DOI: https://doi.org/10.37434/tpwj2023.02.06

INFLUENCE OF EXTERNAL LONGITUDINAL MAGNETIC FIELD ON FORMATION OF ESR INGOT SURFACE

V.B. Porokhonko, I.V. Protokovilov, D.A. Petrov

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The influence of permanent and pulsed longitudinal magnetic fields with the induction B = 0.16–0.30 T on the quality of outer surfaces of titanium ingots of 85 mm diameter, produced by ESR process, was studied. It is shown that alongside the positive effects of magnetic field action, manifested in increase of ESR process efficiency, improvement of chemical homogeneity of the ingots, and refinement of their crystalline structure, application of magnetic fields leads to deterioration of the quality of formation of the ingot side surface. Here, the degree of surface deterioration depends on magnetic field induction and duration of its pulses. It is found that application of pulsed magnetic fields leads to deterioration of the ingot surfaces to a smaller extent than application of permanent magnetic fields. Described are the mechanisms which negatively affect the quality of ingot surface formation under the impact of the longitudinal magnetic field. They consist in removal and solidification of electrode drops near the mould walls and periodical change of the skull crust thickness as a result of the slag and metal pool melt vibration.

KEYWORDS: electroslag remelting; longitudinal magnetic field; pulsed field; ingot; surface; titanium

INTRODUCTION

External magnetic fields are an effective tool for controlling heat transfer and crystallization of metal in ESR [1–6]. The advantage of using them consists in the possibility of a contact-free force effect on the melts of slag and metal pools to achieve certain metallurgical effects. In particular, in [3–6] the possibility of refinement of crystalline structure and increasing the chemical and physical homogeneity of ESR ingots using external magnetic fields was shown. It was established, that under the action of pulsed longitudinal magnetic field in the metallurgical melt, electric eddy currents and vibrations are formed, which provide intensive stirring of liquid metal, intensify the processes of melting of a consumable electrode, contribute to refinement of crystallites formed in a two-phase zone, and the formation of new crystallization centres. This leads to a number of positive effects, expressed in an increased the chemical homogeneity of ingots, refinement of their crystalline structure and enhancing the efficiency of the ESR process. Because of this, the use of magnetic fields at ESR allowed producing titanium alloys, whose cast structure is approaching the structure of a wrought metal.

It was also found that the action of external magnetic fields can lead to a deterioration of the quality of formation of a side surface of the ingots.

Figure 1 shows the appearance of a titanium ingot with a diameter of 65 mm, the lower part of which is melted without the use of magnetic field and the upper one is melted using a permanent longitudinal magnetic field with the induction of 0.25 T. The photo clearly shows the boundary of this interface. In particular, the lower part of the ingot produced without a superposition of the magnetic field is characterized by an excellent quality of surface formation. However, the ingot surface produced using a magnetic field is characterized by the presence of significant cavities, slag inclusions and corrugations. It is quite obvious that the further use of ingots with such a surface requires their mechanical treatment with a large amount of wastes.

Figure 1. Titanium ingot with a diameter of 65 mm, melted without (*1*) and with the use (*2*) of a longitudinal magnetic field with an induction of 0.25 T

The aim of this work is to study the effect of longitudinal permanent and pulsed magnetic fields on the formation of ESR surface ingots and determine the mechanisms that lead to a deterioration of surface quality.

MATERIALS AND RESEARCH PROCEDURE

Experimental studies were performed during melting of commercial titanium VT1-0 of 85 mm diameter with the use of different parameters of a longitudinal magnetic field.

Figure 2 shows the appearance of ingots, melted in the conditions of a permanent magnetic field with the induction of 0.16–0.30 T. The analysis of the obtained data shows that under other things being equal, the quality of the surface deteriorates with an increase in the induction of the magnetic field. If at 0.16 T, the surface of the ingot is satisfactory (Figure 2, *a*), then when it grows to 0.24–0.30 T, on the surface of the ingots, defects in the form of slagging, cavities, corrugations, etc. are formed with the depth of up to 1.5–2.0 mm (Figure 2, *b*, *c*).

The further experiments were performed under the conditions of a pulsed longitudinal magnetic field. Both induction of the magnetic field (within the ranges $B = 0.16–0.24$ T), as well as the duration of pulses and pauses of its action (within the ranges of $t_{pulse} = 0.3–21$ s, $t_{pause} = 10–33$ s respectively) were changed.

