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Magnetically Controlled Electroslag Melting of Titanium Alloys

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Abstract

Series of titanium alloy remelting has been performed in an experimental electroslag setup. The typical electrovortical flow pattern in both the slag and the liquid metal pools has been radically modified by imposing an external magnetic field. Several configurations of the applied magnetic field were considered and tested during actual remelting. The best results were obtained during remelting in the presence of a pulse axial magnetic field providing fine-grained titanium alloy ingots of uniform composition. It has been shown that the new process of magnetically controlled electroslag melting is a highly competitive alternative method for the production of multi-component titanium alloys. Further modifications of the process are proposed with an aim to optimize energy efficiency and equipment costs.

Introduction

One of the actual trends in the modern titanium metallurgy is the development of a new class of multi-component high-strength and heat-resistant titanium alloys. The principal difference of these alloys from traditional ones is the presence of chemical compounds (intermetallics) in their structure [1]. The higher values of strength and heat resistance are attained in these alloys, giving an opportunity to get a new complex of metal properties, which are of great interest for the modern industry.

However, the problems of chemical and structural homogeneity of metal and fine-grain structure are very acute in the production of titanium alloys with intermetallide strengthening. The melting technology must guarantee the preset chemical composition of the alloy with a high level of it homogeneity. Therefore, the development of new processes of melting and metal crystallization, having mechanisms for improvement of these characteristics, is extremely topical.

With the above said, the ElectroSlag Remelting (ESR) process is a promising method for the production of titanium alloys. During the ESR process, a consumable cylindrical electrode is being melted by Joule heat generated in a resistive slag pool. Metal droplets pass through the slag and solidify in a water-cooled copper crucible to form ingots. Since a high operating current passes through the two liquid current conducting media (the slag and the metal pool), the electromagnetic methods to control the heat/mass transfer and metal crystallization are the most promising.

1. Analysis of the Applied Field Effect

The nature and intensity of the action of applied magnetic fields on the ESR are determined by the fields' parameters as well as by the value and nature of the current distribution in the slag and molten metal.

Lines of the electric current at ESR and versions of the applied magnetic fields are shown in Figs.1-2. In all these cases, Lorentz forces $\mathbf{f} = \mathbf{j}\times\mathbf{B}$ have a vortical mode (rot$\mathbf{f} \neq 0$) and, consequently, cause the motion of the melts. In the case of axial and radial applied fields (Fig. 2 a, b), the Lorentz forces are azimuthally directed and cause the melt rotation around the pool axis. In the case of transverse magnetic field (Fig. 2c), the presence of two components of the Lorentz force causes a complicated melt circulation. Additionally, the absence of axial symmetry of the applied field results in skewing of the pool free surface (f_z has different directions at $x > 0$ and $x < 0$).

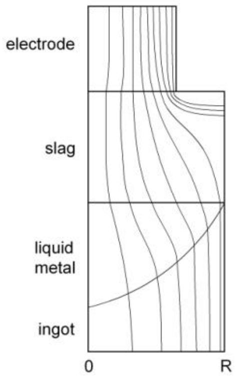

Fig. 1. Electric current lines at ESR

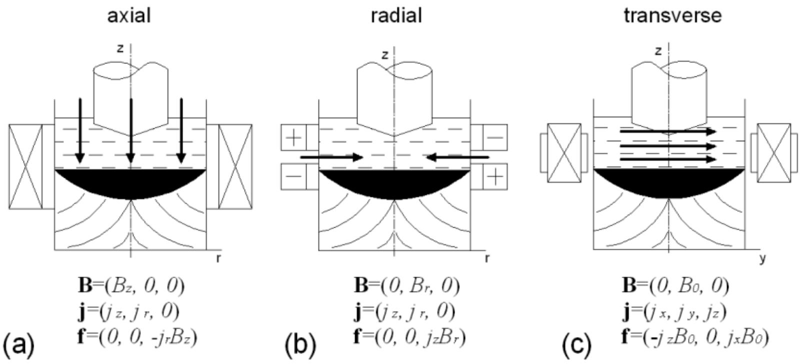

Fig. 2. Versions of the applied magnetic fields: (a) axial, (b) radial, (c) transverse

At ESR, the AC current is used for melting. Therefore, if the AC applied magnetic field is used, electrovortical flows are formed in the slag and in the metal pool. In case of DC magnetic field, the melt vibration is exited. In this case, the vibration frequency is equal to that of the melting current (50 Hz). However, in some cases there is an effect of the melting current partial rectifying at electroslag remelting [2]. Therefore, in this case it is possible to realize both the electrovortical flows and the melt vibration.

