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Arc slag remelting for high strength steel & various alloys

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Arc Slag Remelting (ASR) is a variant of standard ESR that accumulated advantages of ESR and VAR. Principles of ASR and it comparison with the standard ESR are given. Also discussed possibilities and limitation to replace ESR by ASR to reduce specific electric power consumption to the level of 800 kWt* hour per ton. Data full scale rectangular ASR ingot of HSLA and medium alloed steel melting are presented along with the metal quality examination. Requirements to the equipment for ASR commercialization are summarized. Also discussed area of ASR application for high alloyed steel and alloys as well as for titanium.

At the beginning of the seventies a new method of remelting of a metal consumable electrode in a copper water-cooled mould using an electric arc, burning between the edge of the consumable electrode and surface of the molten slag pool, was developed at the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine [1]. This method was named arc-slag remelting (ASR). A lot of the credit must go to the academician Boris Medovar in the creation of the ASR and substantiation of principal priority trends of its development and industrial implementation. This article is an attempt to overview the most important, from authors point of view, result received within almost three decades of ASR investigation along with the new data regarding ASR of high strength steel.

To realize the ASR process, it was necessary to provide the arc isolation from its contact with air and to create a controllable gas atmosphere in the zone of its burning. Two technological diagrams were tested, namely: (1) ASR with the use of a flux gate, a simplest device which is mounted directly on the upper edge of the mould (Figs 1 and (2) ASR in a chamber furnace (Fig. 2). In the latter case the available furnaces for the vacuum-arc remelting, in which a vacuum system was disconnected and also specially designed chamber furnaces for the ASR, which could realize the ASR process in a controllable atmosphere, including that under the pressure, were used.

The arc-slag process combines the capability of treatment of the molten metal with an electric arc, which is burning in the controllable gas atmosphere, and a molten synthetic slag through which the current is passed during the consumable electrode remelting. In addition, a layer of the synthetic slag, covering a metal pool, promotes the heat spreading in its section during the ASR process, thus reducing the metal pool depth, that makes it more shallow as compared with that in VAR and ESR. Moreover, the ASR ingots unlike the VAR ingots have a smooth lateral surface, due to formation of the slag skull, and do not require the obligatory mechanical treatment before the next processing.

The presence of the powerful electric arc in the zone of melting the consumable electrode during ASR in nitrogen creates the favorable conditions for the metal alloying with nitrogen directly from the gas phase, including those up to super equilibrium its concentrations during ASR in nitrogen at a high pressure (ASRP). This is a main advantage of the arc-slag remelting, i.e., the full elimination of expensive nitrided high-alloyed additions (ferroalloys, silicon nitrides, etc.), which are usually used in other methods [2, 3] in production of high nitrogen steels and alloys. The ASR variants in a lined crucible [4] were tested, confirming the feasibility of metal nitriding during ASR in a crucible melting. The application of the arc-slag heating of metal melts with graphite electrodes proved to be effective [5], as it is characterized by a simplicity, reliability and does not require complicated expensive equipment for its realization. The undoubted advantage of this process is also the fact that it allows the metal melt to be treated with reactive gases, for example, metal nitriding from the gas phase.

Both solid and hollow electrodes can be used for remelting. However, the application of hollow electrodes can influence the metal more effectively with gases by feeding the gas through the cavity directly to the arc-burning zone. Remelting with a metal pool (circular slag pool), partially covered with a slag, can be realized both in using hollow and solid electrodes.

In ASR with a complete slag pool (Fig. 1) the heat is generated at the end of electrode, in arc column, at the surface of the slag pool, in an electrode spot and also in a slag pool at the expense of current passing through the slag. When the circular slag pool is used

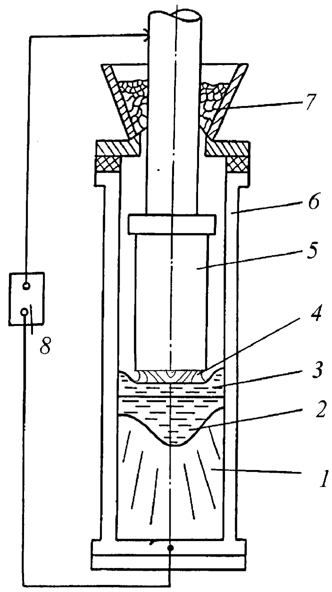

Figure 1 Diagram of arc-slag remelting of the solid consumable electrode: 1, ingot; 2, metal pool; 3, slag pool; 4, electric arc; 5, consumable electrode; 6, water-cooled mould; 7, flux gate; 8, power source.

