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IMPACT OF ELECTRO SLAG REMELTING ON 14 109 STEEL PROPERTIES

The Electro Slag Remelting (ESR) is one of the remelting processes in the field of metal refinery. In this process, the slag plays various roles, such as heat generation, protection of melt, and chemical refining. The main objective of the experiments described in this article was to identify the most appropriate slag composition for the electro slag remelting of the steel in order to achieve the chemical composition compliant with the standard applicable to the given steel, minimum sulphur content, minimum contents of oxide and sulphide inclusions, as well as mechanical properties corresponding to the standard applicable to the steel STN 14 109. Ten electrodes were remelted, whereas the remelting was carried out under 8 slags. The used slags containing 70% of CaF_2 and 30% of Al_2O_3 with different addition of CaO, the slags consisted of the same components as previous slags, whereas the ratio of individual components was 1:1:1, and with SiO_2 and MgO and slag without Al_2O_3. With regard to all the above mentioned facts, the slag types which may be regarded as the most appropriate for the STN 14 109 steel remelting are the basic slags containing 70% of CaF_2 – 30% of Al_2O_3 with added 30 and 45 weight % of CaO.

Keywords: Electroslag remelting, slag, non-metallic inclusions, mechanical properties, chemical composition

1. Introduction

ESR (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. ESR ingots have been successfully used for the production of isotropic materials having same properties in all directions. It has special applications in the 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 [1-5].

The ESR process is a continuous process in which melting, metallurgical reactions and solidification of steel occur simultaneously. The objective of this process is to produce ingots with superior quality and the rate of crystallization determines the production rate.

ESR was well studied standard metallurgical process of producing the high quality complex alloyed steel and ingots. But the decrease of the military orders at the end of the cold war and success of the ladle metallurgy in metal refining let to the period of stagnation in the ESR development.

In ESR consumable electrode is dipped into a pool of slag in a water-cooled mold. An electric current passes through the slag, between the electrode and the ingot being formed and superheats the slag so that drops of metal are melted from the electrode [6-7].

They travel though the slag to the bottom of the water – cooled mold where they solidify. The slag pool is carried upwards as he ingot forms. The new ingot of refined material builds up slowly from the bottom of the mold. It is homogeneous, directionally solidified and free from he central unsoundness that can occur in conventionally cast ingots as they solidify from the outside inwards. Fig 1 shows the principle of electro slag remelting process.

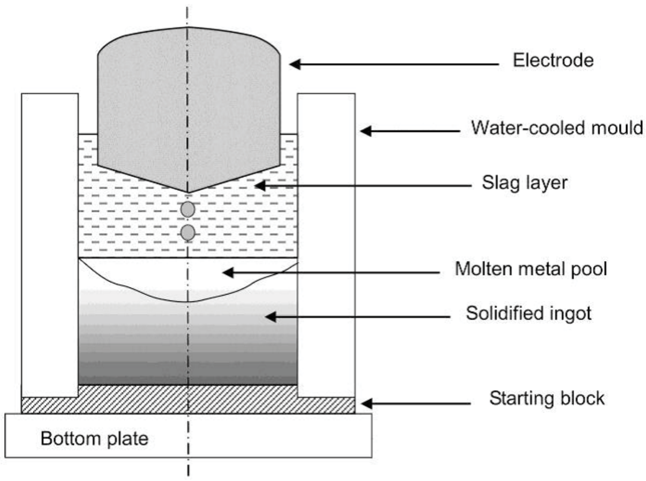

Fig. 1. Principle of electro slag remelting process [8]

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The melting and forming of the ingot is done in the cooper water-cooled mold without a refractory lining which excludes metal polluting with products of its destruction**.**

The key component of electroslag process is slag. The history of slag for ESR began with the fluorine slag on the basis of the fluorspart, the main component of which is calcium fluoride [9]. CaF_2 makes a melt having good electro conductivity and sufficient resistance, excellent fluidity, does not create non-stable modifications under temperatures of the process and does not oxidize the metal. But it is expensive, deficient and ecologically harmful.

The slag forms a layers of skull on the surface of the ingot. The skull prevents the surface from oxidizing. If the remelting regime had been chosen correctly, the ingot has the surface which allows to roll of forge ingot without any additional cleaning [9].

