivostok, Russia
[3]Institute of Tectonics and Geophysics, Far Eastern Branch of the Russian Academy of Sciences; Khabarovsk, Russia

Abstract. The results of experimental studies on the use of mineral raw materials containing zirconium oxides without its deep technological processing to create alloys by electroslag remelting are presented. Dependences of the transition of zirconium into remelted low-carbon steel on the magnitude of electromagnetic pulses have been established. It has been experimentally proven that zircon concentrate can be used as an alloying component to obtain alloyed alloys and coatings in electroslag technologies. In this case, the concentrate is used in a comprehensive manner, without additional technological processing. **Keywords:** zircon concentrate, electroslag remelting, magnetic impulses, mineral concentrates, structure, mechanical properties**.**

1 Introduction

In the modern high-tech world, metallic materials play a fundamental role, ensuring the life and development of human society, being the basis for the further development of technical progress. Despite the huge variety of existing materials, iron-based alloys occupy a special place [1-3]. Possessing a unique combination of properties that vary in a wide range, alloys are widely used in a wide variety of industries.

The most effective way to form the necessary physical, mechanical and operational properties is to change the composition of the alloy by complex alloying, i.e. the introduction of several alloying components into the alloy at once. Traditionally, pure alloying elements are used to produce alloys with specific properties.

Alloying elements often input into steel during its smelting in the form of ferroalloys or in the form of pure powders of alloying elements. Traditional technologies for the production of metallic materials usually give them a coarse-grained structure, since they use high processing temperatures, at which the resulting fine grains are unstable and increase in size as a result of growth. It is well known that pre-prepared particles can be introduced into the melt from the outside (exogenous technology) or provoke their formation from the

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[*] Corresponding author: e_kuzmichev@mail.ru

constituent components in the metal melt (endogenous technology) [4, 5]. To implement such technologies, along with solving the problem of introducing or provoking the formation of particles in the melt, it is necessary to ensure their stability, which implies a certain wettability in the “particle-melt” system. Considering the fact that during mass production steel casting can last tens of minutes, it it can be assume for sure that particles of any nature (endo- or exogenous) in real metallurgical production will not be able to maintain their size.

Production of such alloys by a metallurgical method is usually difficult, since the entire structure is extremely heterogeneous in terms of particle size and distribution over the structure. This structure causes an extremely unsatisfactory combination of strength and plastic properties of alloys therefore they are obtained exclusively by methods of powder metallurgy [6-9]. However, powder metallurgy methods are not available for large-scale power engineering therefore researchers from different countries keep trying to obtain DUS by liquid-phase methods [10, 11] which could open up perspectives for a wider use of these alloys in the manufacture of parts and assemblies intended for operation at high temperatures and stresses [12-14].

In this regard research in the field of resource-saving technologies that make possibility to use mineral raw materials in an integrated manner without its deep technological processing, is acquiring special interest and relevance. In this case, a special role is assigned to technologies for obtaining functional materials based on the complex processing of mineral raw materials [15-17].

At the same time to obtain materials based on the integrated use of mineral concentrates technologies are used associated with local thermal action on the original concentrates of high-energy effects of varying degrees of power. [18] Of particular interest in this regard for the production of alloys is the electroslag remelting of the alloyed charge obtained on the basis of mineral concentrates containing oxides of alloying elements.

Electroslag remelting provides high quality refined metal of very high density and purity. The slag bath is an active medium in which the processes of reduction, alloying and carbidization take place. Products made from alloys obtained by ESR are practically not inferior in quality to forged ones and significantly surpass cast ones [19].

In this study, this problem is studied on the basis of studies of the relationship of the "raw material-technology-material" system with the development of the concept of the maximum possible transition of alloying elements into alloys during remelting from mineral concentrates, excluding the multistage stages of their deep technological processing.

