

Electroslag remelting — Its status, mechanism and refining aspects in the production of quality steels

A.K. VAISH, G.V.R. IYER, P.K. DE, B.A. LAKRA, A.K. CHAKRABARTI*
and P. RAMACHANDRARAO

National Metallurgical Laboratory, Jamshedpur 831 007, India

*Department of Metallurgical and Materials Engg., Indian Institute of Technology,
Kharagpur 721 302, India.

Abstract : Electroslag remelting has been established as a new measure for the production of quality steels. Many properties of ESR steels are dramatically superior to those of conventionally produced steels. Majority of inclusions are eliminated during ESR depending on slag composition, temperature and melt rate. Usually, after ESR, the metal does not contain any inclusions larger than 10-12 gm. The pronounced effect of ESR on desulphurization is a result of slag/metal and gas/slag reactions. Inoculation during ESR is a feasible and effective method of further enhancing the ductility and Charpy U-notch toughness, with some improvement in strength as a result of refinement. ESR is a convenient and economic route for processing steels and alloys which are otherwise difficult to process.

Key words : *Electroslag remelting (ESR), Refining, Inoculation, Quality steels.*

INTRODUCTION

The competitive position of the steel in the market can be secured only if steel product exhibits consistently a high service performance. The properties of quality steels are strongly affected by various phases of manufacturing. The melting, refining and solidification processes have most profound effect on subsequent thermo-mechanical processing behaviour and final property response. There is an ever increasing demand on the quality and performance of steels to meet its growing needs. The quality is determined by the closeness of the composition to the specification, extent of freedom from undesirable impurity elements and nonmetallic inclusions, homogeneity with respect to composition and structure, freedom from defects such as voids and cracks and the isotropy of properties as per requirement. The combination of individual melting and refining processes leads to versatile multiple - melting - refining solidification systems. Generally the bulk of steels is processed through the liquid metal route because of its cost advantage and flexibility. The highest quality of steel can be obtained by using any of three remelting processes electron beam remelting [EBR], vacuum arc remelting [VAR], or electroslag remelting [ESR]. Among these, EBR and VAR use vacuum as the protective and refining medium while ESR is the most widely used remelting process today. It uses a reactive, fluid slag as the protective refining medium as well as the resistance heating element.

ESR (Electroslag remelting) is the abbreviated name given to electroslag consumable electrode remelting and secondary refining process. It is also used to describe three separate processes, using the principle of electroslag namely (i) consumable electrode metal refining and cost structure improvement process (ii) the semi-continuous or

continuous alloy making process and (iii) the bulk metal deposit process for rebuilding worn parts and joining very heavy metal sections.

The U.S. inventor, R.K. Hopkins⁵ developed several variations of the electroslag process concept. G.K. Bhatnagar conducted extensive studies at Mellon Institute, United States to develop some new concepts of ESR process. Some excellent basic electrochemical and thermal research experiments have been performed and reported in Austria⁶, Czechoslovakia⁷, the USSR's⁸ and Canada⁹ to explain the inner workings of the electroslag remelting (ESR) and casting systems. Remelting refining processes such as electroslag remelting and vacuum arc remelting [VAR] are known to have good control over the cleanliness and solidification structure of steels¹⁰. Two variables have a major influence on the metallurgical quality and yield of electroslag remelted [ESR] ingots — the chemical composition of slag and the electrical parameters. Electroslag remelting [ESR] is a secondary refining process for metals. It is used for further purification after completion of the primary extraction and refining operations. The electroslag remelting [ESR] process is now more than 40 years old. The beneficial features of the metals produced using this process are well known, for example their high ductility and toughness transverse to the rolling or forging direction and the reduced level of impurity segregation, which make them superior to the same types of material produced using more conventional techniques¹¹. Various studies have analyzed the deoxidation in ESR. It is possible to modify the chemical compositions of the ingot in relation to the composition of the electrode by means of the continuous or periodic addition of ferroalloys and deoxidizers to the slag. Inoculating steel during ESR with titanium, zirconium, or nitrogen has been found to be effective in further improving the structure and performance of high speed steels¹²;

ELECTROSLAG REMELTING — ITS STATUS

Electroslag remelting is established as a new measure for the production of high grade steels. In many cases it is economically competitive and even superior to conventional processes. Practically ESR has been well suited for high grade nickel and copper base super alloys and special steels, such as high strength steels, which have to meet extreme requirements of consumer industries. ESR ingots have been successfully used for the production of isotropic materials having same properties in all directions. It has special applications in the production of heavy forgings for power industry. These days in steel production, it is not sufficient to adjust to the required chemical composition but rather one aims for the utmost cleanliness in the molten steel.