Slags for ESR are usually based on calcium fluoride (CaF_2), lime (CaO) and alumina (Al_2O_3). Magnesia (MgO), titania (TiO_2) and silica (SiO_2) may also be added, depending on the alloy to be remelted [10-13].

The main objective of the experiments described in this article was to identify the most appropriate slag composition for the electro slag remelting of the steel STN 14 109 in order to achieve the chemical composition compliant with the standard applicable to the given steel, minimum sulphur content, minimum contents of oxide and sulphide inclusions, as well as mechanical properties corresponding to the standard applicable to the STN 14 109 steel.

2. Methodology of experiments

Within the experiments, electro slag remelted electrodes were casted from the steel STN 14 109 with the diameter of 42 mm, the length of 1,200 mm, and the weight of 12 kg. Ten electrodes were remelted, whereas the remelting was carried out under 8 slags with the chemical composition presented in Table 1. The basic slag used was the slag containing 70% of CaF_2 and 30% of Al_2O_3 (A). The base of A10, A20, A30, and A45 slags was the A slag supplemented with 10, 20, 30, and 45% of CaO. The B slag consisted of the same components as previous slags, whereas the ratio of individual components was 1:1:1. Other slags used included C and D slags. The C slag was used very frequently in former Czechoslovakia (an electro slag pilot plant has been operating in Czechoslovakia since 1961, considerable research has been conducted in evaluating the mechanical properties of electro slag – remelted ball – bearing steels in Czechoslovakia). The D slag is a typical slag for electro slag remelting without aluminium oxide and, according to the literature, is it characteristic with high desulphurisation ability. The proposed chemical compositions of slags were based on the experience and the knowledge of the impact of individual slag components on the desulphurisation and the reduction of contents of non-metallic inclusions.

Table 2 presents the chemical composition and mechanical properties of the STN 14 109 steel.

TABLE 1

Composition of slags used in experiments

Slag	Chemical composition, weight %
A	$70\%CaF_2 – 30\%Al_2O_3$
A10	A+10% of CaO
A20	A+20% of CaO
A30	A+30% of CaO
A45	A+45% of CaO
B	$CaF_2 – Al_2O_3$ – CaO (1:1:1)
C	43% of CaF_2 – 17% of Al_2O_3 – 26% of CaO – 3.5% of MgO – 10.5% of SiO_2
D	80% of CaF_2 – 20% of CaO

TABLE 2

Permissible chemical composition of used steel and mechanical properties, as specified in the STN 14 109 standard

C, wt. %	**Mn, wt. %**	**Si, wt. %**	**Cr, wt. %**	**P, wt. %**	**S, wt. %**	**Ni + Cu, wt. %**
0.9-1.2	0.3-0.5	0.15-0.35	1.3-1.65	Max. 0.027	Max. 0.03	Max. 0.5
$Rp_{0,2}$, MPa		441 – mean value				
Rm, MPa		608-726				
A_5, % (min.)		18				
Z, %, (min.)		35				

$R_{p0.2}$ – yield strength; *Rm* – tensile strength; A_5 – elongation; *Z* – contraction

Experimental melting was carried out using the equipment intended for the electro slag remelting at the Department of Ferrous and Foundry Metallurgy, the Faculty of Metallurgy of the Technical University in Košice. To start up the process of electro slag remelting, in addition to working slags (Table 1), iron powder was used (200 g per melting) together with the start-up slag which represented 10% of the working slag's weight. The working slag's weight was 1,200 g, representing 10% of the electrode weight. By remelting the electrode under the working slag layer, the ingot was formed in a metal mould made of copper, with internal water cooling. Parameters of the metal mould were as follows: the height of 300 mm, the internal diameter of 90 mm, and the wall thickness of 15 mm. The weight of the produced cast – an ingot, was approximately 10 kg. Even though rods with identical weights were remelted, the ingot's weight varied, depending on the height above the upper part of the mould at which the process was stopped. In the height of 20 mm above the upper part of the ingot, samples were collected for the chemical and metallographic analysis. The remaining part of the ingot was reforged into a rod with the diameter of 40 mm and thermally processed in compliance with the standard.