2 Methodology and materials

To obtain the materials, the technology of electroslag remelting were used with the use of pulsed electrophysical methods of influencing the slag and metal baths such as magnetic pulses. This approach will ensure the achievement of a controlled formation of the phase and structural composition of the obtained metal composite materials with the introduction of refractory metal carbides (ZrC,) into the metal matrix. Tests of mechanical properties at a temperature of 20 ° C were investigated: under tension - on a Tiratest 2300/1 testing machine in accordance with GOST 1497–84 on five-fold samples; impact bending - on a pendulum impact machine IO 5003-0.3 in accordance with GOST 9454-78 with an impact energy of 300 J. The material of the counter body was 45X steel, hardness HRC 60—62. Vickers microhardness will be determined using the ITBRV-187.5M hardness tester in accordance with GOST 9450–76.

The metallographic analysis of the alloys was carried out in accordance with GOST 8233–56 and GOST 1778–70 using an ES METAM RV 22 microscope and a metallographic complex MPM 3 ФЦ, at a magnification of × 1000. The composition of the materials obtained was studied with a Spectroscan MAKS GV X-ray spectrum analyzer in accordance.

The study of the elemental and phase compositions of the obtained alloys was carried out on a scanning electron probe microscope (ISM-35C JEOL). The resolution in the microscope mode is 60 ºA, the length of the detected waves is up to 7.6 ºA. Depth of field - 30 µm (at × 1000 magnification), magnification range × 10 ... 180,000. Micro X-ray spectral analysis of the obtained samples was carried out with a scanning (scanning) electron microscope "VEGA 3 LMH" (TESCAN, Czech Republic) equipped with an energy dispersive spectrometer "X-Max 80" (Oxford Instruments, Great Britain). The assessment of the number of non-metallic inclusions was carried out in accordance with GOST 1778–70.

3 Results and discussions

The research was carried out using mineral raw materials without its deep technological processing. Limestone was used as the basis of the charge, fluorite concentrate (CaF2) was used to ensure technological properties, the alloying component was zircon concentrate from the Algaminskoye deposit in the Khabarovsk Territory, and aluminum and carbon were used as reducing agents. The components of the charge were formed in the form of grains of ceramic flux using liquid glass. Electroslag remelting of the flux was carried out with a Sv08A welding wire in a water-cooled copper mold with a current of 200-300 A at a voltage of 40-45V.

Due to the fact that the slag bath is an ionic melt and many diffusions and chemical processes occuring in it, an increase in the degree of alloying can be expected due to the influence on these processes and on the movement of ions due to high-frequency vibration of the slag bath. As shown [19], the main factor determining the formation of the toroidal motion of the slag is the action of the electrodynamic forces arising in the slag bath. One of the possible ways to change the direction of the vector of the electrodynamic force, in our opinion, is to influence the slag bath with an external magnetic field (Fig. 1).

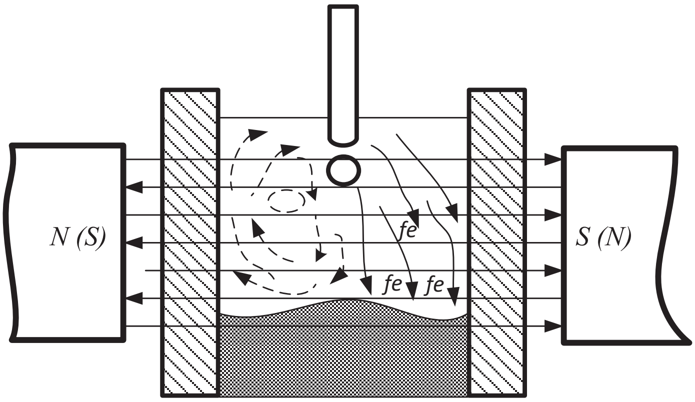


Fig. 1. Scheme of slag movement during exposure to an electromagnetic field.

