Peculiarities of Process of Magnetically-Controlled Electroslag Melting (MEM) of Titanium Alloys

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ANNOTATION
The MEM technology can produce round ingots of 300 mm diameter and more, and also the rectangular ingots of similar mass.

The effect of controllable electrovortical flows, electromagnetic fields and ion melts of mixed fluxes on the solidifying titanium was investigated. The most important advantages of the MEM process are as follows: 1) use of cheap metallurgical equipment operating at alternating current of melting; 2) replacement of two-and three-stage remelting of electrodes by a single-stage remelting; 3) feasibility of using lower-grade spongy titanium; 4) high physical and chemical homogeneity of cast metal without pores and foreign inclusions; 5) high solubility of titanium nitrides in mixed fluxes; 6) low content of harmful admixtures such as gases, carbon, phosphorous, halogenides, etc.

Metal of MEM technology is characterized by high mechanical properties and quality of the ingot surface formation.

Key words: technology, electroslag melting, magnetic field, hydrodynamics, convection, titanium alloys, ingot.

1. INTRODUCTION

Exploitative characteristics of metal titanium products and alloys are already determined on the stage of ingot melting. Titanium, as a constructional material, possesses the unique properties. However, only part of them could be realized through traditional and commonly used melting technologies - vacuum-arc remelting (VAR), electron beam remelting (EBR), electroslag remelting (ESR) due to insufficiently high indicators of homogeneity, density of intercrystallite boundaries of metal, availability of detrimental admixtures, inclusions and pores. These flaws of metal quality originate from the traditional smelting methods and despite the long-lasting efforts of scientists and engineers from over the world this problem has not been solved yet.

The stumbling stone is such sources of heating, as electron beam and electric arc, as well as low hydrodynamic melt activity. These concentrated sources of heating increase the temperatures of central parts of the metal pool up to 4000°C and higher. Neither electric arc nor electron beam do not have any hydrodynamic impact on the titanium melt. At VAR high-temperature arc deepens the axial part of the metal pool which results negatively in ingot properties. At EBR the metal overheated by electron beam crystallizes under conditions of heat convection which results negatively in its properties too.

The important advantage of electroslag process in comparison with VAR and EBR is nonconcentrated source of heating - slag pool. Under traditional ESR of titanium the great potential of chemical and hydrodynamic impact of slag on metal remains unutilized. Uncontrollable electrovortical flows (EVF) of overheated slag deepen the metal pool and deteriorate solidification of ingot (Fig. 1).

Ability to control the heat, chemical and hydrodynamic activity of melt of electroslag pool determines the advantages of MEM compared to VAR, EBR and ESR technologies.
2. PHYSICAL AND CHEMICAL PECULIARITIES OF THE MEM PROCESS

Under the MEM technology (Fig. 2) a consumable electrode from spongy titanium 1 is melting in a slag pool 2 and forms a metal pool 3 and consequently an ingot 4. The process of melting, transfer and solidification of metal is carried out under the influence of natural and external magnetic field, which is created by electromagnetic device 5 and is changing in the melting process according to specified program. Zone of metal melting and the heated to high temperature electrode are isolated from atmosphere by vacuum chamber 6 and crystallizer 7, which is air-tightly connected to it. Before melting the melting chamber is evacuated and then filled with an inert gas.

The basic differences of new technology are the implication of reactive mixed fluxes and magnetic fields, which control the refining, transfer and solidification of metal. In addition, MEM technology implies the following mechanisms of enhancing the titanium casting:

- decrease of atmospheric gases in metal at the expense of thermodynamical reactions, proceeded on the boundary slag-metal, as well as dilution of nonmetal detrimental inclusions and admixtures in slag pool;
- hydrodynamical treatment of the pool and front of ingot crystallization, which allows to grind the crystallites and pack their boundaries providing refining, chemical and physical homogeneity of metal;
- electromagnetic impact which allows to remove some undersoluble alien inclusions into the skull.