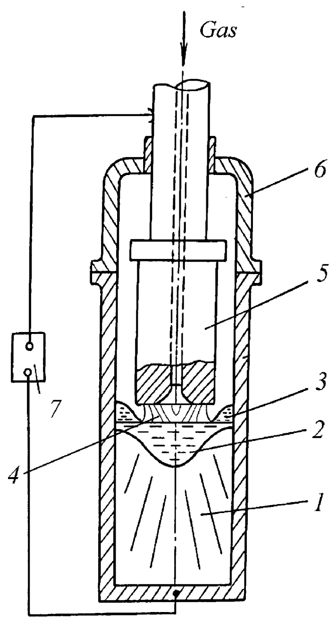

Figure 2 Diagram of arc-slag remelting of hollow consumable electrode: 1, ingot; 2, metal pool; 3, slag pool; 4, electric arc; 5, hollow consumable electrode; 6, mould; 7, power source.

the heat is generated at the end of electrode, in arc column and in electrode spot, which is located directly at the molten pool surface. The presence of the molten slag pool, complete or circular, as in ESR, promotes heating of the periphery part (at the mould walls) of the metal pool. Due to this and the presence of a slag layer between the wall of mould and ingot a good formation of ingots of different section (round, square, rectangular) is provided. This is one of the important advantages of the ASR as compared with VAR.

The depth of the metal pool in melting ingots using ASR is smaller than that in ESR and the pool shape is shallower. This is explained by the fact that in ASR the pool surface is heated more uniformly because the most part of the heat is generated in the arc column. Heat is spread also in the pool due to the transfer of drops to the pool with several streams over the entire section of the electrode.

The use of a hollow electrode favors greatly the more uniform distribution of heat in the pool section (Fig. 2). In this case the drops are formed near the electrode lateral surface and enter the pool at the distance of not less than the half of its radius. The stream of the heated gas through the cavity, if the electrode is blown-through with a gas, is spreading over the pool surface and also promoting the more uniform heating of the entire surface. Moreover, the gas stream, passing through the axial channel contributes to the stabilization of the discharge into the arc space in the electrode axis. In this case the electrode spot (cathode or anode) is located at the inner surface of the hollow electrode.[1]

In the ASR the electric arc is burning in the atmosphere of reactive (or protective) gas and slag vapors. The presence of slag vapors, which has chemical elements of a low potential of ionization, contributes to stabilizing of arc burning at atmospheric and high pressure. In ASR, unlike the VAR, there is no metal crown on the ingot. This is due to the fact that in ASR the metal spatters (fine drops) enter either the slag pool or the slag collar, which is formed around the slag pool perimeter. After assimilating with the slag they are returned to the metal pool. A thin layer of metal vapors can be condensed at the mould wall above the slag pool at the mould wall, but during ingot melting the molten heated slag melts the condensate and the crown is not formed. The gas feeding to the arc burning zone through the cavity in the consumable electrode or using another way promotes the removal of harmful gaseous impurities from the arc space. These can be gases (hydrogen, fluorine, etc.) or vapours of non-ferrous low-boiling metals (tin, lead and so on).

The carried out investigations of ASR ingots (Fig. 3), including those under shop conditions showed that ASR method, as compared with ESR, can decrease the energy consumption on 30% and consumption of a synthetic flux per 1 t of metal by almost 2 times (similar results, presented by Dr. S. Ballantyne [6], were obtained by company Allvac during recently). As to the metal quality the ASR metal is not inferior to the ESR metal (Table I).

At the beginning of the 1990s a new impulse was given to the ASR for its development and industrial implementation, first of all, due to the arising interest in the whole world to the high-nitrogen steels and alloys, and also to the methods of their production [7–10]. Theoretical fundamentals of processes of nitriding steels and alloys directly from the gas phase during pressurized arc-slag remelting were created and the technology of production of ingots alloyed with nitrogen using the ASR method was developed on the basis of research works, supervised by B.I. Medovar [11].

[1] Shape of the slag pool in case of solid consumable electrode could be not only complete as shown on Fig. 1. In some cases, as a result of arc pressure it could be circular shape of slag pool too. Most probably, there is a movement of the slag pool from the center zone to the mold walls and back.

