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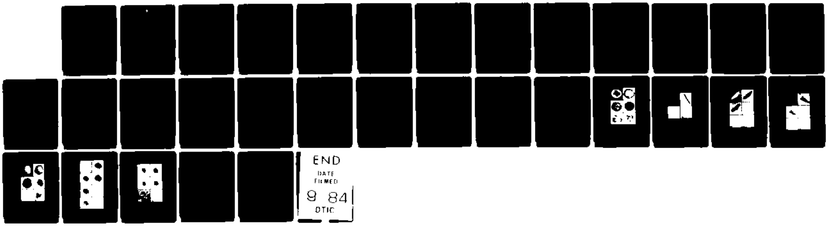

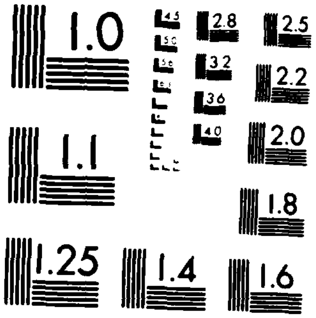

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REPORT

MRL-R-915

ESR STEEL DEOXIDATION AND SLAG PRACTICE - INFLUENCE ON INCLUSION MORPHOLOGY

G.M. Weston and R.C. Andrew

Approved for Public Release

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No significant variations in inclusion type or overall cleanliness were observed for the more conventional ($CaF_2 + CaO + MgO + Al_2O_3$) slags or for those containing up to 10% silica, whether they were combined with aluminium, calcium silicide or Hypercal deoxidation treatment. There were trends towards slightly increased amounts of globular type D inclusions and reduced aluminate levels when using calcium silicide deoxidation, while with aluminium deoxidation slightly higher aluminate levels were recorded. In most instances the globular type D inclusions were < 6-9 μm in diameter and similar to the modified inclusion types observed after conventional calcium ladle modification. The exceptional desulphurizing ability of slags containing rare earth oxides resulted in ingot sulphur levels approaching 0.002 wt% and a population of very fine modified inclusions which almost entirely replaced the usual type II sulphides. In general, oxides were only observed in a duplex modified form, while it was the deoxidant rather than the slag chemistry which had the major influence on inclusion composition and morphology.

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ABBREVIATIONS

CaSi	Calcium silicide, a common deoxidant used in steel making.
Ca-DeOx	Steels deoxidized with calcium compounds.
CaT	Calcium treated steels to control inclusion mophology.
RE	The use of rare earth elements during the refining process.
EF	Electric furnace steels.
Hypercal	A proprietary deoxidizing agent containing calcium, aluminium and barium.

ESR STEEL DEOXIDATION AND SLAG PRACTICE - INFLUENCE ON INCLUSION MORPHOLOGY

1. INTRODUCTION

Two kinds of nonmetallic inclusions are generally recognised in steel, those which are entrapped in the steel inadvertently and those formed within the liquid metal as a result of composition and temperature changes during solidification. The absence of refractory materials ensures that only inclusions of the latter type are found in electroslag refined (ESR) steels.

Although the predominant inclusion types observed in ESR steels are usually sulphides, aluminates and to a lesser extent silicates, their number and morphology can be influenced by the remelting practice followed. This is one beneficial factor in favour of the ESR process, as it has been claimed that the transverse mechanical properties are influenced more by inclusion type than by the amount of inclusions present [1].

This ability of inclusions to influence transverse mechanical properties depends on their inherently different physical behaviour during hot working operations and heat treatment. A number of these differences and their influence on mechanical properties have been reported in the literature [1,2,3]. For example, the ubiquitous manganese sulphide inclusions are found to be deformable at all temperatures of interest in steelmaking, whereas aluminates are not. In the case of sulphides, their lenticular form after hotworking has been shown to severely reduce transverse toughness [4,5], while the harder undeformable aluminates and silicates can give rise to cracking at the inclusion-matrix interface [6]. Aluminates and some silicates are also claimed to lower fatigue resistance in ball bearing steels due to the presence of tessellated stresses at the inclusion-matrix interface as a result of their much lower coefficient of thermal expansion compared with steel. Under cyclic contact stress conditions, this can lead to the development of fatigue cracks [6]. If, however, such aluminates and silicates are in a modified form whereby they are enveloped by a sulphide which has a higher coefficient of expansion than steel, improved fatigue performance has been recorded even though the overall inclusion level may have been higher [5].

The Commonwealth Steel Company (Comsteel), when commissioning their new ESR installation at Waratah, NSW, recognized that little was known about the residual inclusion types associated with the relatively new high silica and rare earth-containing slags recommended for use by the equipment supplier, Consarc. A further area of concern was that deoxidant addition rates were higher than expected in order to compensate for the effects of a forced dry air system operated above the slag bath. These greater amounts of deoxidant might also influence steel cleanliness.

A joint programme was therefore undertaken by MRL and Comsteel with the object of identifying inclusion types in steels remelted with slags of wide ranging composition in combination with different types of deoxidant.

2. ORIGIN AND DEVELOPMENT OF INCLUSION TYPES IN ESR STEELS

During the electroslag refining process the following inclusion types are formed:

(i) oxides

(ii) sulphides

(iii) duplex

For an understanding of their development it is appropriate to review the major factors which influence their formation during remelting.