Due to EVF under MEM heat input is evenly distributed over the volume of metal melt and maximum temperatures are 2000 - 2200°C. For comparison, under VAR and especially EBR the temperatures are 1.5 - 2 times higher.

Last years some research on implications of reactive mixed fluxes in electroslag remelting of titanium has been carried out [1,2]. After break of the USSR, the mixed refining fluxes were successfully used in MEM of titanium for the military conversion purposes. Earlier they were used in magnetically-controlled electroslag welding (MEW) of military equipment.

These fluxes do not decrease the content of the detrimental admixtures in metal. Moreover, they dilute the alien inclusions and prevent them from hitting the ingot. M.Benz and his colleagues have discovered that inclusions of titanium nitride were diluted dozens times faster in reactive slag pool with additions of metal calcium than in metal pool [3].

Under MEM the structure of metallurgical melt is defined by controllable EVF. The speed of EVF reaches 1m/sec and over. These flows form the metal pool, the front of ingot crystallisation and, respectively, the structure of its metal. Controllable EVF intensifies the refining of metal by flux and results in complete removal of gas pores and detrimental inclusions from ingot. The content of detrimental admixtures - nitrogen, oxygen, hydrogen, natrium, calcium, chlorine, etc. - decreases; high chemical and physical homogeneity of metal is achieved; its crystallites are grinded. EVF of melt generate the electromagnetic forces \( \mathbf{F} = \mathbf{j} \times \mathbf{B} \), where \( \mathbf{j} \) - is the current density in melt; \( \mathbf{B} \) - is the inductance of the magnetic field. EVF appear where the direction and densities of current are changed. Moreover, the vortical electromagnetic force is always directed to the side of decreasing the current density. The MEM is aimed at the creation of either trajectories of the moving melt.

3. THE METHODS OF MEM OF TITANIUM

We have developed a number of mechanisms of EVF control of slag and metal melts in natural and external magnetic fields. Some of them are given below.

3.1. MELTING IN A NATURAL MAGNETIC FIELD

Melting in a natural magnetic field of current is given in Fig. 3. Distribution and intensity of EVF of metallurgical melt in this case are determined by the distribution of electrical current in electrode, slag and metal pools and in ingot. The alternating current of melting defines the peculiarities of distribution of current lines in elements of the melting circuit. The full melting current is passed through these elements as the non-

Fig. 2. Magnetically-controlled electroslag melting (MEM) of titanium.
electroconductive slag crust between the ingot, metal pool, from the one side, and a lateral wall of the mould, from the another side, prevents the radial leakage of the electrical current.

Direction of current lines in the melt approaches the axial direction. The alternating current forms a skin-layer in the electrode and ingot which is remarkably thinner than that in metal and, especially, in slag pool (Fig.4). Differences in thickness of current layers is due to a different electric conductivity of the above-mentioned elements of the melting circuit:

\[ \sigma_m > \sigma_{m.t} > \sigma_{m.s} \]

where \( \sigma_m \) - is the specific electric conductivity of the solid titanium of electrode and ingot;
\( \sigma_{m.t} \) - is the specific electric conductivity of the molten titanium;
\( \sigma_{m.s} \) - is the specific electric conductivity of the molten slag.

In addition, \( \sigma_{m.s} \) is less than \( \sigma_{m.t} \) by approx. 2 orders and less than \( \sigma_m \) by 3 orders.

Intensive heat and mass transfer of the melt is realized at maximum permissible interelectrode gap of slag pool. Toroidal EVF envelops the entire volume of slag pool. The higher densities of electric current in skin-layer of metallurgical melt determine the insignificant hydrodynamic pressure in the central part of the pool, deepening it slightly.

Turbulent EVF on the interphasing surfaces of partition (electrode - slag, slag - liquid metal, liquid metal - ingot) are caused by electroconductivity jump (Fig.4). Even on the plane bottom of the metal pool electroconductivity jump causes EVF [4]. These EVF activate the purifying of metal from detrimental admixtures and inclusions by flux.