2. Achieved results and their evaluation

Ingots produced by the electro slag remelting under various slags did not contain any draws, hollows, or any other cast defects forming during the hardening; their surface was smooth and the slag skin formed on their surface was 1-2 mm thick and easy to separate from the ingot's surface. On the upper part of the ingot, there was a slag skin through which the process of electro slag remelting was running, with the thickness of 5-6 cm. Chemical composition of remelted electrodes as well as chemical composition of ingots are presented in Table 3.

As Table 3 shows, remelting under all 8 slags has not caused almost any change in the carbon and phosphor contents, which corresponds to the data in literature [13]. However, significant change occurs with regard to the silicon and manganese contents. The silicon content decrease was ranging between 33 and 80%. The highest decrease in the silicon content was observed with remelting under the D slag and the lowest decrease under the A slag (in both, A and B remelting procedures). The manganese content was higher in all remelting procedures and its increase was ranging between 20 and 95%. The maximum permissible manganese content, as specified in the standard, was only exceeded in two cases, particularly in case of remelting under the A10 slag and under the D slag. Literature allows increased manganese content after remelting, but in this case the manganese content increase was very significant. The only source of manganese was the start-up slag containing more than 50% of Mn which might have melted into the steel.

TABLE 3

Chemical compositions of electrodes and ingots remelted under individual slags

Melting	Slag		C, wt. %	Mn, wt. %	Si, wt. %	P, wt. %	S, wt. %	Cr, wt. %
M(A)	A	a	0.98	0.34	0.27	0.012	0.0200	1.39
		b	0.98	0.43	0.18	0.012	0.0090	1.4
M(B)	A	a	1.01	0.32	0.27	0.012	0.0138	1.35
		b	1.00	0.42	0.17	0.012	0.0086	1.37
M(C)	A10	a	1.05	0.36	0.29	0.01	0.0089	1.45
		b	1.05	0.62	0.12	0.01	0.0061	1.47
M(D)	A20	a	0.97	0.32	0.27	0.012	0.0118	1.35
		b	1.01	0.40	0.12	0.012	0.0058	1.34
M(E)	A30	a	1.07	0.34	0.30	0.010	0.0142	1.44
		b	1.09	0.40	0.16	0.010	0.0046	1.52
M(F)	A45	a	1.09	0.35	0.29	0.010	0.0116	1.42
		b	1.07	0.39	0.14	0.010	0.0047	1.43
M(G)	B	a	0.96	0.34	0.27	0.011	0.0190	1.39
		b	0.98	0.41	0.13	0.021	0.0070	1.39
M(H)	B	a	1.00	0.32	0.27	0.012	0.0136	1.35
		b	1.00	0.38	0.15	0.012	0.0059	1.34
M(I)	C	a	1.01	0.32	0.27	0.012	0.0123	1.35
		b	1.02	0.40	0.13	0.012	0.0064	1.35
M(J)	D	a	1.05	0.34	0.29	0.010	0.0078	1.45
		b	1.00	0.66	0.06	0.012	0.0067	1.46

Note: a – content of the element in the electrode prior to remelting, b – content of the element in the ingot after remelting under the given slag (average value from three chemical analyses).

One of the main roles of the ESR is to reduce the sulphur content in steel after remelting. The sulphur content in electrodes was ranging between 0.0078 and 0.0200% of weight and in ingots between 0.0047 and 0.0090% of weight. As the final sulphur content is affected not only by the slag but also by the initial sulphur content in the electrode being remelted, the final sulphur content parameter is not absolutely objective and it is more appropriate to use the desulphurisation degree which takes into consideration both, the initial and the final sulphur contents.

The steel desulphurisation degree is determined by the relation (1)

$$D_s = \frac{S_E - S_k}{S_E} \cdot 100\% \qquad (1)$$

D_S – desulphurisation degree, %,
S_E – sulphur content in an electrode, %,
S_k – sulphur content in a cast, %.

The lowest sulphur content was observed after remelting under the A30 slag (0.0046% of weight) and the A45 slag (0.0047% of weight); the highest desulphurisation degree was achieved after remelting under the same slags. The best impact on desulphurisation was observed with A30 and A45 slags. Chemical composition of slag is thus a parameter with the major contribution to steel desulphurisation.