2.1 Reaction Sites

In ESR there are three main sites where slag metal reactions can proceed:

(i) Electrode/slag interface

(ii) Liquid/droplet interface

(iii) Molten pool/slag interface

2.1.1 Electrode/slag interface

The electrode/slag interface is considered to be the most important in the removal of non-metallic inclusions from the electrode material [6,7,8,10]. Factors favouring this site are the high temperatures developed prior to the detachment of a metal droplet and the large surface area of the electrode over which the thin newly formed liquid film is exposed to the reactive slag environment. Although the mechanism is not entirely clear, evidence suggests that dissolution of the majority of silicates, aluminates along with the sulphides occurs in the residence time during liquid droplet formation and prior to their detachment from the electrode. From the work hitherto carried out, it is considered that inclusion dissolution in the metal and physical absorption in the slag must take place simultaneously [4,7-9]. Early proposals claiming inclusion flotation and slag entrappment as a major mechanism of removing electrode inclusions are now largely discredited [6,7,9]. Once dissolved, both oxygen and the deoxidant along with sulphur are capable of transferring to a basic slag by slag-metal reactions of the type:

$$[Si] + 2[O] \rightleftarrows (SiO_2) \quad .... (1)$$

$$2[Al] + 3[O] \rightleftarrows (Al_2O_3) \quad .... (2)$$

$$[S] + (O^{2-}) \rightleftarrows (S^{2-}) + [O] \quad .... (3)$$

where [ ] and ( ) refer to metal and slag phases respectively.

Where sulphur is concerned, the rate of removal will depend on the sulphur capacity of the slag which in turn depends on slag basicity [10]. In slags of low basicity, it is important that sulphur be transferred from the slag to the furnace atmosphere to ensure that continuing satisfactory metal/slag sulphur transfer rates are achieved via equation 3. This transfer of sulphur to the atmosphere occurs by the following reaction:

$$(S^{2-}) + 3/2\ \{O_2\} \rightleftarrows \{SO_2\} + (O^{2-}) \quad .... (4)$$

Where { } refers to the gas phase. The distribution coefficient (L) for sulphur between the gas and slag phases in this reaction is given by:

$$L = \text{Constant.}\ \frac{P\{O_2\}^{\frac{3}{2}}}{N_{(O^{2-})}} \quad .... (5)$$

where $P\ \{O_2\}$ equals partial pressure of oxygen in the atmosphere above the slag and $N(O^{2-})$ represents the mole fraction of O^{2-} ions in the slag. A high oxygen partial pressure in the furnace atmosphere aids this stage of the desulphurization process, and so enhances the effect of a low slag basicity.

2.1.2 Droplet/slag interface

The above chemical reactions will continue as the droplet falls through the slag. However, due to the short residence time, this site is considered less important.

2.1.3 Liquid pool/slag interface

Although the electrode/slag interface is considered the major reaction site, the large surface area of metal in contact with the slag, the long residence time and the convectional movement of the slag all contribute toward enabling the oxygen and sulphur activities of both the slag and metal to equilibrate.

In general therefore, the final oxygen content of the ingot is dependent on the oxygen content of the slag bath [6,7,9.10]. In practice this is achieved by having a high slag basicity (CaO/SiO_2) ratio of at least 2, aluminium contents above 0.03 Wt%, while at the same time maintaining the Al_2O_3/CaO ratio as low as possible [12].

3. INCLUSION FORMATION

During remelting, much of the final inclusion content in an ESR ingot is formed within the mushy interdendritic region during the final stages of solidification [7,8,9]. In the case of sulphur, the high solubility product of the sulphide and oxysulphide of manganese in liquid iron ensures that these inclusions will only be formed in the solute-rich interdendritic regions during the final stages of solidification. The type of oxide inclusion formed will be influenced by slag composition and deoxidation practice [7,13], while their size and final distribution will depend on the local solidification time and profile of the solid liquid interface. In the commonly used slags containing 15-30% Al_2O_3 the predominate oxide is usually a spherical aluminate, but with insufficient deoxidation aluminate clusters have been reported [14]. Due to the high supersaturation necessary in the final liquid to nucleate aluminates as a separate phase, the vast majority are usually small and less than 5 μm in diameter. Once formed, these aluminate inclusions appear to act as nuclei for the subsequent precipitation of sulphides when complex inclusions are formed. For the same oxygen content in the steel, silicates are usually larger than aluminates as they require a lower degree of supersaturation before nucleating.

The presence of the more reactive modifying elements such as calcium, magnesium and cerium will influence the formation of both oxides and sulphides. Because these elements have a high affinity for both sulphur and oxygen, small modified inclusion types containing these elements precipitate from the melt at higher temperatures ahead of the solidification front and with little solute supersaturation during cooling. This results in an even distribution of very fine modified inclusions throughout the melt. The tying-up of sulphur in this way prevents interdendritic solute build-up during the final stages of solidification and hence the formation of coarse eutectic sulphides.

4. INCLUSION MORPHOLOGY

In electric furnace (EF) steelmaking practice the beneficial influence of calcium and rare earth (RE) elements basically Ce on the number, size, shape, hardness and composition of retained inclusions is well established [15,16]. At low RE levels (0.008-0.020%) manganese sulphides are blockier and do not elongate to the same extent as unmodified sulphides [15,16]. At intermediate RE levels (0.02-0.07%) spherical sulphides consisting of a central core of RE oxysulphide $(RE)_2 O_2S$ surrounded by a darker rare earth sulphide of composition $(RE)_x S_y$ are observed. Rare earth aluminium oxides of the type $(RE) Al_{11}O_{18}$ are formed at low RE concentrations while at levels approaching 0.02% the softer $(RE) AlO_3$ particles predominate and the harder Al_2O_3 types disappear [15]. In practice, the modified inclusion form is usually a complex oxide embedded in a complex manganese sulphide. However, both the oxide and sulphide phases can form independently and have been observed as separate modified inclusion types [15,16,19].