TABLE I Mechanical properties of the steels produced by ESR and ASR methods in the 560 mm mould

Steel grade	Method of the melting	Yield strength (MPa)	Tensile strength (MPa)	Fracture elongation (%)	Impact energy (J)
19CrMnNi	ESR	1200	1450	17	96
19CrMnNi	ASR	1160	1410	15	94
18CrNiW2.4	ESR	850	1150	12	110
18CrNiW2.4	ASR	990	1290	18	140
20CrNi1.3	ESR	1010	1130	12	134
20CrNi1.3	ASR	1090	1150	10	100

Figure 3 Appearance of ASR ingot of steel 19CrMnNi, 560 × 560 mm, 4 t.

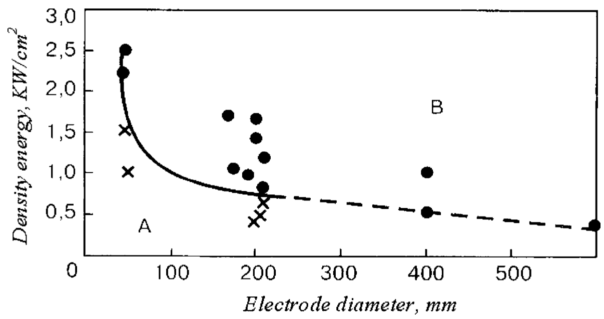

Figure 4 Regions of steady (B) and non-steady (A) remelting conditions using electrodes of different diameters.

The ASR process in a nitrogen-containing atmosphere combines three technological processes: arc melting of electrode, metal alloying. The ASR can be realized under the high-pressure conditions, because the electric arc burning is quite stable even at pressure measured by tens of atmospheres. The main thing is to select the electrical and technological condition parameters properly. Heat, required for proceeding the ASR process is generated mainly in electric arc, wherein current passes through the ionized discharge gap consisting of vapors or oxides of metal, vapors of slag and ionized gases. In ASR the surface of the molten slag (or metal) pool is one of electrodes. The slag pool represents a melt of an electrolyte with a large amount of complex and simple ions. Its temperature can reach 2000°C. One of slag components at such temperatures can evaporate, other components are decomposed (dissociate) into separate ions and, having this form they can participate in the process of current transfer. However, as the temperature of the arc discharge is much higher than that of the slag pool, the processes of evaporation, dissociation and ionization are more clearly expressed. Important point is that for ASR can be used the same slag composition as for standard ESR of the same steel and alloys.

The ASR can be performed both at direct and alternating current. And here the main advantages and drawbacks typical of VAR and ESR at DC and AC are preserved. In each concrete case of remelting of either alloy and steel it is necessary to select a type of current coming from a comprehensive comparison of their advantages and drawbacks.

Important parameter, which defines the process of consumable electrode melting in the ASR, is a supplied power, which is selected depending on the electrode section. As is seen from the Fig. 4, which presents the results of different laboratory and industrial melting, made by the ASR method, the required energy density to provide stable conditions is reduced and less dependent of the diameter with an increase of the electrode diameter (more than 150 mm). Pluses denote melting under non-steady conditions, they are located in region A. The values of energy density under steady conditions are located in region B.

In ASR the nitrogen can be fed easily through the axial cavity to the electrode, or in pipings, fixed at its external surface, directly to the zone of the electric arc burning. Therefore, during the ASR there is interaction of particles of nitrogen possessing an increased level of of intermolecular energy, with a film of molten metal that promotes the process of their absorption.

The investigations, including those performed in the industrial conditions, show that nitriding in the ASR is rather intensive in that case when a partial baring of the metal pool mirror from the slag is attained. In this case the process of nitriding from the gas phase occurs more completely both at the stage of film and drop and at the stage of the metal pool [12]. The ASR technology has been developed which makes it possible to alloy the molten metal with nitrogen from the gas phase at atmospheric and excessive pressures at a complete elimination of nitrogen-containing materials. Fig. 5 presents the large-tonnage CrMn18.18 nitrogen-containing steel ingots of 560 × 560 mm section and up to 3 t mass, produced in the ESR-5VG industrial