In this case, it is possible to use both constant and alternating electromagnetic fields. The imposition of an external magnetic field on an electrodynamic force, which has a similar nature of occurrence, will lead to the appearance of a resultant force that will contribute to a change in the movement of the slag in the slag bath. In our opinion, exposure to a constant magnetic field will lead to distortion of the existing self-oscillating system of the slag bath, and exposure to an alternating magnetic field will lead to chaotic movement of the slag. To create an external magnetic field in the slag bath, the author made an electromagnet. A break is provided in the magnetic core of the electromagnet, into which the mold is placed. When an electric current passes through the windings of an electromagnet, a magnetic flux arises in the magnetic circuit, and the mold penetrates a transverse (perpendicular to the mold axis) magnetic field. The material of the crystallizer - copper, being a diamagnet, has good magnetic permeability and practically does not reduce the modulus of the induction vector of the magnetic field passing through it.

The effect of constant and alternating magnetic fields with different values of magnetic induction was explored. The magnitude of the magnetic induction was varied by changing the voltage across the windings of the electromagnet. The amount of zirconium that has passed into the alloy when exposed to a magnetic field is presented in Table 1, Table 2.

The tables show that the effect of an external magnetic field has a significant effect on the transition of zirconium to the remelted metal. At the same time, with an increase in the magnitude of the magnetic field, an increase in the content of zirconium in the metal occurs (Fig. 2).

Table 1. Chemical composition of experimental alloys, wt. %.

№	**Mode**							**Zr in slag**
	Current tupe	**V. T**	**Zr**	**C**	**Si**	**P**	**S**	
1	Direct	0.14	1.32	0.039	0.08	0.03	0.03	5.52
2	Direct	0.24	2.81	0.041	0.09	0.03	0.04	4.47
3	Direct	0.36	4.15	0.044	0.11	0.04	0.03	3.22
4	Direct	0.48	5.12	0.042	0.15	0.04	0.04	2.83
5	Direct	0.52	4.42	0.045	0.14	0.03	0.04	2.67

Table 2. Chemical composition of experimental alloys, wt. %.

№	**Mode**							**Zr in slag**
	Current tupe	**B. Тл**	**Zr**	**C**	**Si**	**P**	**S**	
1	Alternating	0.14	2.64	0.047	0.16	0.05	0.04	3.89
2	Alternating	0.25	3.63	0.048	0.14	0.06	0.04	2.32
3	Alternating	0.36	4.18	0.045	0.16	0.05	0.03	2.21
4	Alternating	0.43	5.20	0.044	0.17	0.06	0.04	1.81
5	Alternating	0.52	9.02	0.039	0.19	0.06	0.04	1.41

The effect of the alternating magnetic field is more influential. We consider it can be explained by the emerging effect of vibration of an electrode immersed in a slag bath with the frequency of an alternating magnetic field, which additionally distorts the magnetic force lines and crushes the detached metal drop, increasing the area of interaction between the metal and the slag.

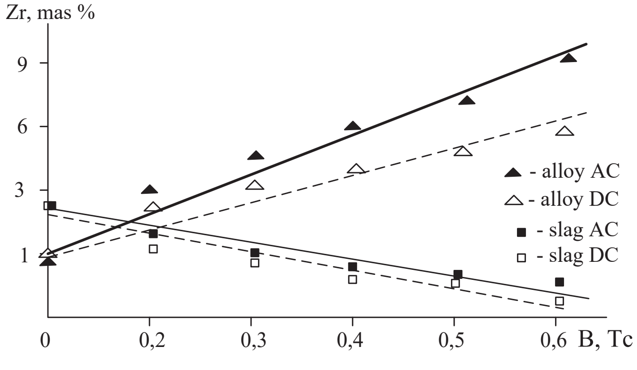


Fig. 2. Dependence of the amount of zirconium in the alloy and slag on the magnitude of the constant and alternating magnetic field.

At a magnetic induction of 0.52 T, the transition of zirconium to metal in comparison with ESR without control action increased by about 3 times.