In calcium deoxidized (Ca-DeOx) steels the first-formed calcium aluminate inclusions are enveloped by a Mn sulphide inclusion containing ~ 6% calcium in solution. Sufficient calcium ensures the absence of alumina galaxies and eutectic sulphides.

5. EXPERIMENTAL

Electroslag remelting, of low alloy steel types (Table 1) was carried out using a 33 tonne Consarc AC installation with 800 mm diameter round and 380 mm square moulds. Different slag/deoxidant combinations (Table 1) were tried in selected production runs. Forging reductions for these ingots varied between 2.5:1 to 5:1 depending on the end application and mould size. After forging, discs were taken from the top and bottom of ingots. Samples ~ 12 mm square were removed from the mid-radial position of each disc and after a suitable preparation the identification of inclusions was performed using electron probe microanalysis (EPMA). Other areas of these discs were used for routine chemical analysis and inclusion assessment using the standard chart method, namely ASTM-E45 method D. To prevent the leaching of calcium from inclusion prior to examination, no water was used during sample preparation. In order to make a comparison with inclusion types found in EF steels, similar sections were removed from an (EF) ordnance steel.

6. RESULTS

The variation in composition between electrode and remelted ingot is summarized in Table 2. The average cleanliness rating for each ingot/slag/deoxidant combination is shown in Table 3. Table 4 shows the different elements detected in major inclusion types for each remelting combination. The composition of the deoxidants used is given in Table 5.

From Table 4, it is evident that very few individual oxide inclusions were detected in the ESR remelted ingots by optical means; most of the visible oxides had a sulphide phase association with them to form duplex inclusions. When individual oxides were identified, they tended to be very small, ~ 5 μm diameter, and of a complex nature having both calcium and magnesium in association with the aluminate. Very few silicate inclusions were observed and when present they were partially or wholly enveloped by a sulphide (Fig. 1).

For all remelting conditions, the more heavily worked ellipsoidal sulphides observed in each ingot tended to be straight manganese sulphides, while the less deformed, blockier types were often of a complex nature having calcium present (Figs. 2 and 3). Trace amounts of magnesium and cerium (when present in the slag) were also detected in some of these blockier inclusions.

6.1 Different sulphur levels

For the high sulphur ESR steels (0.025 wt%), the vast majority of sulphides were either of the heavily worked elongated or blockier types, and in this respect were similar in appearance and chemistry to the sulphides present in the high-sulphur EF steel investigated (Fig. 4). A background of fine modified duplex inclusions was also present in these ESR steels while the duplex inclusions observed in the equivalent EF steel were less numerous and larger.

At intermediate sulphur levels 0.006 wt% the vast majority of inclusions observed in ESR steels were small (< 10 μm diameter) and of the modified duplex type whereby a complex calcium and or magnesium oxide was enveloped or partially enveloped by a complex calcium and or magnesium sulphide (Fig. 5). Small ellipsoidal type II and blockier sulphides were still prominent in all ESR steels at this sulphur level. Their size and distribution varied from ingot to ingot. Although magnesium x-ray indications were generally weak, x-ray indications from the oxide areas appeared stronger when this element was present as a slag constituent.

In very low sulphur steels (~ 0.002 wt%S) produced under slags containing (RE) oxides (ingots 14 and 15, Table 1) the inclusion population was almost entirely made up of very fine modified inclusion types ~ 4-6 μm in diameter. The occasional small isolated ellipsoidal type II sulphides still persisted in ingot 14 remelted under the 11% Bastnasite slag, however, with higher RE concentrations (25 wt% Bastnasite ingot 15) Type II unmodified sulphides were rare. For the majority of these very small modified inclusions both the oxide and sulphide phases appeared indistinguishable, Fig. 6. This is most likely the result of a very fine dispersion of the complex oxide phase throughout the complex sulphide matrix. It would be expected that the more reactive elements such as calcium and cerium would be associated with both the oxide and sulphide phases. Modified inclusion types similar to that shown in Fig. 5 were also observed with cerium being present in both the oxide and sulphide areas. Very small spherical modified sulphides containing both cerium and calcium were also identified in these two steels, Fig. 7.

6.2 Differences in deoxidants

The use of different deoxidants did not appear to significantly influence steel cleanliness and inclusion morphology. However, calcium indications appeared to be stronger in both oxides and sulphide areas when calcium silicide (CaSi) was used as a deoxidant; while a trace of barium was detected in the sulphide regions of some duplex inclusions when Hypercal was used as a deoxidant. From the cleanliness ratings (Table 3), a slight increase in Type B (aluminate) inclusions is indicated with aluminium deoxidation, while silicate inclusions (Type C) were only observed with CaSi addition rates of 0.22% MR* which was considered in excess of that necessary for adequate deoxidation. There also appeared to be a small increase in the globular Type D inclusion types when using CaSi deoxidation along with a small decrease in aluminates. In this regard the use of Hypercal appeared slightly more effective in reducing the amount of aluminates present.

7. DISCUSSION

In the present work it has been found that, irrespective of sulphur content, the vast majority of small globular inclusions in ESR steels were similar to those modified inclusion types previously reported after conventional ladle treatment of EF steels with calcium and cerium [15-18].