Figure 3, *a–c* presents ingots produced at the same induction of the magnetic field (0.24 T), but with different duration of pulses of its action $t_{pulse} = 0.3–2.0$ s. The duration of pauses in all cases was equal to $t_{pause} = 10$ s.

The obtained results showed that with the duration of pulses of the magnetic field $t_{pulse} = 0.3$ s, their effect on the quality of the ingot surface is almost unnoticeable (Figure 3, *a*). On the surface of the ingot, the traces of the magnetic field action are barely visible. This suggests that with such a small duration of field pulses, in the metallurgical pool enough powerful hydrodynamic currents, that would affect the quality of the ingot surface, do not have time to form. However, as the pulse duration is increased to $t_{pulse} = 1–2$ s, corrugation is already noticeable on the surfaces of the ingots, which grows with an increase in the duration of the magnetic field pulses (Figure 3, *b–d*). In general, with the duration of pulses of up to 1.5 s, the surface of the ingots can be considered as good (Figure 3, *a–c*).

In the further experiments, the value of the magnetic field induction was reduced to 0.22–0.16 T, and the duration of pulses and pauses of the magnetic field was increased to $t_{pulse} = 11–21$ and $t_{pause} = 21–33$ s, respectively (Figure 3, *e–g*). In this case, on the surface of the ingots, zones of action of the magnetic field are clearly visible, which were manifested in the form of transverse bands (corrugations). The depth of such corrugations was up to 1–2 mm, and the height was 2–5 mm, and with an increase in the duration of pulses of magnetic field, the depth and length of these zones increased (Figure 3, *f*, *g*).

It should be emphasized that the effect of the pulsed magnetic field on the formation of surfaces with a lower induction ($B = 0.16$ T), but with the longer pulse duration ($t_{pulse} = 21$ s) (Figure 3, *g*) is higher than at the induction $B = 0.24$ T and the duration of the pulse action $t_{pulse} = 1$ s (Figure 3, *b*). Obviously, the explanation for such a phenomenon may be the results of physical modeling, which show that for the formation of hydrodynamic flows of the maximum in-

Figure 2. Appearance of titanium ingots, melted by ESR using a longitudinal permanent magnetic field of a different induction, T: *a* — 0.16; *b* — 0.24; *c* — 0.30

Figure 3. Appearance of titanium ingots, melted by ESR with the use of a longitudinal pulsed magnetic field: *a* — B = 0.24 T, t_{pulse} = = 0.3 s, t_{pause} = 10 s; *b* — B = 0.24 T, t_{pulse} = 1.0 s, t_{pause} = 10 s; *c* — B = 0.24 T, t_{pulse} = 1.5 s, t_{pause} = 10 s; *d* — B = 0,24 T, t_{pulse} = 2.0 s, t_{pause} = 10 s; *e* — B = 0,22 T, t_{pulse} = 11 s, t_{pause} = 21 s; *f* — B = 0.16 T, t_{pulse} = 11 s, t_{pause} = 33 s; *g* — B = 0.16 T, t_{pulse} = 21 s, t_{pause} = 33 s

tensity in the slag pool, the duration of the magnetic field pulse should exceed some value, which for the ingots of the corresponding diameters (60–100 mm) is about 2.5 s [7, 8]. At a lower pulse duration, the flow intensity will be lower and, therefore, the impact on the surface formation will also be lower.

Thus, when applying a pulsed magnetic field, the formation of the ingot surface is affected not only by the value of the magnetic field induction, but also by the duration of pulses and pauses of its action.

It is obvious, that the mechanisms of effect of the magnetic field on the formation of ESR ingots are associated with the power action of the magnetic field on the melts of slag and metal. This action occurs as a result of the interaction of the longitudinal magnetic field with the electric current of melting. As a result of such interaction in the current-carrying melts of slag and metal, a volumetric electromagnetic force (Lorentz force) is formed, which leads to the movement or vibration of liquid slag and metal.

Directly the mechanisms of deterioration of the formation quality of the ingot surface can be associated with periodic changes in the thickness and destruction of the skull crust on the surface ingot, caused by the vibrations of the melt, and also by the spread of electrode metal drops and their solidification on the mould walls and the ingot surface (Figure 4).

Thus, during physical modeling of the drop transfer at ESR, it was found that a longitudinal magnetic field can lead to twisting and spreading drops of electrode metal in the slag pool and their removal to the mould walls [7, 8]. In this case, during ESR, drops of electrode metal will be subjected to intensive cooling and crystallize near the walls of the mould or in the skull crust on the ingot surface, which will lead to deterioration of the quality of its formation (Figure 4, *b*, *c*).