The solidification of the molten steel into an ingot should be free from internal defects. An ideal ingot should have (i) uniform chemical composition without having any segregation (ii) absence of nonmetallic inclusions and undesirable and harmful elements and (iii) a uniform structure without having any micro-porosity or blow holes. These requirements can be achieved in conventionally cast ingots to a limited extent only. However, it is possible only with the continuous solidification of droplets of molten metal. Generally in conventionally cast ingots, the solidification of a large volume of liquid steel in the ingot moulds leads to ingot segregation. The extent of such segregation depends upon the crystallization behaviour of the solidifying the multiphase system. The local accumulation of nonmetallic inclusions, the formation of micro-porosity and shrinkage cannot be avoided. The Fig. 1a shows the dendritic structure of the ingot and globular solidification patterns with varying orientation, while in the electroslag remelting process relatively small amount of liquid metal solidifies continuously according to the melting rate of the electrode. This

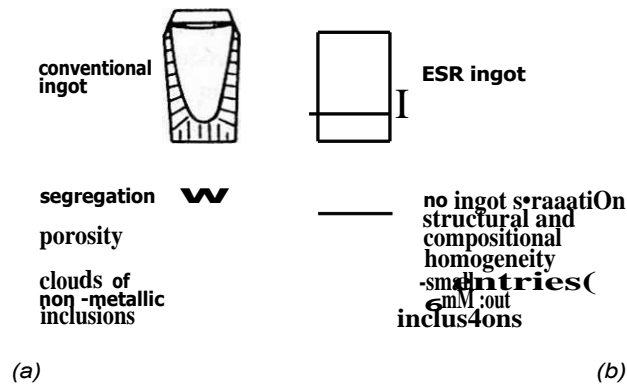


Fig. 1 : Comparison of the structure of a conventionally cast and a remelted ingot.

solidification progresses into a shallow liquid — metal pool. In this case the **macro-segregation**, accumulation of nonmetallic inclusions and micro-porosity will not occur and the remaining minor amounts of nonmetallic inclusions are evenly distributed. The Fig. 1 b shows columnar crystals which are slightly inclined towards the longitudinal axis of the ingot. The remelted ingot meets most of the conditions prescribed for an ideal ingot.

The ESR process is a continuous process in which melting, metallurgical reactions and solidification of steel occur simultaneously. Here the heat conduction of the solidified metal is limited and does not allow an increase of the rate of crystallization at random. The objective of this process is to produce ingots with superior quality and the rate of crystallization determines the production rate. The important features of electroslag remelting are metallic charge, power supply, mould design and the shape of the ingot. The metallic charge is usually a cast electrode of suitable cross section. Of course, both forged as well as rolled electrodes can be equally used in the ESR process. The metallic powders together with a strip electrode can also be used for the production of remelted ingots. Auxiliary electrodes can be used for the additional heating of the slag. The melting heat is usually produced by resistance heating the slag bath. The design of the mould varies namely fixed long moulds or collar type moulds [Movable moulds and movable base plate]. Compared to fixed long moulds, the use of collar type moulds gives the possibility of producing ingots of any required length. The electroslag remelting produces not only round ingots but also ingots of practically any desired shape such as square, rectangular or hollow. It is possible to manufacture preforms even with varying cross sections.

Today ESR has become the most widely used remelting process. About four decades back ingots of upto 20 tons or more were produced in France, USA, U.K., Germany and Japan. Long back Germany scaled up the process to produce large ingots of upto 160 tons weight and 2300 mm diameter while still large ingots of upto 200 tons weight and 3300 mm diameter are being produced in China. In India ESR process is in operation at Mishra Dhatu Nigam Ltd., Hyderabad, Kalyani Steels Limited, Pune and Metal and Steel factory at Ishapur, with ingot sizes of upto 600-800 mm diameter. Nasik Steels Ltd., Nasik has also adopted ESR process on a smaller scale while AV Alloys Ltd., has established an ESR plant for producing high speed steels, die steels and other steels at Hyderabad. ESR Steels even in the as cast condition exhibit excellent properties and performance in service. Their properties namely notch and fracture toughness, fatigue resistance, cold and hot ductility, weldability, corrosion resistance and creep resistance are superior to those

hot worked material obtained from continuous castings or conventional ingots. Comparatively the ESR process has low productivity and consumes high energy. It is not very efficient in removing hydrogen from steel but generally results in 10-15% or higher increase in yield. In expensive grades of steels/alloys, this saving may more than offset the cost of ESR. The principal application of ESR is in the manufacture of materials for use in highly critical areas, such as aerospace, nuclear and defence industries. Another important and growing area of application of ESR is in the production of heavy ingots used in the manufacture of forgings with final weights of 100 tons or more, such as turbine and generator rotor shafts, for power plants. ESR has its another important application in the production of rolling mill rolls. Since 1970, ESR has been increasingly used for the production of high speed steels. Today a considerable proportion of premium high speed steels and die steels are produced by ESR.

ESR can be a means for developing new steels. Since several properties of alloys are improved significantly by ESR, modification of composition can give new combination of properties. New ultrahigh strength steel has been produced in tonnage quantities by ESR with inoculation at Mishra Dhatu Nigam Ltd., Hyderabad for Vikram Sarabhai Space Centre (VSSC). After hot rolling into plates, UTS in excess of 1700 MPa has been obtained. ESR can be a convenient and economic route for processing steels and alloys which are otherwise difficult to process.