Experience of the electromagnetic influence at ESR evidences that the steady electrovortical flows in the metal pool can lead to the formation of different kinds of defects in the ingot. Therefore, the DC magnetic fields were used in these investigations.

2. Experimental

The effect of different configurations of the applied magnetic fields on the technological features of the electroslag process and properties of melted ingots were tested. Titanium ingots of 80 ... 160 mm in diameter were melted. DC axial and transverse magnetic fields were applied. The melting voltage was 25 ... .40 V, current 2 ... 10 kA.

A transverse DC magnetic field of 0.05 ... 0.25 T was induced by an electric magnet, whose poles were located from the opposite sides of the mould. This field initiates vibrations (50 Hz) of the melt in transverse planes. The vibration influence on the electrode melting nature was found. Drops were formed around the entire edge of the consumable electrode, but not only in its central part; the frequency of the metal drop detachment increased and their average weight was reduced (Fig. 3). However, the stability of the electroslag process and the conditions of the ingot formation has got worse (Fig. 4).

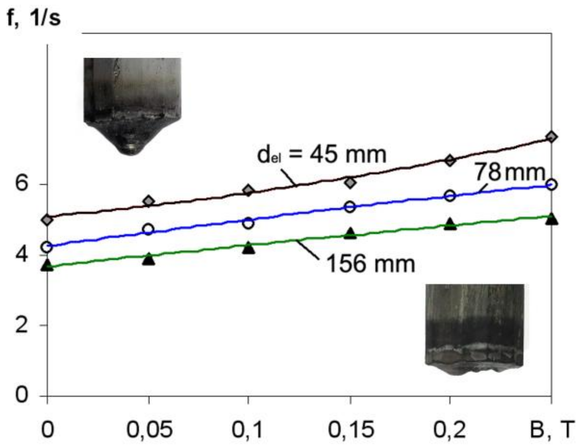

Fig. 3. Frequency of the metal drop detachment versus the transverse field induction

Fig. 4. Appearance and macrostructure of a Ti ingot melted under the transverse magnetic field B = 0.2 T

The axial DC magnetic field was generated by a solenoid, which embraced the mould. A continuous and pulsed influence with a pulse duration of 0.3 to 20 s and a pause duration of 3 to 30 s was used. The magnetic field induction in the melting zone was varied in the range 0.05 to 0.3 T.

The best results were obtained under the effect of a pulse magnetic field. Its application allowed, first, to increase the electromagnetic action owing to the hydrodynamic impact at the moment the magnetic field is imposed and, second, to reduce the mass and energy consumption of the electromagnetic device. In addition, the pulse magnetic fields promote the continuous restructuring of the hydrodynamic flows in the metallurgical pool, thus providing an intensive stirring of the liquid metal.

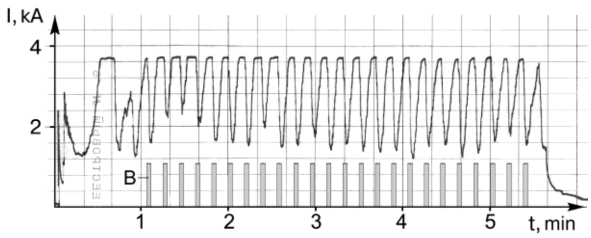

Fig. 5. Fluctuations of the melting current under the pulsed actions by the axial magnetic field (B = 0.22 T)

It is found that the pulse influence by the magnetic field leads to appropriate pulse fluctuations of the melting current (Fig.5). At the moment of the magnetic field impulse the melting current decreases. Then, when the magnetic field is switched off, the melting current recovers to its initial value. This is caused by some factors; the main among them is the deformation of the slag pool free surface and the decrease in immersion depth of the consumable electrode into the slag at the moment of the magnetic field impulse.