The curves shown in Fig. 2, with the value of the approximation reliability R2 = 0.96, are described by dependencies (1) for exposure to an alternating magnetic field and (2) for exposure to a constant one:

$$y = 378{,}1x^3 - 348x^2 + 113{,}7x + 10{,}73. \quad (1)$$

$$y = -15{,}22x^2 + 27{,}45x + 11{,}09. \quad (2)$$

The nature of the dependences allows us to say that a further increase in the content of zirconium in the alloy is possible with an increase in the magnitude of the magnetic induction vector B. the alloy and the reduction of the residue in the slag confirm the fact of the influence of the magnetic field on the movement of the slag along the torus, transforming it into a chaotic one.

As you can see, the effect of an alternating electromagnetic field is more effective, with the use of which a higher content of zirconium is achieved.

Fig. 3 shows the change in the remainder of zirconium in the slag at different stages of remelting (different heights of the deposited ingot) as well as the corresponding content of zirconium in the ingot. The graph showes that the effect of a magnetic field does not significantly change the character of the curve illustrating the amount of zirconium in the slag in comparison with the types of effects considered above which allows us to assume a similar nature of the change in the intensity of the transition of zirconium into the alloy at different stages of remelting.

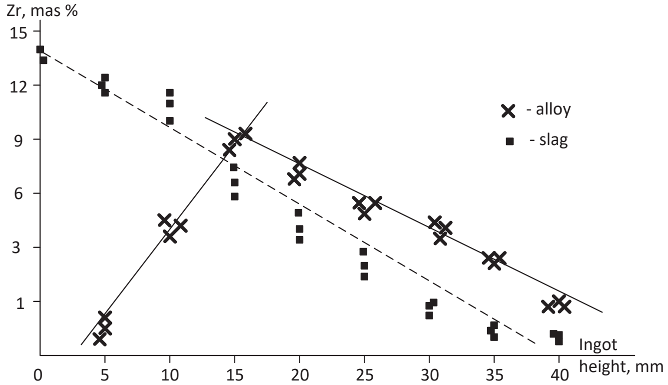
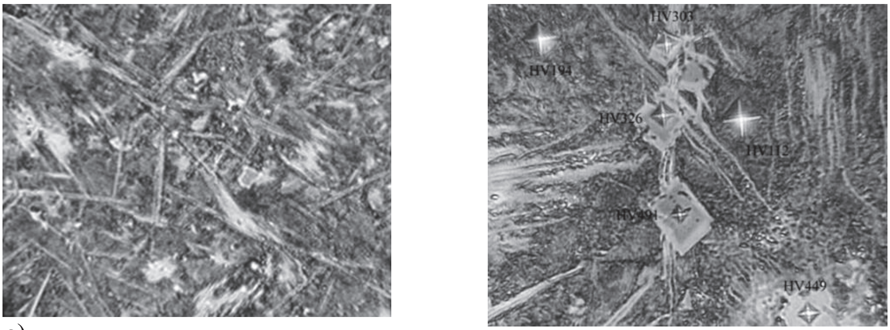


Fig. 3. Change in the remainder of zirconium in the slag during remelting in comparison with its amount in the alloy when exposed to an alternating magnetic field (0.52 T).

The hardness of the alloy (9.02 wt. % Zr) was 42 HRC, the heat resistance was 6.0321 mg/cm^2, and the impact strength was 69 J/cm^2.

Thus, it has been experimentally proved that the effect of a magnetic field affects the processes occurring in the slag bath during electroslag remelting, as a result of which the transition of the alloying element into the alloy increases. In this case, a greater effect is given by the action of an alternating magnetic field, with the help of which the content of zirconium in the metal reached 9 wt. %, which is 3 times higher than the amount obtained under normal conditions. This result, in our opinion, is explained by the appearance of chaotic auto-oscillations in the slag bath, which increase the intensity of the transition of the alloying element into the metal.