ELECTROSLAG REMELTING — ITS MECHANISM

The principle of electroslag remelting is shown in Fig. 2. The electrode is moved downward as melting progresses. The liquid flux acts as heat generating medium and protects the metal from atmospheric contamination. It contributes to pick up several residuals such as Si, Al, P, C, Pb. Strong interactions between highly reactive metal constituents and oxide components in the superheated fluoride based flux can result in significant and intolerable compositional variations over the length of the ingot. Most mold systems are capable of withdrawing heat at a rate controlled by the conductivity of the air gap between ingot (slag) and mold. Once a shell thickness of a casting exceeds about 1/2" (in or out

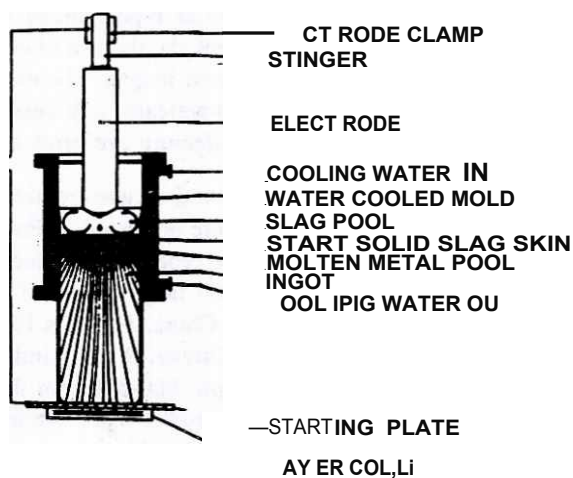


Fig. 2 : The principle of the ESR proces.i.

of the mold), the rate of solidification of the casting is a function of the amount of metal in the liquid pool and its superheat. In a moving mold ESR system, where the slag pool is moved up as the ingot forms, surface tension of most slags is such that 80% of the ingot surface is not covered by slag. For equivalent melt rates, heat transfer in the moving mold system provides 15-20% lower metal pool depth than in a static mold system.

AC Versus DC—ESR Optimum Melt Rate and Metal Refinement

For ingots of 20 cm diameter or greater, single phase AC-ESR will give optimum refinement and melt rate with a permissive latitude in electrode diameter for a given ingot size while DC-rp (reverse polarity) ESR will require a lower melt rate for metal refinement almost equal to that of AC-ESR, with a restrictive, 0.80 or higher electrode/ingot diameter ratio. The DC-rp ESR will give the highest melt rate per unit of power consumption, if metal refinement is not a criteria. The present practice¹²⁶¹ is to utilize single phase AC-power supply and low electrode/ingot diameter ratio namely 0.4 to 0.7.

Factors Affecting the Mechanism of ESR

The electrical characteristics, heat balance, electrode/ingot diameter (d/D) affect the melt rate and quality. It has been established that electrical transfer is ionic (physical movement of ions) rather than electronic. No arc can be permitted for the process to remain stable. However arcing takes place initially on cold starting. The electrical flow during ESR can be expressed as

$$IR = \frac{\rho L}{(d^2 + D^2)/2}$$

Where R = Voltage

I = Amperage

L = Slag depth

d = Electrode diameter and

D = Ingot diameter

$(d^2 + D^2)/2$ = Effective cross section of the slag

ρ = Specific resistivity of slag, SI cm.

The electrical balance in ESR melting is shown in Fig. 3. This figure illustrates the position of these factors on the functional elements of ESR. The slag must be held within a specific temperature range to prevent surface defects. The slag is chosen for optimum deoxidation, desulfurization and element burn-off. With varying d/D ratio, the composition and the temperature of the slag should be changed accordingly, however its specific resistance should remain same. Ideally, the slag, the resistance gap, the voltage and the current should remain constant.

An increase in the ratio of d/D in the above equation can be balanced by increasing the slag depth, L without increasing either voltage or amperage. Generally 30% or more of the heat generated in ESR is lost from the slag pool to the mold wall. This heat is not effective

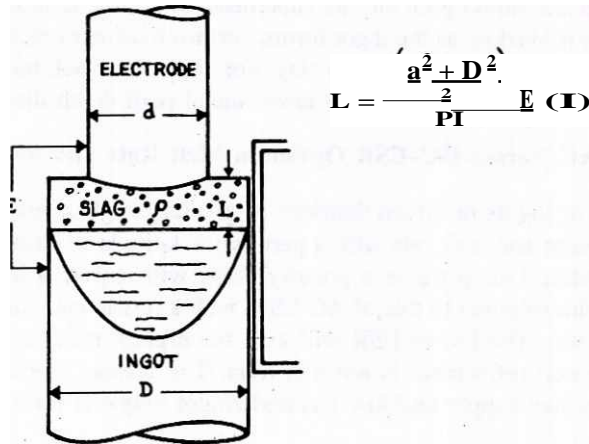


Fig. 3 : Electrical balance in ESR melting.

in melting the electrode. Therefore in order to cover up this heat loss from the slag to the mold wall, both voltage and amperage are increased with the increase in the ratio of d/D . With increasing ratio of d/D , the radiant heat loss from the slag surface to the mold wall and to free radiation decreases. However, the loss from the slag pool to the mold wall exceeds the gain from decreased radiation losses when going to a large ratio of d/D . The mold wall is water cooled. This change in heat balance with increasing d/D is shown schematically in Fig. 4.