In conventional calcium treated (CaT) steels, the modified inclusions have a calcium aluminate core enveloped or partially enveloped by a complex calcium and/or magnesium sulphide [15,16,17]. In this respect they are similar to the globular inclusion types observed in the present examples of ESR steel which had been remelted under conventional slags not containing rare earth (RE) oxides. Calcium levels in these present steels were found to increase from ~ 2 ppm to 14 ppm after using CaSi deoxidation. This higher calcium activity in the slag would account for calcium being more readily identified in inclusions from these steels, and for the small increase observed in globular (Type D) inclusions.

The higher slag silica activity associated with the introduction of silica through the use of CaSi and silica based slags has been observed to reduce both the loss of silicon from ingot to slag and also ingot aluminium pick-up [13,19]. This second effect could account for the slightly lower ingot aluminate levels experienced in the present work when using CaSi and CaSi/silica based slag combinations. In earlier work [19] the type of deoxidant used was found to have the major influence on the metal/slag transfer behaviour of aluminium and silicon.

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* Per cent of melt rate, %MR, is the rate of addition of a deoxidant or other substance, expressed as a percentage of the rate at which the steel is melted from the feedstock bar.

The predominant inclusion type observed in ingots remelted under slags containing RE oxides were either straight RE oxysulphides or duplex inclusions which appeared to consist of a fine RE-oxide-alumina phase dispersed throughout a complex RE oxysulphide matrix. Although detailed thermodynamic calculations have not been undertaken, the interaction of RE and aluminium to form a complex RE-Al oxide rather than a straight RE oxide (RE_2O_3) was not unexpected as this inclusion type had been previously observed [15,20]. This type of inclusion is favoured when aluminium has been used as a deoxidizer either during the electrode preparation (as would be the case for most ESR electrode material) or during the remelting operation as was the case for ingot 14 (Table 1). Oxysulphides are believed to exist in the present steels because oxygen levels in all the remelted ingots were in the range 20-35 ppm, from which the stable deoxidation product according to thermodynamic data would be a RE-oxysulphide [20,21]. In practice, it is doubtful if ingot oxygen levels could ever be maintained consistently low enough (< 10 ppm) during ESR remelting to achieve the formation of straight RE sulphides.

For the elimination of individual MnS particles, RE/S ratios greater than 3 are considered necessary [17,18]. For ingot 14 where very few individual sulphides were observed, this would have required initial RE levels in the molten pool prior to solidification to be in the order of 0.006 wt%. As X-ray fluorescence (XRF) techniques failed to detect cerium in either ingots 14 or 15, the known sensitivity of this analytical technique suggests that residual cerium levels were at most 0.005 wt%. In electroslag remelting, an additional factor for consideration is the accumulative influence of other modifying elements such as calcium and magnesium which may be present in the steel.

The presence of some modified inclusion types containing both calcium and magnesium in EF as well as in ESR steels is of no surprise as these elements would be available during processing through interaction with basic slags, deoxidants and furnace linings.

For the ESR steels containing higher levels of sulphur, the predominant inclusion type was the unmodified type II sulphide which deforms readily during hot working operations. Under these circumstances, a dispersion of small modified inclusion would not be expected to significantly influence either the transverse mechanical properties or the degree of property anisotropy associated with steels having high sulphur levels. In this regard, the expected properties of a high - sulphur ESR steel would be similar to an equivalent electric furnace steel [19].

At intermediate sulphur levels (0.010-0.006 wt%), which covers most of the ESR steels produced, type II sulphides were still prominent. However, they were smaller and less numerous than would be expected for an equivalent EF steel [19]. Most of the small globular inclusions were of the modified complex type: very few individual oxides were observed in any of the ESR steels studied. When observed singly they were usually small (~ 4-6 μm in diameter) and therefore many may have remained undetected, being beyond the resolution of the optical techniques employed for inclusion assessment. For these steels, the presence of smaller type II sulphides combined with the higher proportion of globular modified inclusions and lower oxide levels would provide a basis for the improved transverse toughness and fatigue resistance when compared with an equivalent EF steel [14,16,17].

In the two very low sulphur ESR steels (0.002 wt%) remelted under the influences of slags containing RE oxides, very few unmodified type II sulphides remained. Most sulphur was tied up either in the form of modified sulphide particles or small duplex inclusions. Increasing RE slag concentrations did reduce the likelihood of small unmodified type II sulphides being present. These steels, therefore, could be expected to provide excellent transverse toughness with little directionality in mechanical properties. However, at these very low sulphur levels the directional influence of inclusions on mechanical properties would be small irrespective of the processing route, [20,21].

From the above it is clear that the sulphur levels required to ensure a high degree of inclusion modification are sufficiently low that inclusions would have little influence on mechanical properties whether the steel be EF or ESR [20]. The majority of property improvements associated with ESR steel can therefore be considered to be achieved in part by the ability of the process to lower the overall level of impurities. However, of greater significance with respect to mechanical properties, is the ability of the process to distribute residual impurities finely and evenly throughout the ingot. Both the above process advantages would be enhanced by increasing the activity of such reactive elements as calcium, magnesium and cerium in the slag. Such elements improve slag basicity and promote metal/slag reactions involving sulphur removal (~ 100 wt% reduction with the present RE slags) while at the same time, they have a strong affinity for the formation of small modified oxides and sulphide particles during solidification. As mentioned earlier (Section 5) these elements promote fine modified inclusion types at the expense of coarse type II sulphides.