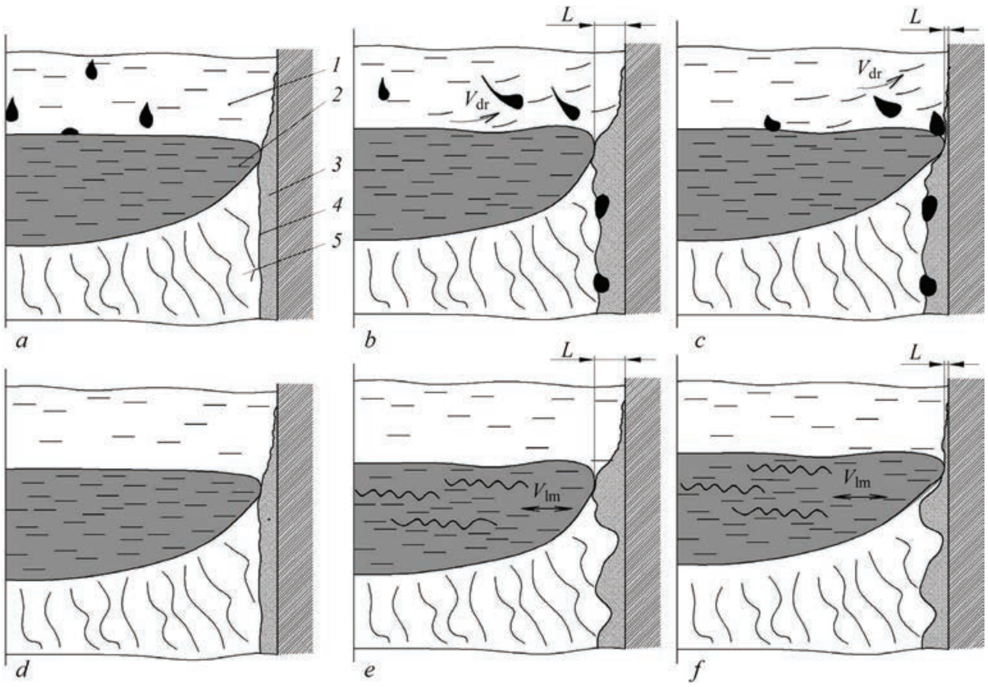

Figure 4. Mechanisms of deterioration of the surface of ESR ingots when using a longitudinal magnetic field due to chaotically spread drops (*a*–*c*) and vibration of melts of slag and metal pools (*d*–*f*): *1* — slag pool; *2* — metal pool; *3* — skull crust; *4* — ingot surface; *5* — ingot; *L* — thickness of the skull crust; V_{dr} — movement of electrode metal drops; V_{lm} — vibration of liquid metal

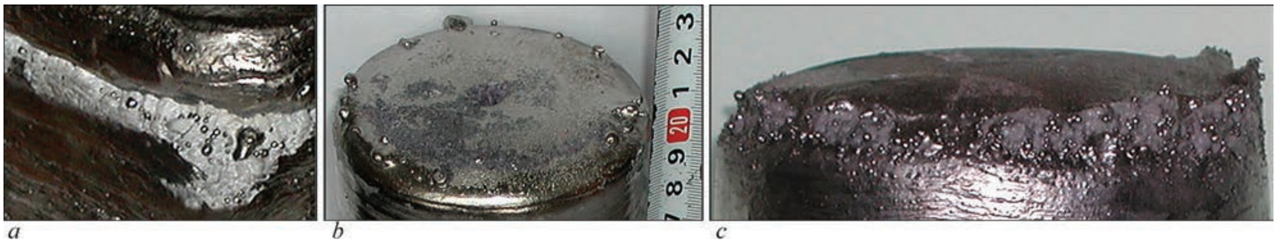

Figure 5. Electrode metal drops in ESR in a magnetic field: *a* — in a slag crust; *b*, *c* — in the peripheral sections on the ingot surface

The high probability of the mechanism described above is indicated by the detection of electrode metal drops in slagging (Figure 5, *a*) and directly on the surface of the ingots that were melted in a magnetic field (Figures 5, *b*, *c*).

Another mechanism of deterioration of the ingot surface may be associated with the vibration of the melts of slag and metal pools due to the action of the magnetic field (Figure 4, *d*, *f*). Such vibration with a frequency of 50 Hz is formed at the interaction of alternating current of melting with a permanent magnetic field. When the pulsed magnetic field is used, the vibration is enhanced by the hydrodynamic shocks that occur at the moment of switching on/off the magnetic field. Such oscillations in slag and metal pools lead to a chaotic change in the thickness of the skull crust *L* (Figure 4, *e*, *f*) and to the deterioration of the quality of the ingot surface formation.