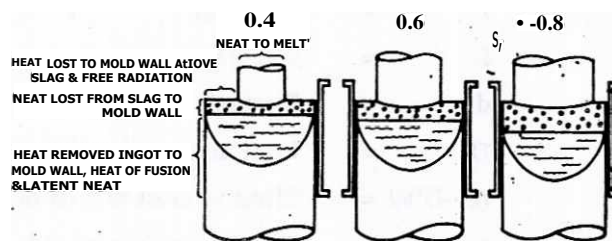


Fig. 4 : Electrode / ingot diameter ratio vs. heat balance.

Theoretically it is possible to compensate for increasing electrode/ingot diameter ratio while maintaining constant slag depth and power input by increasing amperage and decreasing voltage. Practically it has been observed that slag pool depth increases in AC-ESR. The current density at the slag-metal interface increases, increasing metal/pool superheat. While in the case of DC-ESR, the polarization at the slag-electrode interface can cause the liquid metal to be refined at the electrode-slag interface and may be contaminated at the liquid pool-slag interface or vice versa, depending on dc polarity. This phenomena depends on the current density at the electrode tip, a function of d/D ³¹.

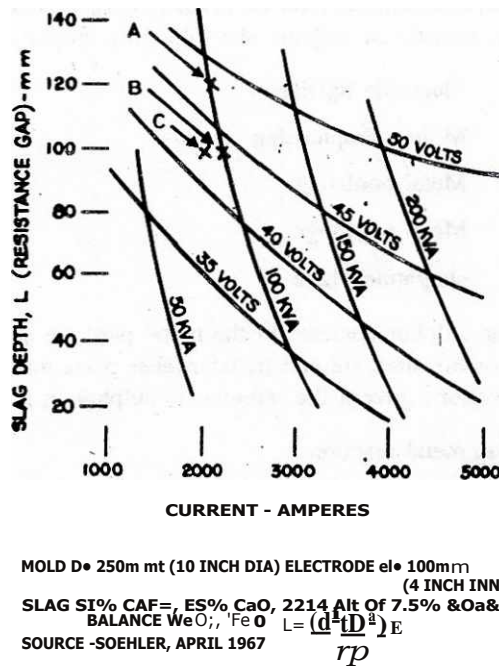


Fig. 5 : ESR power and voltage relative to slag depth vs. current.

ESR Power Voltage Relation

In order to acquire the controlled operation of ESR, the approach should be to have constant amperage, voltage, pool depth, and resistivity with the electrode continuously being fed into the slag. When the electrode advances too fast, slag depth may change. These electrical changes have been illustrated in Fig. 5. The changes in ESR power and voltage have been shown relative to slag depth vs. current.

If the electrode is about 120 mm from the molten metal pool and is operating at 100 kVA, its position in Fig. 5 will be at point 'A'. The corresponding operating current and voltage would be 2100 amperes and 48 volts. Similarly if the electrode tip is instantaneously driven to within 100 mm of the pool, maintaining the operating voltage at 100 kVA, the position of the electrode will be at point 'B'. The corresponding operating current and voltage would be 2200 amperes and 45.5 volts. As such there is no noted change in kilovolt amperes to signal a reduction in the rate of electrode travel. But if the transformer is regulated for constant current, a change decrease in slag pool depth will signal a change in kilovolt amperes at point 'C'. AT point 'C' the corresponding operating current and voltage would be 2100 amperes and 43 volts at 90 kVA. This signal will in turn actuate a variable voltage unit, reducing electrode travel.

ELECTROSLAG REMELTING — SECONDARY REFINING PROCESS

ESR removes upto 68% of the sulphur contained in the metal. The pronounced effect of ESR on desulphurization is a result of slag/metal and gas/slag reactions. After completion of the primary extraction and refining operations, ESR is used for further purification.

Different sulphur removal ratios ranging between 5 to 75% have been reported¹²²⁻³¹¹. During the transfer of sulphur, the following interfaces can be considered in ESR process^{3,351}.

- Electrode tip/slag
Molten droplet/slag
- Metal pool/slag
Metal pool/ingot
- slag/atmosphere

The sulphur contents in the metal pool are same as those in the ingot⁶¹. Among above possible sites, sulphur transfer takes place mainly at two interfaces and the following two reactions govern the removal of sulphur in ESR.

Slag/metal reaction:



gas/slag reaction:



where [], () and { } refer to metal, slag and gas phases respectively.