All used slag types, except for the C slag, consisted of three basic components: CaF_2, CaO, and Al_2O_3. The CaO and CaF_2 contents in the slag have the most significant impact on desulphurisation. Increased CaF_2 content in the slag led to a slight increase in the final sulphur content in steel after ESR, but its negative impact was significantly manifested with regard to the desulphurisation degree, as shown in Figure 2.

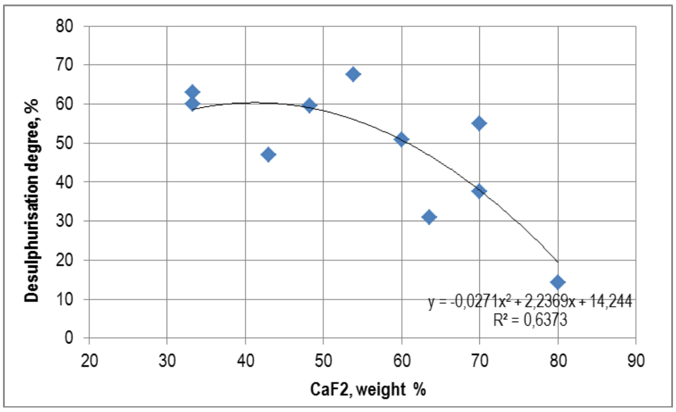

Fig. 2. Impact of the CaF_2 content in the slag on the steel desulphurisation degree

CaO has the opposite effect on the steel desulphurisation. Increased CaO content in the slag caused significant decrease in the sulphur content in steel as well as increase in the desulphurisation degree, Figure 3. Authors [6] explain it by the fact that in systems similar to electrometallurgical slags, CaF_2 behaves as the inert solvent which reduces the slag's desulphurisation ability.

Steel quality depends not only on its chemical composition but also on the contents of non-metallic inclusions, particularly the contents of both, sulphides and oxides. Table 2 presents the contents of oxides and sulphides prior to remelting and after remelting under individual slags. Content of oxide inclusions in an electrode prior to remelting was 0.05% of the area and the content of sulphide inclusions was 0.06% of the area. The lowest content of sulphide inclusions after remelting was observed with remelting conducted using the A30 slag (0.0075% of the area). In all ingots, except for the M(A) and M(B) ingots, the content of sulphide inclusions was lower than in an electrode (M(A) and M(B) melting procedures were carried out under the A slag without any CaO content). The content of oxide inclusions decreased in the middle of the melting processes down to the level of 0.04% of the area; only after remelting using the A20 slag, there was no reduction in their contents. The total content of non-metallic inclusions is affected, to a great extent, particularly by the CaO content in the slag, as shown in Figure 4.

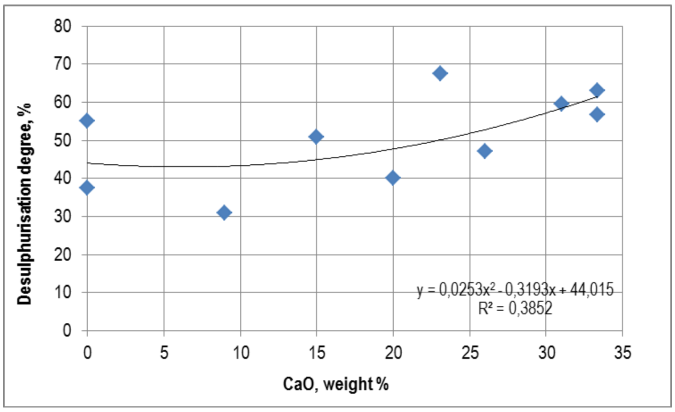

Fig. 3. Impact of the CaO content in the slag on the steel desulphurisation degree after the ESR

The achieved results confirmed the well-known impact of the slag's chemical composition on the contents and morphology of non-metallic inclusions. Adjustment of slag composition has the potential to change, in a wide range, the quantity of non-metallic inclusions. The same slag type, however, is not appropriate for all steel types.