It should be noted that such fluctuation of the melting current does not result in a considerable instability of the electroslag process and ingot formation. Therefore, the pulse field causes a discrete-portion heat input assuring additional feasibility for ingot crystallization process control.

Fig.6 shows the magnetic field effect on the ingot surface formation. Under the continuous action of the magnetic field a lateral surface of the ingot is deteriorated (Fig.6a). Under the pulsed action it is possible to obtain a good quality ingot surface at a definite ratio of the pulse and pause duration (Fig. 6d). For 100 mm diameter ingots and 0.22 T induction, these conditions are as follows: pulse duration 1s, pause 10 s.

Fig. 6. Ti ingots melted under the pulsed action of the axial magnetic field (B = 0.22 T):
(a) continuous influence,
(b) pulse 10 s, pause 30 s,
(c) pulse 1 s, pause 3 s,
(d) pulse 1 s, pause 10 s

The magnetic field effect on the crystallization of titanium ingots is illustrated in Fig.7. The structure of ESR ingots is characterized by the coarse columnar crystallites, which are formed under conditions of directed heat dissipation through the mould wall (Fig.7*a*). The action of magnetic field leads, first, to thinning and reorientation of the crystallites (Fig.7*b*) and, with the induction increase, to refining of the ingot structure (Fig.7*c*). Here, the macrostructure of the ingots is dense and homogeneous, consisting of equi-axial grains. The mechanism of ingot structure refining is associated with the destroying action of the melt electromagnetic vibration on the growing crystallites caused by the interaction of the AC melting current with the DC magnetic field. The refining of the ingot structure also stimulates intensification of heat/mass exchange at the liquid-solid phase interface.

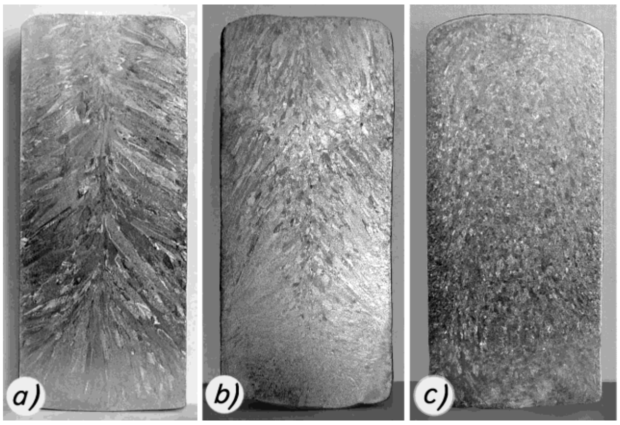

Fig. 7. Macrostructures of 110 mm diameter Ti ingots melted at different induction values of the axial magnetic field:
(a) B =0, (b) B = 0.08 T, (c) B = 0.22 T

The structural homogeneity and the grain size are the most important factors determining the quality of multi-component titanium alloys. Therefore, the refining of the ingot crystalline structure might be the main result of the magnetic field action.

However, with the increase in diameter of the melted ingot (more than 140 mm), the effectiveness of the metal structure refining decreases that is due to a scale factor and reduction in densities of the operating current in the pool. This necessitates the increase of the magnetic field induction in the melting zone, thus providing the increase in mass-dimensional characteristics of the electromagnetic device. In this connection, the further investigations of feasibility of intensification of the hydrodynamic effect on molten metals are topical with the aim to reduce the dimensions of the electromagnetic device and improve the technological parameters of melting.

The challenging direction of the investigations is the application of charge of capacitor banks to supply the solenoid windings. In this case, it is possible to obtain high peak currents and necessary magnetic field induction values in the melting zone at a relatively small cross-section of the solenoid windings.

Another way to improve the effectiveness of the axial magnetic field is the increase of the radial component of the melting current. This can be achieved by increasing the current passing through the mould circuit (Fig. 1) and by synchronizing the action of the axial field with the mould current [3].

3. Technology of Magnetically Controlled Electroslag Melting

The results of the investigations have become the basis for the development of a technology of the Magnetically-controlled Electroslag Melting (MEM) of titanium alloys (Fig.8).