For reaction (1)

$$K = \frac{a(S^{2-}) \cdot a(O)}{a_{rse} \cdot a(O^{2-})} \quad 3$$

$$\text{Hence } \frac{a(S^{2-})}{a_{sl}} = \frac{K \cdot a(O)}{a_{O1}} \quad 4$$

Henry's law is applicable for dilute solutions. Therefore, for very small values of $1 \setminus l_{(s^{2-})}$ and N_{sl} equation (4) becomes

$$\frac{\% (S^{2-})}{\% [S]} = \frac{\text{Constant} \cdot N(O^{2-})}{N_{O1}} \quad 5$$

Thus, the transfer of sulphur from metal to slag is promoted by high slag basicity $N_{(O^{2-})}$ and low concentration of oxygen in the metals N_{Oy}

For reaction (2) :

$$K = \frac{P\{SO_2\} \cdot a(O^{2-})}{P\{O_2\} \cdot a(S^{2-})} \quad 6$$

$$\text{or } \frac{P\{SO_2\}}{a(S^{2-})} = \frac{K \cdot P\{O_2\}}{a(O^{2-})} \quad 7$$

This indicates that sulphur transfer from slag to gas phase is promoted by a high partial pressure of oxygen P_{10} in the atmosphere and low slag basicity N_{O1} .

Studies of Hlimeny and Buzek³⁷ indicated that most of the sulphur removed from the metal enters the gas phase when using air atmosphere. Whereas very small losses of sulphur takes place from metal when melting under argon atmosphere. Medovar et. further confirmed the reduction of desulfurization when remelting under argon atmosphere compared with the air atmosphere. It can therefore be concluded that the gas/slag reaction plays more important role compared to slag/metal reaction. According to Cooper et. al.⁴¹ and Kate", the interface of the electrode tip/slag pool is most important for the sulphur removal. Mamdouh Eissa and Alaa El-Mohammadif⁴⁰ investigated the desulfurization process in electroslag remelting [ESR] and concluded that desulfurization occurs as a result of slag/metal and gas/slag reactions, the greatest portion of sulphur is removed by gas/slag reaction and the metal/slag reaction represents the rate controlling step over all the desulfurization process. Slag/metal reaction occurring at the metal droplets/slag interface is the most effective and enhancing by relatively high slag viscosity and high CaO content in the slag. Slag composition of 70 CaF₂, 15CaO and 15 Al₂O₃ had a good combination of chemical activity and physical properties (Table 1) for attaining the highest degree of desulfurization among the three investigated slags. Three different grades of tool steel's compositions (Table 2), were used as consumable electrodes (1200 mm long and 60 mm.diameter) in ESR. The chemical composition of the remelted steels are given in Table 3, while Table 4 shows the electrical parameters maintained during electroslag

Table 1 : Chemical composition and physical properties of ESR slags used

Slag No.	Chemical Composition, mass contents (%)			Physical Properties			Activity of CaO (measured at 1500°C) in the system
	CaF ₂	CaO	Al ₂ O ₃	Viscosity 0.1 Pa.s	Density g/cm ³	Interfacial tension in mN/m	
1	70	15	15	0.08	2.75	910	0.25
2	80	20	–	0.01	2.60	960	0.46
3	70	–	30	0.50	2.68	890	–

Table 2 : Chemical composition of the investigated steels

Steel No.	Steel Grade	Chemical composition, mass contents in %									
		C	Si	Mn	P	S	Cr	Ni	V	Mo	W
1	Cold work tool steel	2.36	0.04	0.33	0.026	0.015	14.6	–	–	–	–
2	Hot work tool steel	1.34	0.04	0.35	0.015	0.025	0.79	0.80	–	–	–
3.	High speed steel	1.23	0.18	0.30	0.030	0.15	4.70	–	2.3	4.0	7.9

Table 3 : Chemical composition of the remelted steels

Steel No.	Slag No.	Chemical composition, mass contents in %									
		C	Cr	Mn	S	P	Si	Ni	V	W	Mo
1	1	2.08	13.57	0.32	0.005	0.027	0.011	–	–	–	–
	2	1.98	12.65	0.30	0.008	0.025	0.020	–	–	–	–
	3	2.10	14.10	0.33	0.006	0.028	0.012	–	–	–	–
2	1	1.31	0.74	0.30	0.008	0.014	0.022	1.80	–	–	–
	2	1.21	0.65	0.23	0.012	0.015	0.024	0.6	–	–	–
	3	1.32	0.75	0.32	0.009	0.015	0.023	1.78	–	–	–
3	1	1.18	4.3	0.28	0.006	0.030	0.09	–	2.45	8.40	4.50
	2	1.10	4.0	0.22	0.010	0.025	0.11	–	2.50	9.47	5.49
	3	1.20	4.5	0.29	0.007	0.030	0.10	–	2.40	8.30	4.17

Table 4 : Electrical parameters of ESR furnace used during investigation

Main current, kA	5.3
Melting current, kA	1.5 - 1.55
Melting voltage, V	28 - 30
Melting power, kW	45