TABLE 4

Contents of sulphides, oxides, and basic mechanical properties of steel in the electrode and after remelting under various slag types

Electrode/bar (after ESR)	Slag	Sulphides [% of area]	Oxides [% of area]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]
Electr.	—	0.050	0.060	430	680	23.6
M(A)	A	0.05	0.055	422	710	26.2
M(B)	A	0.045	0.055	433	679	28.6
M(C)	A10	0.015	0.04	435	689	28.1
M(D)	A20	0.03	0.06	416	682	27.2
M(E)	A30	0.0075	0.04	441	700	28.6
M(F)	A45	0.015	0.04	440	701	27.2
M(G)	B	0.03	0.045	433	699	26.8
M(H)	B	0.02	0.04	433	688	27.4
M(I)	C	0.015	0.04	414	686	28.4
M(J)	D	0.01	0.04	431	686	26.5

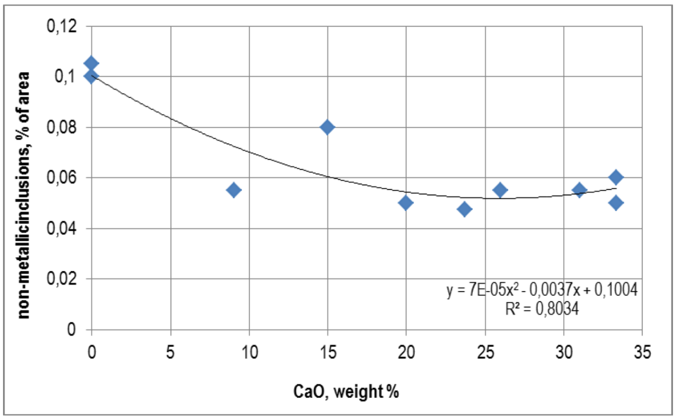

Fig. 4. Impact of the CaO content in the slag on the content of non-metallic inclusions in steel (after ESR)

Table 4 presents, in addition to contents of non-metallic inclusions, also mechanical properties of steel prior to remelting and after remelting under various slag types. In addition to steel chemical composition, mainly the sulphur content, mechanical properties are also affected by the contents of non-metallic inclusions and by thermal processing. Tensile strength prior to remelting was 430 MPa and after remelting it was ranging between 414 and 441 MPa; a value lower than the one prior to remelting was only observed after remelting under the C slag. The strength limit in an electrode was 680 MPa and after remelting it was in the interval of 679 – 710 MPa. A value lower than the one in an electrode, and at the same time the lowest value, was measured after remelting under the A slag. Elongation values were ranging between 26.2 and 28.6%. In all cases, the elongation values were higher than in an electrode.

Conclusion

The main objective of this article was to identify the slag composition which ensures achieving the chemical composition compliant with the standard, as well as the lowest possible sulphur content and the highest possible desulphurisation degree, the minimum content of sulphide and oxide inclusions, and the highest values of mechanical properties, compliant with the standard. The following conclusion follows from the achieved results:

1. Contents of carbon and phosphor do not change after the electro slag remelting; the electro slag remelting does not cause the chrome loss.
2. Remelting results in significant silicon loss. The lowest loss was observed with remelting under the A and A30 slag types. Due to the loss, it is necessary to recommend the maximum permissible silicon content value in the remelted electrode.
3. After remelting, increased manganese contents were observed in all steels. The lowest increase in the manganese content was observed when A30 and A45 slag types were used. With regard to the used electro slag remelting technol-

ogy, it is required to count with the increased manganese content in an ingot; therefore, in order to adhere to the maximum permissible manganese content, the recommended manganese content in an electrode should be in the middle of the permissible range.

4. Increased CaO content in the slag led to the decrease in the sulphur content in the remelted metal. The opposite effect was observed with the CaF_2 content in the slag; its increase resulted in the sulphur content reduction and the desulphurisation degree reduction.
5. After the electro slag remelting, there was a decrease in the contents of sulphide inclusions. However, the content of sulphide inclusions also relates to the sulphur content.
6. Values of strength, yield strength, and elongation values observed after remelting and thermal processing were within the range permitted by the standard, and at the same time higher than in the electrode being remelted.
7. With regard to all the above mentioned facts, the slag types which may be regarded as the most appropriate for the STN 14 109 steel remelting are the A30 and A45 slag types, i.e. the slags with the basic slag containing 70% of CaF_2 – 30% of Al_2O_3 with added 30 and 45 weight % of CaO.

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