8. CONCLUSIONS

1. The number, shape and chemical composition of ESR inclusions can be influenced within certain limits by adding or restricting the presence of strong oxide-forming elements in the remelting system.

2. For high sulphur ESR steels (0.02-0.03 wt%) the number and size of type A sulphides are similar to those experienced with equivalent electric furnace steels.

3. Increasing the presence of reactive elements in the remelting system enhances sulphur removal and promotes the formation of very small modified oxide and sulphide inclusions.

4. The morphology of modified inclusions in ESR steels is similar to that experienced in conventional calcium and cerium treated electric furnace steels.

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TABLE 1

ALLOY/SLAG/DEOXIDANT COMBINATIONS SELECTED

INGOT NO	STEEL TYPE	INGOT SIZE	SLAG TYPE	DEOXIDANT	DEOXIDATION SET
1	AISI P20	800 ϕ	70/0/0/30/0	Al	.10
2	En39B	"	40/30/0/30/0	Al	.08
3	AISI H11	"	"	CaSi	.10
4	*DHC	"	"	Hypercal	.18
5	AISI P20	"	70/15/0/15/0	Al	.05
6	AISI 4340	"	"	CaSi	.18
7	AISI 4340	380	65/15/0/10/10	Al	.10
8	AISI 4340	800 ϕ	"	Al	.10
9	En25	"	"	CaSi	.18
10	DHC	"	49/17/7/17/10	Al	.10
11	DHC	"	"	CaSi	.18
12	AISI 4340	"	"	Al/CaSi	.05/.08
13	DHC	"	"	Hypercal	-
14	AISI 4340	380	60/15/0/0/0/25B+	Al	.10
15	AISI 4340	380	62/10/0/17/0/11B	CaSi	.18
†16	En25	-	-	Al	-

* Comsteel Deep hardening Chromium Roll steel.

\+ Bastnasite - A naturally occurring element containing rare earth oxides.

† Electric Furnace ingot.

TABLE 2

CHEMICAL COMPOSITION BEFORE AND AFTER REMELTING

INGOT No.	STEEL TYPE	ELECTRODE/ INGOT	CHEMICAL COMPOSITION									
			C	SI	Mn	P	S	NI	Cr	Mo	V	Al
1	AISI P20	E	.36	.58	.87	.030	.027	.15	1.90	.41	.01	.002
		I	.39	.49	.82	.027	.023	.11	1.95	.37	.01	.033
2	En39B	E	.15	.29	.38	.019	.026	4.03	1.17	.20	.01	.002
		I	.16	.23	.38	.020	.004	4.03	1.13	.20	.01	.032
3	AISI H11	E	.42	.92	.45	.022	.013	.52	4.77	1.18	.50	.002
		I	.43	.88	.45	.019	.002	.50	4.83	1.17	.50	.012
4	*DHC	E	.85	.61	.28	.032	.028	.16	2.94	.30	-	.002
		I	.87	.57	.28	.031	.002	.13	2.98	.29	-	.014
5	AISI P20	E	.32	.70	.69	.022	.027	.28	1.76	.42	-	.002
		I	.36	.65	.73	.024	.013	.26	1.74	.44	-	.012
6	AISI 4340	E	.41	.27	.79	.007	.016	1.85	.81	.26	.09	.003
		I	.40	.28	.74	.007	.002	1.81	.78	.26	.07	.006
7	AISI 4340	E	.41	.27	.79	.007	.016	1.85	.81	.26	.09	.003
		I	.42	.26	.79	.010	.006	1.86	.82	.25	.08	.020
8	AISI 4340	E	.41	.27	.79	.007	.016	1.85	.81	.26	.09	.003
		I	.42	.29	.78	.009	.005	1.80	.82	.27	.09	.027
9	En25	E	.28	.23	.56	.022	.027	2.43	.62	.46	.01	.002
		I (T)	.27	.23	.57	.020	.028	2.35	.61	.45	.01	.002
		I (B)	.29	.25	.42	.023	.041	2.37	.59	.45	.01	.002
10	DHC	E	-	-	-	-	-	-	-	-	-	-
		I	.92	.62	.31	.024	.005	.11	3.04	.29	-	.016
11	DHC	E	-	-	-	-	-	-	-	-	-	-
		I	-	-	-	-	-	-	-	-	-	-
12	DHC	E	.30	.27	.62	.014	.014	2.40	.92	.59	.12	.006
		I	.30	.28	.60	.015	.004	2.32	.92	.63	.12	.009
13	AISI 4340	E	.86	.63	.26	.018	.030	.11	3.05	.28	-	.002
		I	.92	.56	.20	.020	.004	.08	3.08	.28	-	.008
14	DHC	E	.41	.27	.79	.007	.016	1.85	.81	.26	.09	.003
		I	.41	.22	.79	.009	.002	1.86	.82	.24	.08	.023
15	AISI 4340	E	.41	.27	.79	.007	.016	1.85	.81	.26	.09	.003
		I	.41	.22	.73	.007	.002	1.78	.78	.23	.08	.020
16	En25	I	.30	.26	.67	.021	.025	2.58	.65	.50	-	.018