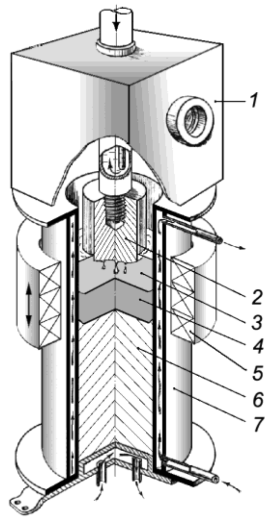

Fig. 8. Schematic of the MEM of titanium: 1 - vacuum chamber, 2 - electrode, 3 - slag pool, 4 - metal pool, 5 - electromagnetic system, 6 - ingot, 7 - mould

The melting process is realized in a chamber-type electroslag furnace in the controllable atmosphere of inert gas. The melting of the consumable electrode extruded from spongy titanium and alloying elements is implemented under the action of an applied magnetic field generated by an electromagnetic system embracing the mould. The main benefit of the magnetic fields application at MEM is the increase of homogeneity of the metal and refining of its crystalline structure. Depending on the ingot composition, type, size and purpose, different melting schemes were proposed (Fig. 9).

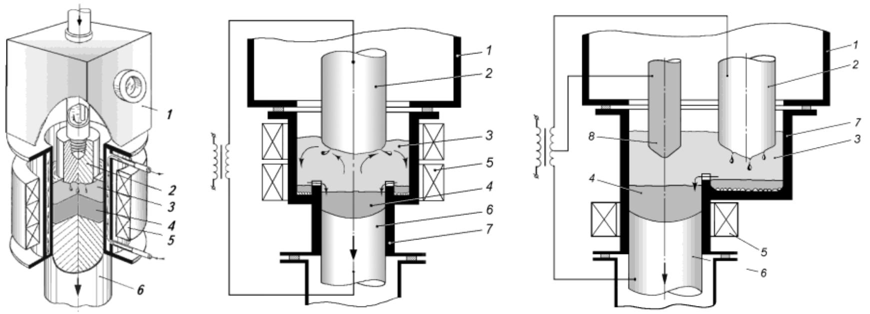

Fig. 9. Technological schemes of MEM (pos. see Fig. 8)

The rational application of the MEM technology is the melting of ingots of multi-component titanium alloys, including those with the intermetallic strengthening. An example of these alloys can be a VT22 alloy (Ti-5Al-5V-5Mo-1Fe-1Cr) strengthened additionally by C, B, Si, or eutectoid TiSn (Table 1).

Tab. 1. Mechanical properties of titanium alloys by MEM technology at room temperature*

Alloy	Ultimate Tensile Strength, MPa	Elongation, %	Area Reduction, %	Impact Strength (U-notch), J/cm^2
VT22 + 0.2%C	1288-1366	14-16	37-40	20-22
VT22 + 0.2%B	1330-1340	8-12	27-36	22-24
VT22 + 0.25%C + 0.2%B	1320-1370	7-9	20-28	15-18
VT22+0.1%Si + 0.1%C + 0.1%B	1300-1370	8-14	22-30	18-22
VT22+4%Sn	1190-1280	5-8	9-16	18-21

*After heat treatment

As the metal investigations showed, the MEM technology allows realization of advantages of titanium alloys with intermetallic strengthening, mainly owing to the uniform distribution of alloying elements and intermetallic phase in the ingot volume and refining of its crystalline structure.

Conclusions

1. Electroslag technologies are favorable processes for electromagnetic processing. The wide range of conditions for its stability and the fact that a high electric current passes through the melts of slag and metal contribute greatly to this.

2. The applied magnetic fields are effective tools to control the hydrodynamics of the melts of slag and liquid metal, allowing to influence the melting of the electrode metal, transfer of electrode metal drops through the slag pool and the ingot crystallization.

3. It is shown that the most efficient scheme of the electromagnetic action at ESR is the pulsed action of the axial field. Its application assures the increase of the metal homogeneity and refines its macrostructure, thus preserving the high quality of ingot formation.

4. A technology of the magnetically controlled electroslag melting of titanium alloys has been developed, providing the preset chemical composition of the metal, its homogeneity and fine-grain structure. A new technology can be a promising process for the production of multi-component titanium alloys.

References

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