The microstructure of the obtained alloy is a pearlite matrix interspersed with zirconium carbides (Fig. 4). Microhardness of pearlite was $HV_{0.005}$ 112 ... 194, carbides - $HV_{0.005}$ 1280 ... 1406. The micro-X-ray profile of the alloy is shown in Fig. 5, the qualitative picture of the distribution of elements in the structure is shown in Fig. 6. The figures show that zirconium carbide is evenly distributed in the matrix and represents inclusions of the correct shape. The microhardness values, appearance, distribution pattern give reason to believe that the inclusions are the carbide phase of zirconium, which is confirmed by the results of X-ray phase analysis (Fig. 7).



a) b)

Fig. 4. Microstructure of the alloy a) x250; b) x500.

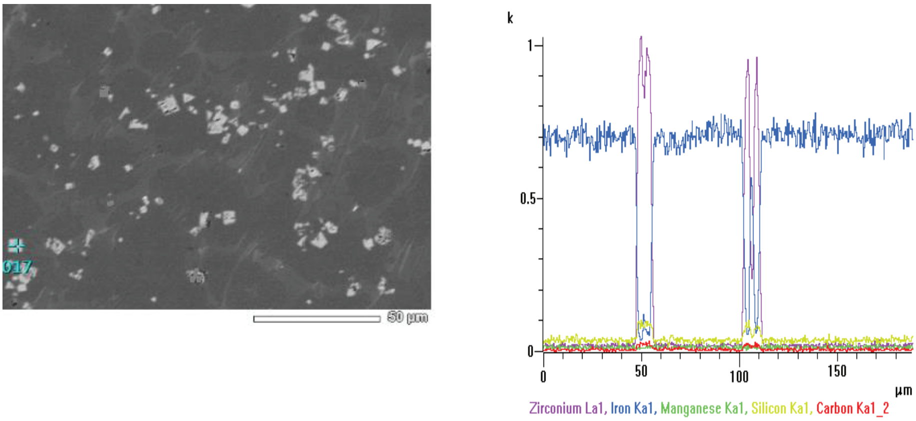
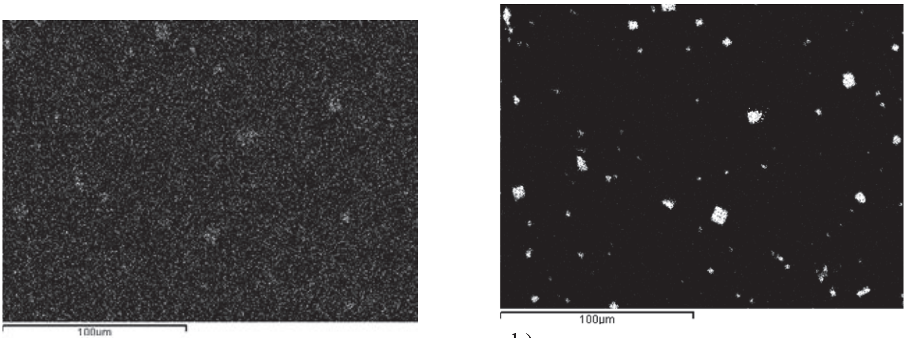


Fig. 5. Micro X-ray profile of the alloy containing ZrC.



a) b)

Fig. 6. Distribution in the structure of the main elements of the alloy a) silicon; b) zirconium carbide.