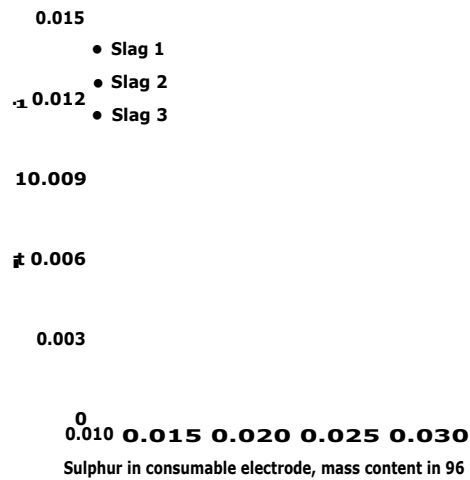


Fig. 6 : Relation between sulphur content in both consumable electrode and ESR ingot.

remelting. The sulphur content in ESR ingots was found to be dependent on the sulphur content of the consumable electrode. It is clear from Table 2 and 3 that during remelting of electrodes with a relatively low sulphur content, 0.015%, the sulphur content in ESR ingot is low (with an average of 0.006-0.008%) while increasing the sulphur content in the consumable electrode to 0.025% resulted in a relatively higher sulphur content in the produced ingot (0.008-0.012%) Fig. 6 illustrates a relation between sulphur content in both consumable electrode and ESR ingot.

EFFECT OF INOCULATION DURING ELECTROSLAG REMELTING

High strength steels find applications in many critical parts such as rocket motorcases, aircraft undercarriages, turbine rotors, pressure vessels etc. Inoculating steel during ESR with titanium, zirconium, or nitrogen has been found to be effective in further improving the structure and performance of high speed steels. Chattel jee et. al." studied the influence of ESR and inoculation on the structure and properties of a high strength steel 15C DV6 which is widely used in Indian space programme. The nominal compositions and properties of 15C DV6 steel are given in Table 5. They subjected 15C DV6, high strength steel with relatively low alloy content to electroslag. remelting (ESR) which resulted not

Table 5 : Nominal composition and properties of 15C DV6 steel

Composition, wt. %							
C	Si	Mn	P _{max}	S _{MX}	Cr	Mo	N
0.12-0.18	0.20	0.80-1.10	0.02	0.025	1.25-1.50	0.8-1.0	0.2-0.3
Properties*							
UTS, MNm ⁻²		0.2% PS, MNm ⁻²		Elongation, %		Charpy Unotch, Idm ⁻² energy	
980-1175		830-980		8-12		650-700	
*Heat treatment: austenitise at 970-980°C, quench, temper at 625-650°C.							

Table 6 : Effect of slag composition and slag deoxidation on the degree of desulphurisation during ESR

Sl. No.	Slag composition	Slag deoxidation during ESR	Sulphur content, wt. %		
			Electrode	ESR ingot	Desulphurization %
1	60CaF ₂ -20CaO-20Al ₂ O ₃	0.1% Al	0.028	0.013	53
2	70CaF,30Al ₂ O ₃	Nil	0.028	0.019	32
3	60CaF,-20CaO-20Al ₂ O ₁	Nil	0.028	0.015	46
4	70CaF,-30Al ₂ O ₁	0.1% Al	0.028	0.017	39

Ei Z	Material	Inoculant added, wt. %	Inclusion index d ₀ x500	Inclusion size distribution (percent of total in various size ranges)																
				0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10							
1	Bloom	-	0.48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	ESR ingot*	Nil	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	ESR ingot*	Nil	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	ESR ingott	Nil	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	ESR ingott	0.2 Zr	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	ESR ingott	0.2 Nb	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	ESR ingott	0.3 Zr	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	ESR ingott	0.3 Nb	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

* In ESR melts nos. 4-8 the slag used was 60 CaF₂-20 CaO-20Al₂O₃

only in a significant decrease [by 55-75%] in nonmetallic inclusion content, but a complete elimination of inclusions >12µm in size. The remelted steel even in the as cast and heat treated condition had marginally higher strength and 30 and 40% higher ductility and Charpy toughness, respectively, than conventionally produced steel. After hot work the remelted steel had much better isotropy of properties. Introducing inoculants into the steel during ESR by coating the electrode with ferroalloy powder was found to be an effective and reproducible means of further improving the properties, particularly ductility and toughness. Niobium and zirconium were found to be very effective inoculants. The ESR ingots were sound and free from usual solidification defects. During ESR, 5 to 8% losses of silicon, manganese and chromium were observed. However, deoxidation of the slag with aluminium additions amounting to 0.1% of the ingot weight during the process eliminated these losses. The chemical composition was completely uniform over the entire ingot in the longitudinal and transverse directions.