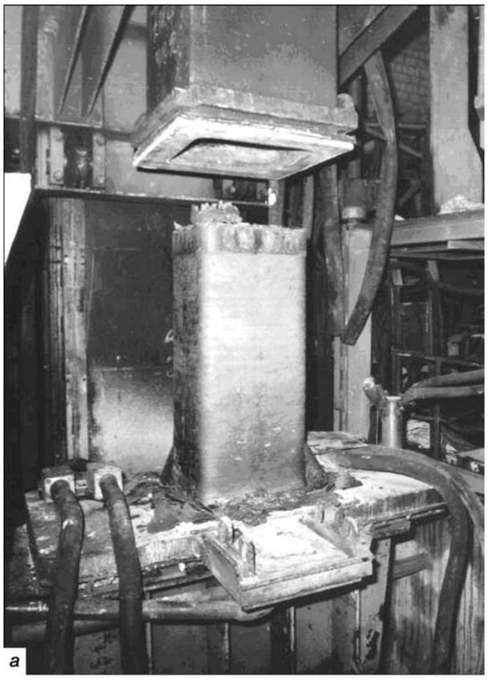

Figure 5 Appearance of ASR ingots of steel CrMn18.18 , 560 × 560 mm, 3 t (a) and 860 mm dia., 1900 mm height, 8 t (b).

furnace and ingots of 860 mm diameter and 8 t mass, melted in the ESR furnace of the "Consarc" company.

It is also shown [13] that the arc slag remelting in nitrogen-containing atmosphere, including that under the pressure, which is used in production of high-nitrogen stainless duplex-steels, allows introduction of a preset amount of nitrogen from the gas phase to the molten metal and, thus, provides a high chemical homogeneity and structural stability of the ASR ingot metal.

Alongside with a rising interest to the high-nitrogen steels, titanium, the former aerospace structural metal, becomes before our eyes a metal of the civil application. The fact that titanium acquires a quite civil use makes it possible to consider anew all the structure of the titanium industry.

Strict requirements specified to the titanium by the creators of the aerospace engineering, military shipbuilding, armament, ammunition and other military products, are also justified completely now. However, they can somewhat be softened, if titanium finds its main application for the manufacture of objects of home appliances, different kinds of civil constructions, bicycles, motor cars and other peaceful products. Coming from these considerations, all efforts should be applied for making titanium and its alloys cheaper, to make them quite competitive relative to stainless nickel-containing steels and alloys. In the solution of this problem the ASR process will have a challenging future [14, 15]. With undoubted advantages, such as an excellent surface of ingots, feasibility of producing large-tonnage ingots of rectangular section (Fig. 6) for direct rolling of sheet, feasibility of realizing the single-stage remelting of spongy pressed electrode with a producing of ingot or slab, being ready for processing, it can reduce considerably the metal losses in production of rolled metal, thus leading to the reduction of cost of the titanium products.

New opportunities for producing defect-free titanium ingots using the method of arc-slag remelting are opened up as a result of creation of the new technological process developed on the basis of use in the ASR of a current-carrying mould in combination with reactive slags, containing a metallic calcium, thus allowing more complete dissolution of hard high-nitrogen inclusions during remelting, if they occurred occasionally in the consumable electrodes. However, this active technological process of the ASR, as shown in [16] can be realized only in a chamber furnace with a controllable atmosphere.

Over the recent years some new promising fields of the ASR application were defined. Thus, research works were carried out by the suggestion of B.I. Medovar and due to the problems of utilization of military engineering objects.

They were aimed at the assessment of efficiency of application of the ASR method in remelting of artillery barrels of tank guns made from steel 38CrNiMoV1.3 with a simultaneous alloying of ingot metal with nitrogen directly from the gas phase [17]. Here, it was assumed that the most effective technological scheme can be realized in the process of the ASR of the artillery barrels, according to which the nitrogen is supplied directly to the zone of arc burning through the barrel channel (Fig. 2).

The arc slag remelting was performed in ESR furnace using a stationary 400 mm diameter mould with a flux gate. After removal of the slag skull all the ingots had a good surface. The appearance of the one of the 400 mm diameter ASR ingots is given in Fig. 7.

As seen from Table II, the content of nitrogen in ingots of steel 38CrNiMoV1.3 after the ASR was 0.023 – 0.031%, i.e., it was 2 – 3 times increased as compared with its initial content (0.009 – 0.013 %). Moreover, the increase in consumption of nitrogen, supplied to the consumable electrode channel, to 70 l/min