E - Electrode Values I - Ingot Values

TABLE 3

AVERAGE WORST FIELD CLEANNESS RATING FOR EACH STEEL

Ingot No.	Slag Type	Deoxidant	Average inclusion rating			
			Type A	Type B	Type C	Type D
1	70/0/0/30/0	Al	1.00H	0.35T	-	1.05T/H
2	40/30/0/30/0	Al	0.60H	0.30T	-	0.80T/H
3	"	CaSi	0.15H	0.10T/H	-	1.50T
4	"	Hypercal	0.50H	-	-	0.90T/H
5	70/15/0/15/0	Al	1.20H	0.60T	-	1.00T
6	"	Al	0.20H	0.30T	-	1.20T
7	65/15/0/10/10	Al	-	-	-	-
8	"	Al	0.75H/T	0.35T	-	0.55T
9	"	CaSi*T	0.90H	-	-	0.85T
		B	1.50H	-	-	1.00T
10	49/17/7/17/10	Al	0.65H	0.15H	-	0.75T
11	"	CaSi	0.60H	0.10T	-	1.10T
12	"	Al/CaSi	0.50H	0.15T	-	1.00T
13	"	Hypercal	0.50H	-	-	0.80T
14	60/15/0/0/0/25B	Al	-	-	-	1.0T
15	62/10/0/17/0/11B	CaSi	-	-	-	1.5T
16	-					

*T - TOP of ingot which was resulphurised during Remelting

B - BOTTOM of ingot which was resulphurised during Remelting

TABLE 4

ELEMENTS DETECTED IN MAJOR INCLUSION TYPES FOR EACH SLAG/DEOXIDANT COMBINATION

INGOT NO.	SLAG TYPE	DEOXIDANT	MAJOR INCLUSION TYPES		
			SULPHIDES	OXIDES	DUPLEX
1	70/0/0/30/0	Al	Mn,S,Ca,Mg	Not Detected	S,Ca,Mg (trace of each) Al
2	50/30/0/30/0	Al	S,Mn,Ca (trace)	"	S,Ca Al,Mg.
3	"	CaSi	S,Mn,Ca	"	S,Ca Si,Al,Mg.
4	"	Hypercal	S,Ca,Mn	"	S,Ca,Mg,Ba (trace) Al.
5	70/15/0/15/0	Al	S,Mn,Ca	"	S,Ca Al, Mg (trace).
6	"	CaSi	S,Ca (trace)	"	S, Si,Ca Al,Mg.
7	65/15/0/10/10	Al	S,Mn,Ca	"	S, Al,Ca
8	"	Al	S,Ca,Mg (trace)	"	S,Ca (trace) S,Al,Mg.
9	"	CaSi	S,Mn,Ca (trace)	Al,Ca,Mg	S,Mn,Ca (trace) Al,O,Mg
10	49/17/7/17/10	Al	S,Mn,Ca (trace)	Not Detected	S,Ca,Mg,Al.
11	"	CaSi	S,Ca,Mg,Mn	"	S,Ca,Mg Al,Mn.
12	"	Al/CaSi	S,Ca,Mg	"	S,Ca,Mg Al.
13	"	Hypercal	S,Ca,Mg (trace)	"	S,Mg (trace) Al.Mn.
14	60/15/0/0/0 + 25B	Al	S,Ca,Ce		S,Mg,Ca,O, Al,Ce.
15	62/10/0/17/0 + 11B	CaSi	S,Ca, Ce(trace)		S,Mg,Ca, Al,Ce.
16	-	-	S,Ca,Mg (trace)	Al	S,Ca,Mg (trace) Al.

* Comsteel Deep hardening Chromium Roll steel.

TABLE 5

ANALYSIS OF DEOXIDANTS USED

DEOXIDANT	ELEMENTS								
	Al	Ca	Mn	Si	Fe	Mg	Cu	Ba	C
Aluminium	97	-	0.26	0.15	1.29	0.15	0.33	-	-
Calcium Silicide	1.0	28.8	-	62.9	4.5	-	-	-	0.14
Hypercal	22.5	9.6	-	41.8	14.0	-	-	10	-