The effect of slag composition and slag deoxidation on the degree of desulfurization during ESR is shown in Table 6. The desulfurization was 32% and 46% respectively, when using 70 CaF₂ - 30 Al₂O₃, and 60 CaF₂ - 20 CaO - 20 Al₂O₃, slags. Desulfurization improved to 39 and 53% respectively, when the slags were deoxidized with aluminium during ESR. The improved desulfurization is attributed to the increased sulphide capacity of the slag because of the introduction of CaO and the decreased, oxygen potential of the slag owing to deoxidation with alumina. The significant reduction in the content as well

Table 8 : Effect of ESR and inoculation on grain size of 15C DV6 steel

SI No.		Inoculant addition, %	Grain size, p.m
1	Conventional bloom	Nil	35
2	ESR ingot	Nil	38
3	ESR ingot	0.2 Zr	15
4	ESR ingot	0.2 Nb	13

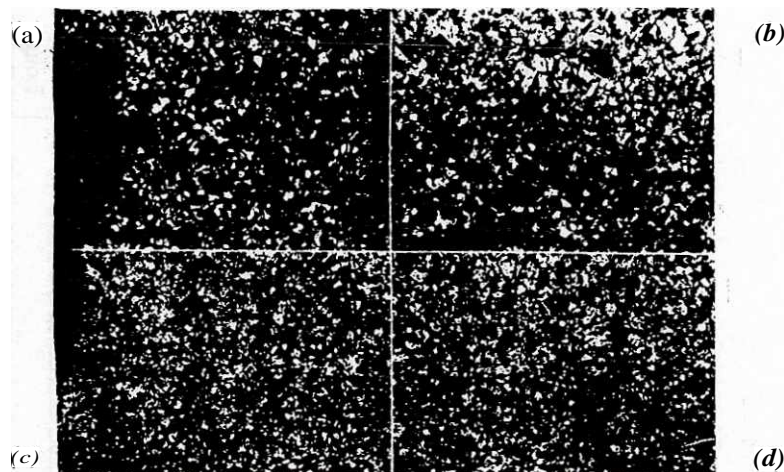


Fig. 7 : Grain size of 15C DV6, before and after ESR, optical micrographs.

Table 9 : Influence of hot deformation on mechanical properties of 15C DV6 steel before and after ESR

Si. Material No.	Hot deformation (%)	UTS, MNm ⁻²	Anisotropy coeff. L/T	0.2% PS, MNm ⁻²		Anisotropy coeff. L/T		
				Long.				
Si. Material No.	Hot deformation (%)	σ_y	σ_u	Elongation, %		Anisotropy coeff. L/T	Anisotropy coeff. L/T	Chapy U-notch impact energy kJm ⁻² (Long)
			Trans.	Long				
				15				510
		46		17	15			690
		40		19	12		1.58	940
				20				740
		55		21	20		1.05	920
		52		23	19		1.21	1200

Effect of heat treatment, ESR and hot work on properties of 15C DV6 steel

Material	Heat Treatment*	Hot deformation %	UTS, MNm ⁻²		Anisotropy coeff. L/T			0.2% PS, MNm ⁻²		Anisotropy coeff. L/T			
			Long	Trans.	6.	5.	4.	3.	2.		Long.	Trans.	
													1.
Bloom	A	30	3. 1110	—	—	—	—	—	—	—	—	—	—
Bloom	B	30	1340	—	—	—	—	—	—	—	—	—	—
Bloom	B	40	1380	1340	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Bloom	B	70	1380	1360	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
ESR ingot	A	Nil	1150	—	—	—	—	—	—	—	—	—	—
ESR	B	Nil	1390	—	—	—	—	—	—	—	—	—	—
ESR ingot	B	40	1420	1400	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
ESR ingot	B	70	1420	1380	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03

Material	Heat Treatment*	Hot deformation %	W _F		Anisotropy coeff. L/T			Elongation (%)		Anisotropy coeff. L/T			
			Long	Trans.	6.	5.	4.	3.	2.		Long.	Trans.	
													1.
Bloom	A	30	40	—	—	—	—	—	—	—	—	—	—
Bloom	B	30	25	—	—	—	—	—	—	—	—	—	—
2. Bloom	B	40	40	30	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
Bloom	B	70	43.	27	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
ESR ingot	A	Nil	40	—	—	—	—	—	—	—	—	—	—
ESR ingot	B	Nil	27	—	—	—	—	—	—	—	—	—	—
ESR ingot	B	40	50	48	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
<u>ESR ingot</u>	<u>B</u>	<u>70</u>	<u>55</u>	<u>45</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>	<u>1.22</u>

Section size 4-6 mm, austenitised 980°C in cyanide bath, oil quenched: tempered 625°C, oil cooled

Table 11 : Effect of inoculation during ESR and hot deformation on properties of I5C DV6 steel