The solid nonmetal particles and gas bubbles change the direction and densities of its electric current (Fig.5). They are also influenced by electromagnetic forces formed by these changes of electric current lines. In addition, they are also influenced by external flow of EVF of melt. Under influence of the above mentioned forces, particles and gas bubbles are transferred in the external flow of the pool into its peripheral areas to the crystalizer wall. Magnetically-static pressure of metallurgic melt "press them out" into skull. On this way they dilute intensively in slag, moreover, the dilution is accelerated by external flow of EVF. Mass transfer and dilution of solid inclusions in melt under influence of external flow of EVF are faster by a factor of 1-2 if compare to pure diffusion [5].

\[ \delta = (\pi / \mu_0 \sigma) \frac{1}{2} \]

\( \delta \) - thickness of a skin layer,
\( f \) - current frequency,
\( \mu_0 \) - magnetic permeability of substance,
\( \sigma \) - specific electroconductivity.

Fig.4. Skin effect in MEM of titanium.

\[ P = P_0 + \mu_0 j^2 (R^2 - r^2) / 4 \]

\( P_0 \) - pressure at the mould wall,
\( \mu_0 \) - magnetic permeability of substance,
\( j \) - density of electric current in melt.

Fig.5. "Pressing-out" of non-electroconductive particles and gas bubbles to the mould walls.
Insoluble particles come directly to skull cover on the ingot surface from the slag pool. Part of them comes to skull through the metal pool. This was due to the fact that the toughness of the molten metal is approximately by one order less than that of the slag. Therefore, the rates of moving particles in metal will be, respectively, by one order higher than those in slag. For example, time of transfer of the hard particle to the mould wall through the metal will be 5-6 s, while that of a gas bubble will be 3-4 s. The larger depth of periphery regions of the metal pool in MEM, as compared with ESR, will contribute to the improvement of the reliability of its purifying from inclusions and pores. Therefore, it is very important to conclude here that the absence of nonmetal inclusions and pores in the MEM-metal is the result of implication of controllable EVF of melt.

3.2 MELTING WITH THE DISPLACING LINE OF ZERO MAGNETIC FIELD

Electroconductive titanium nitrides are moving in the melt towards the line of zero magnetic field. Under VAR and ESR this line coincides with the electrode axis. Therefore, nitrides from consumable electrode come to the ingot metal. The presence of these inclusions in metal deteriorates significantly its mechanical properties, cyclic fatigue strength and performance.

To prevent this the line of zero magnetic field is transferred to the forming surface of crystallizer. Nitrides are intensively diluted on the way to the side forming wall of crystallizer. Undiluted big nitrides are transferred to skull skin on the ingot surface.

One of the methods of changing the position of the line of zero magnetic field is a passing of the electrical current \( I_2 \) in a conductor, located beyond the pool and parallel to its axis (Fig. 6). At unidirectional nature of melting current \( I_1 \) and current in an auxiliary conductor \( I_2 \) the latter "attracts" the line of the zero field.

At zero point of the magnetic field \( B_y = 0 \). The distance of this point to the pool axis is

\[
r = a \pm \left( a^2 - \beta R^2 \right)^{1/2},
\]

where \( 2a \) - distance between the pool axis and the axis of an additional conductor with current \( I_2 \);

\( \beta = I_2 / I_1; \)

\( R \) - pool radius.

In this case the electroconductive particles are "extruded" into a skull crust at the ingot lateral surface.