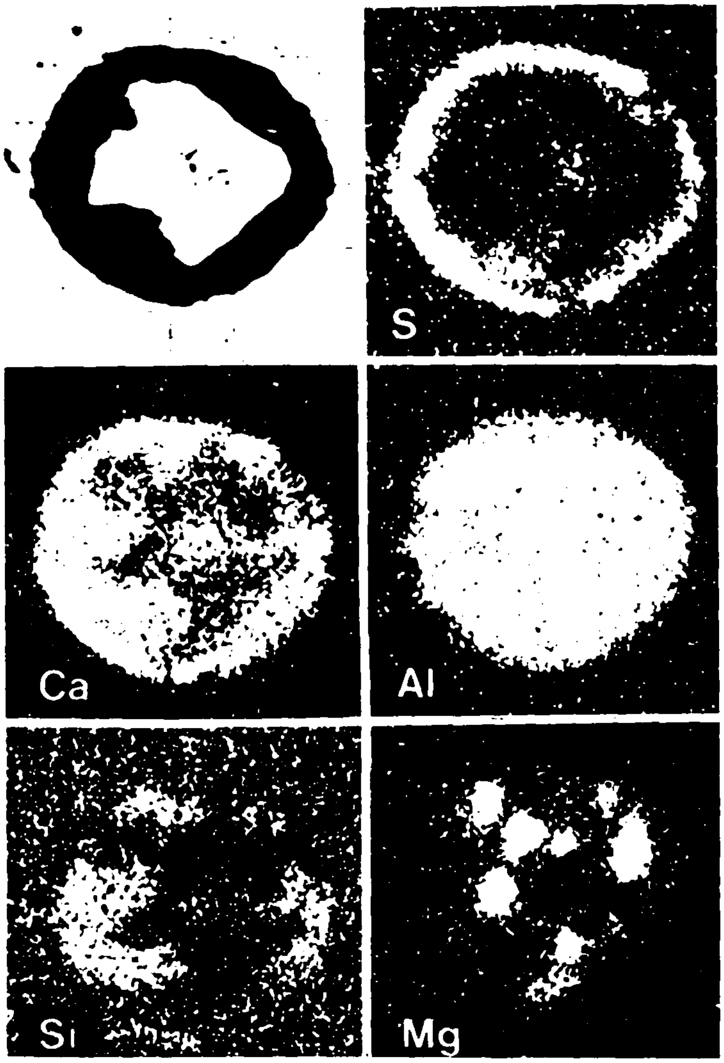

FIGURE 1 X-Ray microprobe images showing the complex nature of silicate inclusions observed in ESR steels when calcium silicide deoxidation was excessive. In this and subsequent figures, the secondary electron image of inclusion is at top left, and other images represent the element labelled. X1500.

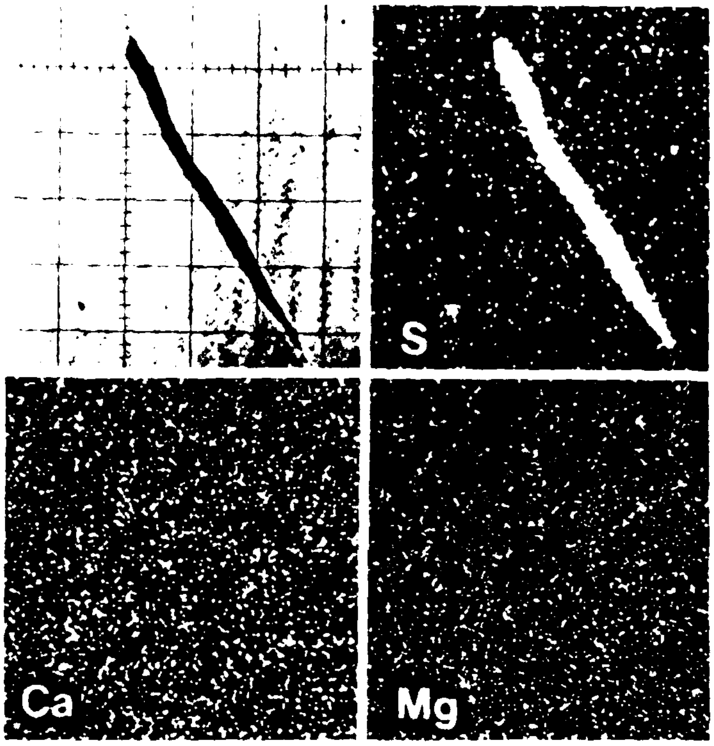

FIGURE 2 X-Ray microprobe images of a Type II sulphide inclusion which has undergone extensive deformation during hotworking. X1000.

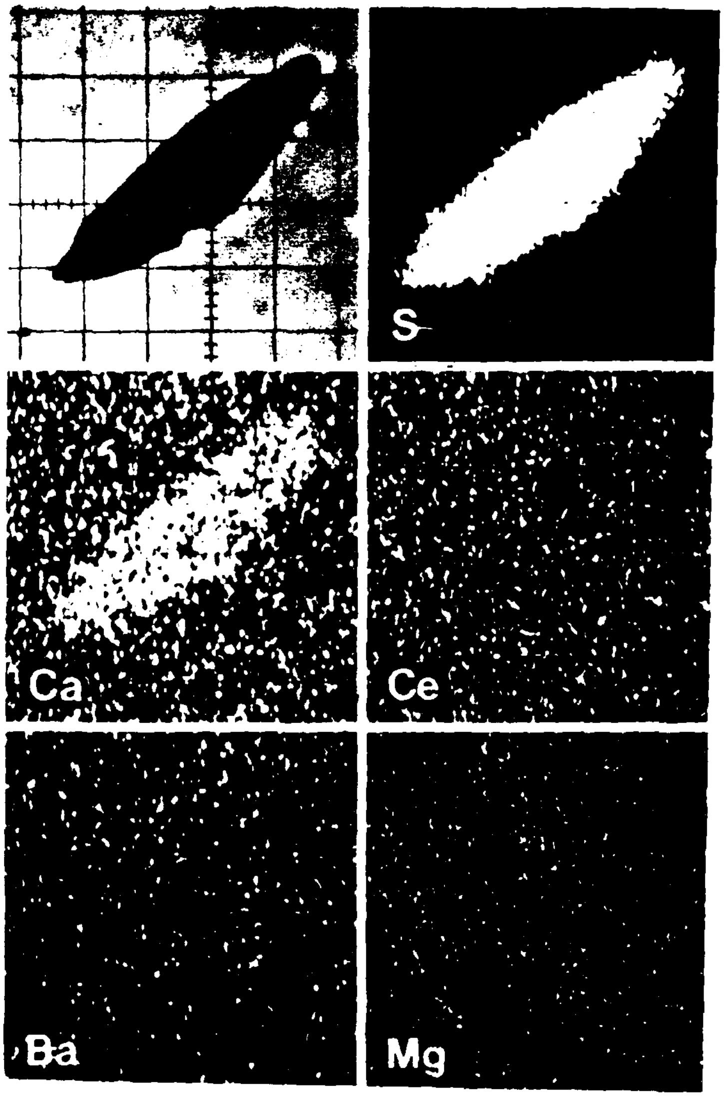

FIGURE 3 X-Ray microprobe images of a more or less deformed sulphide containing calcium often detected in the steels. X3000.