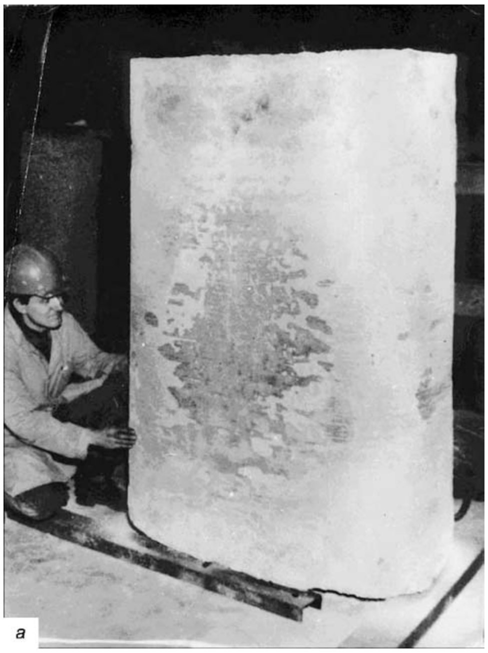

Figure 6 Appearance of ASR slag ingot of titanium VT1-0. 650 × 1150 mm section, 1700 mm height and 5 t mass (a) and 115 mm thick plate, rolled from it (b)

(melting No. 2) allowed the nitrogen content in the ASR ingots to be increased by 14% as compared with melting No.1. The further increase in nitrogen consumption to 80 l/min (melting No. 3) did not cause any increase in nitrogen content in the ASR ingot metal. It should be noted that the equilibrium content of nitrogen calculated according to [11] for a definite chemical composition of steel 38CrNiMoV1.3 used for production of a pilot batch of the ASR ingots is 0.048 %. Using the technological conditions, mentioned in Table II, we reach about 64% of nitrogen in ingot from its equilibrium concentration at the nitrogen atmospheric pressure. This is

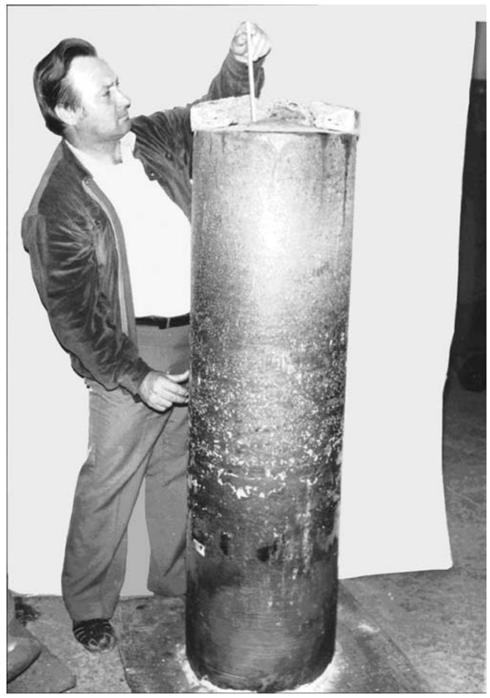

Figure 7 Appearance of ASR ingot of steel, 38CrNiMoV1.3 400 mm diameter and 1500 mm height.

explained by the fact that process of nitriding during the ASR is proceeding in a kinetic condition. Therefore, to produce higher nitrogen concentrations in ingot it is necessary to perform the ASR process under the excessive pressure of nitrogen this is possible to realize only in the chamber furnaces.

The ASR process can be also used efficiently for the utilization of the artillery barrels and without the additional alloying of metal with nitrogen. The existing ESR furnaces can be used for this purpose. As compared with ESR, as was above-mentioned, the consumption of energy and flux is greatly decreased in the ASR. Thus, the ASR process can find the widest and efficient application in industry for the utilization of the artillery barrels.

In the forthcoming years a great deal can be and should be done to make the arc slag remelting challenging in the metallurgical industry. In this case, the combination of ASR with the formation and solidification of metal in a current-carrying mould (CCM) seems challenging. The separation of processes of melting and solidification in CCM makes it possible to create the new possibilities to control the metal pool shape during the melting process and, thus, to provide the most favorable conditions of the ingot structure formation and to provide the higher level of properties. The

TABLE II Technological parameters of ASR melting with a flux gate of steel 38CrNiMoV1.3 to the 400 mm diameter mould

No. of melting	Electrode diameter (mm)		Electrical conditions of melting		Slag pool height (mm)	Gas consumption l/min	Nitrogen content (%)	
	Outside	Inside	I (kA)	U (V)			In electrode	In ingot
1	215	115	3	92	30	50	0.013	0.023
2	215	115	4	98	30	70	0.009	0.031
3	180	115	2.5	100	50	80	0.010	0.029

first experiments in this direction gave very inspiring results.

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