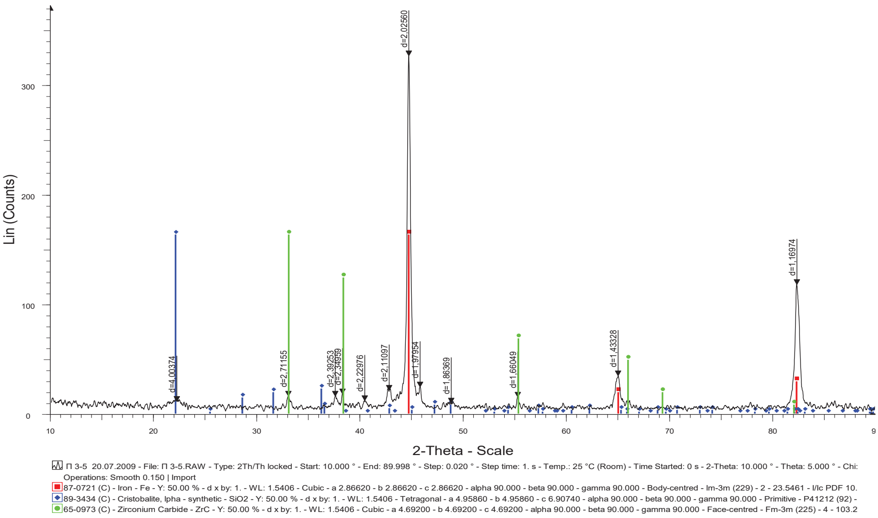


Fig. 7. X-ray diffraction pattern of the test alloy.

In order to reduce the anisotropy and obtain granular pearlite, cyclic triple annealing was carried out in the temperature range of 680-920 ° C.

After annealing, flaky graphite was formed in the metal (Fig. 8). The size of graphite inclusions ranges from 0.47-5.2 microns, with more than 90% of inclusions with effective sizes from 0.47 to 2.8 microns. The inclusions are elongated. The total area occupied by graphite is 5.4%. The microstructure of the experimental annealing and etching alloy is shown in Fig. 9.

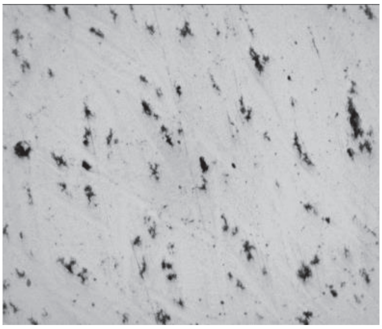


Fig. 8. Graphite in deposited metal after annealing.

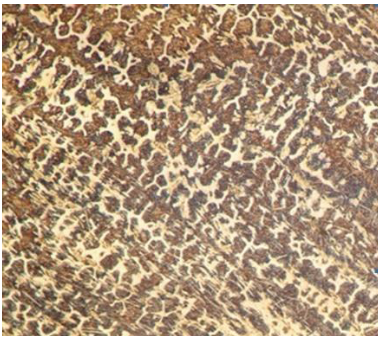


Fig. 9. Microstructure of the experimental alloy after annealing.

The structure shown in Fig. 9 has a skeleton of primary carbides with a length of 12-15 microns and a width of 4-13 microns, there are elements up to 30 microns long. The amount of structurally free carbide phase is 23-25%. The anisotropy of the structural components after annealing slightly decreased, the average grain score after annealing was -11.

4 Conclusions

1. Experimental studies have shown that during electroslag remelting with a low-carbon welding wire it can be alloyed with elements with a high affinity for oxygen, which are in the flux in the form of oxides. These elements in particular include zirconium, which stands in the line of activity directly near oxygen.

2. It has been established that the most rational reducing agents for zirconium are aluminum and carbon, but the degree of reduction efficiency is different. In addition these elements performed the function of additional alloying elements.

3. The wear resistance of the obtained alloys exceeds the wear resistance of 40X steel by 5%. Tensile strengths are in the range of 620 ... 675 MPa, impact strength ranges from 47 to 59 J/cm^2. These properties correspond to the properties of alloyed steels of the type 50G, 05G4DMF, 18Khgt, etc., intended for the manufacture of loaded parts operating under the influence of vibrations, shock loads and significant friction forces.

4. The developed materials make it possible to form hardening coatings with a zirconium content of up to 9 wt. %. The alloys obtained by electroslag remelting can be used for the manufacture of highly loaded parts or as a basis for tool steels of the KhVG type.

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