3.3. MELTING IN TRANSVERSE MAGNETIC FIELD

The change in directions and densities of current along the front of ingot crystallization creates the electrovortical motion of the melt around the growing crystals. However, the EVF intensity at the front of crystallization is not sufficient for refining the growing crystals. At the same time the increased densities of melting current in the periphery regions of the pool at superimposition of a negligible inductance of the transverse field permit to refine crystallites which are growing along the front of crystallization (Fig. 7). The interaction of axial component of the alternating current of melting \( I_m \) with a constant transverse magnetic field generates the magnetic forces \( f_r \) in the melt. The direction of action of these forces is changed for opposite direction with a frequency of the industrial current (50Hz). This results in vibrating the melt and destroying the branches of the crystallites which are projected beyond the front of crystallization. The MEM metal is crystallized with the fine and homogeneous structure of casting grains.

3.4 MELTING IN LONGITUDINAL MAGNETIC FIELD.

This method has sense to be applied for electrode melting with transverse section several times smaller than ingot has. In this case the radial component presents a remarkable part of the current which is passed through the
melt. The interaction of the current radial component with a longitudinal magnetic field generates a primary axial rotation of the melt. In its turn this horizontal rotation results in secondary ascending flow of melt in the centre of the pool (Fig. 8). The secondary flow destroys the traditional toroidal rotation of the pool by its reversing. We get the optimal, from the point of view of ingot solidification, plane bottom of metal pool or one with peripheral deepening (Fig. 9). Solidificating metal has small-crystal structure.

**3.5. MELTING IN RADIAL MAGNETIC FIELD**

In MEM the electrodes are mainly used whose section is compatible with a section of the ingot. Therefore, the basic electrical current in slag and metal pools is passing in an axial direction. In this case, to provide the axial rotation of the current-carrying melt the longitudinal field action is not almost effective. It is necessary to use the external radial magnetic field. However, the axial rotation of the slag pool itself affects the properties of the cast metal most probably negatively than positively. The metal can have the liquation zones which drastically deteriorate the metal quality.

MEM in radial alternating magnetic field improves effectively the metal quality and prevents the formation of these defects (Fig. 10). The result of this effect is a complex movement which covers all the metallurgical melt. The opposite directed lines of the external field at the interaction with an axial component of current generate the electromagnetic forces which rotate the slag pool in one direction, and the metal pool in the opposite direction. Such reciprocal MHD-rotation of the metal and slag in the spot of their contact, at their interface, intensifies greatly the metal purification with a slag. New and new portions of the metal enter into interaction with a fresh flux.

In addition, such axial rotation creates the secondary flows, which move the melt meridionally. The centrifugal forces which are created by the differential reciprocal rotations generate 2 secondary toroidal rotations both in a slag and a metal pool. In addition, the adjacent torus are rotated in opposite directions. Direction of rotation of the slag torus, at the surface of the metal pool, and liquid-metal torus, at the bottom of the slag pool, provide the formation of a flat bottom of the metal pool. This plane front of crystallisation enhances the quality of ingot metal. Toroidal rotation of slag intensifies the purification of electrode drops. Simultaneously, external flows of the primary MHD-rotations and secondary toroidal rotations extend the mechanical trajectory of solid particles and gas bubbles in melt. The effectiveness of its dilution and transfer into skull increases.
4. PROPERTIES OF MEM METAL

The effectiveness of the MHD mechanisms mentioned above is justified by the results of comprehensive investigations of titanium properties under MEM technology.

Examination of the macrostructure of ingots showed a complete absence of such defects as pores, non-metallic inclusions, porosity along the ingot axis. Moreover, the metal is characterized by a dense, uniform and fine-grained structure (Fig. 11). When examining the longitudinal tempel of the titanium ingot of 105 mm diameter the size of the primary grain was approx. 5 mm, while it was 40 mm in similar ingots of VAR technology. Thus, the total length of grain boundary in ingots of the MEM technology is larger by about two orders as compared with that of the ingots of the traditional technology. It is evident that even at similar total amount of impurities in titanium of the new and traditional technologies of melting the segregation enrichment of the primary grain boundaries for the titanium of the MEM technology will be by one order less.