It is quite possible that the mechanisms described above operate simultaneously and lead to a deterioration of the quality of ESR ingot surface formation under the effect of a longitudinal magnetic field.

CONCLUSIONS

1. It is shown that the use of an external longitudinal magnetic field in ESR along with the positive effects (enhancing the efficiency of the ESR process, increasing the chemical and structural homogeneity of the ingots) has also a negative impact, which manifests in the deterioration of the quality of formation of the reverse side ingot surface. Moreover, the degree of deterioration of the ingot surface depends on the type and parameters of the magnetic field.

2. It is established that at an increase in the magnetic field induction and the duration of pulses of its action, the quality of the surface formation deteriorates, as well as the use of pulsed magnetic fields to a lesser extent leads to a deterioration of the ingot surface and is manifested only in the form of transverse bands. Their depth and elongation depend on the parameters of the pulsed magnetic field. At a short duration of magnetic field pulses, its negative impact on the formation of the ingot surface is hardly noticeable. It can be assumed that the mechanisms of surface deterioration consist in removing drops to the walls of

the mould and their solidification there, as well as associated with the action of vibration of the melts of slag and metal pools on the formation of a skull crust on the ingot surface.

3. This article did not consider the positive effect of the longitudinal magnetic field on the structure formation of metal and its chemical homogeneity. However, in real conditions of ESR, obviously it is necessary to determine the ratio of the degree of deterioration of the ingot surface to the effectiveness of improving the inner characteristics of ESR ingots produced under the effect of external magnetic field.

REFERENCES

1. Dudko, D.A., Rublevsky, I.N. (1960) Electromagnetic stirring of slag and metal pool in electroslag process. *Avtomatich. Svarka*, **9**, 12–16 [in Russian].
2. Trochun, I.P., Chernysh, V.P. (1965) Magnetic control of crystallization in ESR. *Svarochn. Proizvodstvo*, **11**, 3–5 [in Rusian].
3. Paton, B.E., Medovar, B.I., Us, V.I., Tomilenko, S.V. (1989) Development and examination of methods of control of ESR crystallizing ingot structure by magnetic field superposition. *Problemy Spets. Elektrometallurgii*, **4**, 3–7 [in Russian].
4. Kompan, Ya.Yu., Protokovilov, I.V. (2002) Some technological aspects of magnetically-controlled electroslag melting (MEM) of titanium alloys. In: *Proc. of Int. Sci.-Tech. Conf. on Special Metallurgy: Yesterday, Today, Tomorrow (Ukraine, Kyiv, 8–9 October 2002)*. 256–262.
5. Kompan, Ya.Yu., Nazarchuk, A.T., Protokovilov, I.V. (2007) Towards the problem of intensification of electromagnetic action in magnetically-controlled electroslag melting of titanium alloys. *Advances in Electrometallurgy*, **4**, 3–7.
6. Kompan, Ya.Yu., Nazarchuk, A.T., Protokovilov, I.V., Petrov, D.A. (2012) Possibilities of application of pulsed electromagnetic effects in electroslag processes. *Advances in Electrometallurgy*, **2**, 8–13.
7. Protokovilov, I., Shapovalov, V., Porokhonko, V. et al. (2021) Effect of the longitudinal magnetic field on the droplets evolution during electroslag remelting process. *Magnetohydrodynamics*, 57(**4**), 559–568. DOI: https://doi.org/10.22364/mhd.57.4.10
8. Protokovilov, IV., Porokhonko, V.B. (2017) Physical modeling of electrode metal drop transfer in ESM with superposition of pulsed magnetic fields. *Suchasna Elektrometal*., **3**, 9–13 [in Ukrainian]. DOI: https://doi.org/10.15407/sem2017.03.02

ORCID

V.B. Porokhonko: 0000-0002-6490-7221,
I.V. Protokovilov: 0000-0002-5926-4049,
D.A. Petrov: 0000-0003-2937-9299

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.B. Porokhonko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: lab38@paton.kiev.ua

SUGGESTED CITATION

V.B. Porokhonko, I.V. Protokovilov, D.A. Petrov (2023) Influence of external longitudinal magnetic field on formation of ESR ingot surface. *The Paton Welding J*., **2**, 41–45.

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 29.09.2022
Accepted: 30.03.2023