Sl. No.	Material (% hot deformation)	Inoculant addition, (%),	UTS, (MNrrr ²)	0.2% PS (MNm ⁻²)	Elongation, (%)	RA, (%)	Charpy U-notch impact energy (kiln ⁻²)
1.	Conventional bloom (30%)	Nil	1060	1020	15	50	510
2.	ESR ingot	Nil	1090	1050	20	60	740
3.	ESR ingot	0.1 Zr	1130	1070	20	58	910
4.	ESR ingot	0.2 Zr	1150	1130	21	57	970
5.	ESR ingot	0.3 Zr	1160	1110	21	57	1000
6.	ESR ingot	0.1 Nb	1100	1060	20	60	800
7.	ESR ingot	0.2 Nb	1140	1110	22	65	940
8.	ESR ingot	0.3 Nb	1160	1130	22	65	960
9.	ESR ingot	0.1 V	1120	1080	19	62	790
10.	ESR ingot	0.2 V	1140	1100	21	64	920
11.	ESR ingot	0.3 V	1080	1040	22	64	820
12.	ESR ingot	0.01 N	1080	1040	22	64	820
13.	ESR ingot	0.02 N	1130	1110	22	64	890
14.	ESR ingot	0.03 N	1100	1080	23	64	920
15.	Conventional bloom (40%)	Nil	1110	1070	18	51	690
16.	ESR (40%)	Nil	1140	1090	21	59	920
17.	ESR (40%)	0.2 Zr	1230	1170	23	60	1160
18.	ESR (40%)	0.2 Nb	1210	1160	23	64	1080
19.	ESR (40%)	0.2 V	1190	1150	22	62	1010
20.	ESR (40%)	0.02 N	1180	1150	23	64	1040

as the size of inclusions as a result of ESR is shown in Table 7. The inclusion index decreased from 0.48 in the bloom used for the electrodes to 0.11-0.17 in the ESR ingots. In the refined steel 95% of the inclusions were below 6 gm in size and no inclusions larger than 12 p.m were observed. Inoculation during ESR had no noticeable influence on either the quantity or the size distribution of inclusions. CaO containing slags gave slightly better cleanliness in the refined steel (inclusion index 0.11-0.14) than 70 CaF₂ - 30 Al₂O₃ slag (0.14 - 0.17). This may be the result of the better desulfurization with slag containing CaO.

The grain size of steel after ESR appears to be marginally coarser than that if the conventional bloom (Table 8, Figs. 7a and 7b). Inoculation with 0.2% Zr or 0.2% Nb during ESR resulted in significant refinement of the grain size from 35 p.m to 13 - 15 gm (Table 8,

Fig. 7c, Fig. 7d). Jeznitzer and Prosenč¹⁴²¹ also observed that the addition of nucleants Nb, Ti, V and Zr and compounds containing boron, carbon or nitrogen to steel during ESR bring about grain refinement and reduced segregation. These effects are also detectable even after hot deformation and structure transformation.

The significant improvement in toughness and ductility values due to ESR even in the cast condition may be attributed to the decrease in the sulphur content, reduction in the quantity as well as the size of inclusions, and enhanced homogeneity of the ingot resulting from the steady state solidification of the metal from a shallow liquid pool during ESR.

The properties of ESR steel in the as cast condition are comparable with those of hot worked conventional steel. Hot deformation leads to further improvement in properties of the ESR steel which is also more isotropic than conventional hot worked steel Table 9 shows the influence of hot deformation (forging) on the mechanical properties of the heat treated steel before and after ESR. In all cases the properties of the ESR steel were significantly higher than those of the corresponding material from the conventional bloom.

The elongation and reduction in area in the transverse direction decreased with increasing degree of hot deformation in both the conventional material as well as after ESR. Anisotropy of these properties was observed in the deformed steel, the ESR steel being much less an isotropic than the conventional steel (Table 10) Table 11 shows the influence of inoculation during ESR and hot deformation of the ingot on the properties. As a result of inoculation during ESR, the strength, ductility and charpy toughness all improved.

Thus inoculation during ESR is a feasible and effective method of further enhancing the ductility and charpy U-notch toughness, with some improvement in strength as a result of refinement of structure and grain size. Niobium and zirconium are superior to vanadium and nitrogen.

CONCLUSIONS

- ESR is finding a place where consistently very low sulfur levels in combination with low oxygen are required, such as in maraging and high strength plate steels.
- Desulfurization occurs as a result of slag/metal and gas/slag reactions.
- The greatest portion of sulphur is removed by gas/slag reaction. This reaction is enhanced by decarburization and using slag with low viscosity.
- The metal/slag reaction represents the rate controlling step over all the desulfurization process.
- High degree of desulfurization in ESR can be attained by using slag containing (mass contents in %) 70 CaF₂, 15 CaO and 15 Al₂O₃.
- Electroslag refining of 15 C DV 6 steel gives considerable improvements in ductility, charpy U-notch impact toughness along with a marginal improvement in strength.
- The properties of ESR steel in the as cast condition are comparable with those of hot worked conventional steel. Hot deformation leads to further improvement in properties of the ESR steel, which is also more isotropic than conventional hot worked steel.
- Tool steels, high-temperature alloys, low-alloy aircraft and bearing steels, high strength plate, gun barrel and rotor steels show justified improvements.

- Electroslag remelting will have an important role to play in providing high quality materials required by the rapidly expanding industrial base of India

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