Chemical composition of the commercial titanium of MEM technology meets completely the requirements of the standard. In addition, as compared with VAR ingots, in ingots of MEM titanium melted using the spongy titanium of one grade the amount of the harmful impurities such as \( \text{O}^\text{2-} / \text{O}^\text{2-} / \text{Na}^\text{+} / \text{K}^\text{+} / \text{Cl}^\text{-} \) decreased by 15-20%, and \( \text{Na}^\text{+} / \text{K}^\text{+} / \text{Cl}^\text{-} \) by one order (Table 1).

<table>
<thead>
<tr>
<th>Metal (VTI-0)</th>
<th>Chemical composition, wt.%</th>
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<tbody>
<tr>
<td>Ti</td>
<td>O</td>
</tr>
<tr>
<td>VAR base</td>
<td>0.12</td>
</tr>
<tr>
<td>MEM base</td>
<td>0.10</td>
</tr>
<tr>
<td>Industrial standard base</td>
<td>0.20</td>
</tr>
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Tensile tests within a wide temperature interval \(+20^\circ°C; -196^\circ°C\) showed high ductility properties of the commercial titanium of MEM. The fracture of specimens at all temperatures was accompanied by the formation of a neck after a remarkable elongation.

Mechanical properties of the commercial titanium of MEM technology are given in Table 2.

<table>
<thead>
<tr>
<th>Test temperature</th>
<th>Yield strength, MPa</th>
<th>Tensile strength, MPa</th>
<th>Elongation, %</th>
<th>Reduction in area, %</th>
<th>Impact strength, J/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+20^\circ°C)</td>
<td>360</td>
<td>440</td>
<td>28</td>
<td>57</td>
<td>186</td>
</tr>
<tr>
<td>(-196^\circ°C)</td>
<td>544</td>
<td>709</td>
<td>24</td>
<td>49</td>
<td>167</td>
</tr>
</tbody>
</table>
As is seen from the Table 2, the temperature reduction from +20°C to -196°C led to the deterioration of ductile characteristics of the metal and its impact strength only by 10-14%, thus proving a high margin of ductility of titanium of the MEM technology.

In addition to the improvement of the titanium quality the MEM technology possesses a number of important technical and economical advantages, such as:
- increase in process productivity due to a feasibility of producing the quality metal after the first remelting;
- low cost of metallurgical equipment;
- decrease in energy consumption (use of alternating current);
- decrease in spongy titanium consumption (minimizing the allowances for ingot machining);
- possibility of producing both round and rectangular ingots (Fig. 12).

Now the E.O. Paton Electric Welding Institute has available the technological operations and the pilot equipment for pressing the consumable electrodes, induction melting of flux and MEM of titanium ingots of up to 260 mm diameter and up to 175x175 mm² section. The comprehensive works are carried out for the development of the technology of melting the high-strength, high-alloyed titanium alloys, where the advantages of the new technology are most clearly manifested.

5. CONCLUSIONS AND PERSPECTIVES

The intensive melt flows activate the purifying of titanium from detrimental admixtures, non-metal inclusions and atmospheric gases by mixed flux. Moreover, magnetically controlled flows provide the homogeneity of allocation of admixtures over the metal and absence of non-metal inclusions and gas pores in it. These peculiarities determine the higher level of MEM metal quality in comparison with traditional metal.

The low cost of alloy production under MEM technology is based on the usage of cheap and low sort spongy titanium as the raw material for consequent remelting and purification. The economic sense of such technology lies also in the fact that the raw material is remelting by alternating current on the cheap metallurgical equipment during a single stage.

The most promising implication of the MEM technology is melting of titanium alloys in shipbuilding and airspace equipment. Thus, the production of important components for airplane engines and assemblies for the modern airplanes from nondefect MEM metal significantly extend the service life and safety of flights.

5. ACKNOWLEDGMENTS

We are grateful to academician D.A. Dudko for helpful discussions during preparation of this paper. The present work was financed by the Science and Technology Centre in Ukraine (project No.336).

7. REFERENCES