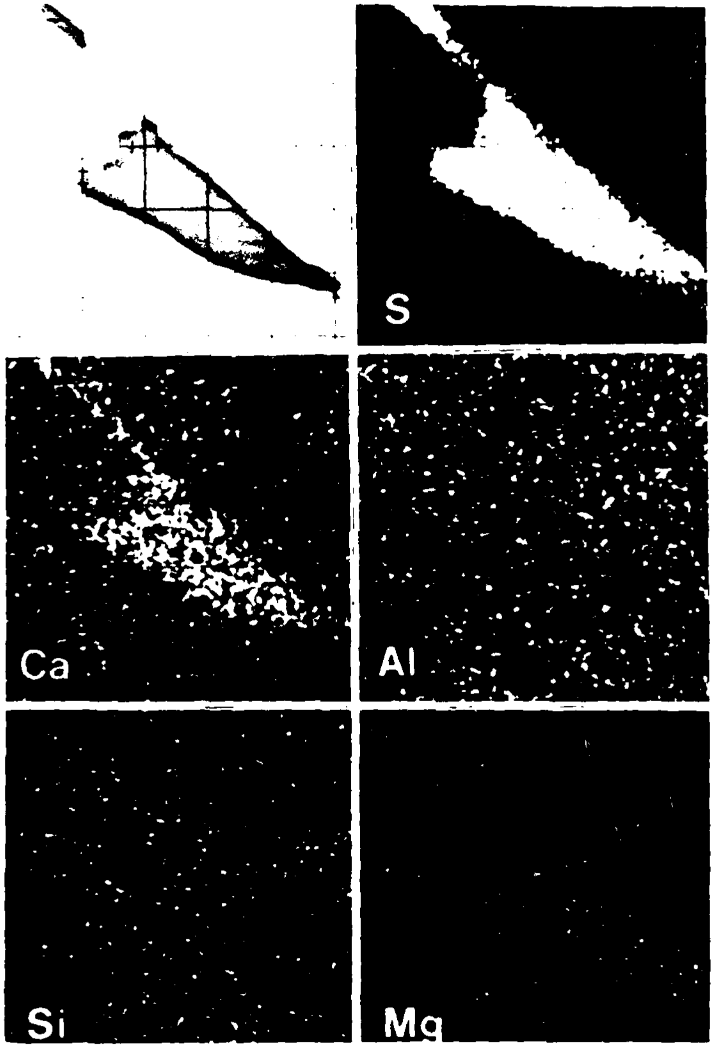

FIGURE 4 X-Ray microprobe images of a blockier sulphide inclusion containing calcium found in electric furnace steel. X1500.

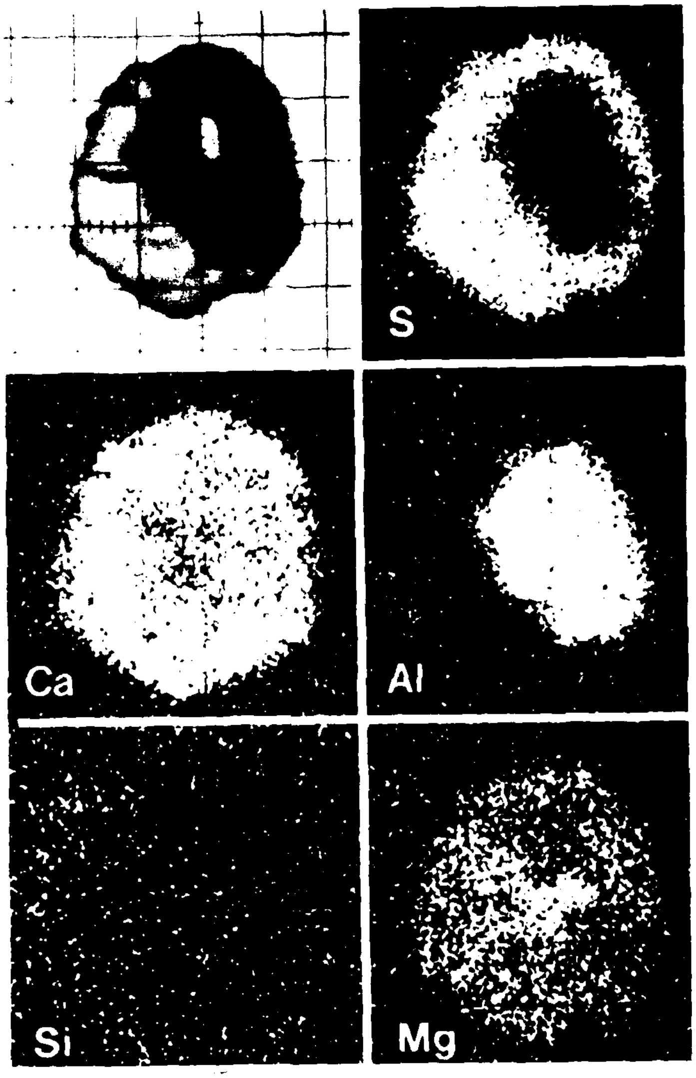

FIGURE 5 X-Ray microprobe images of a typical small modified inclusion type observed in steels remelted with conventional ESR slags. Similar inclusions would also show cerium in both the oxide and sulphide areas when using RE containing slags. X3000.

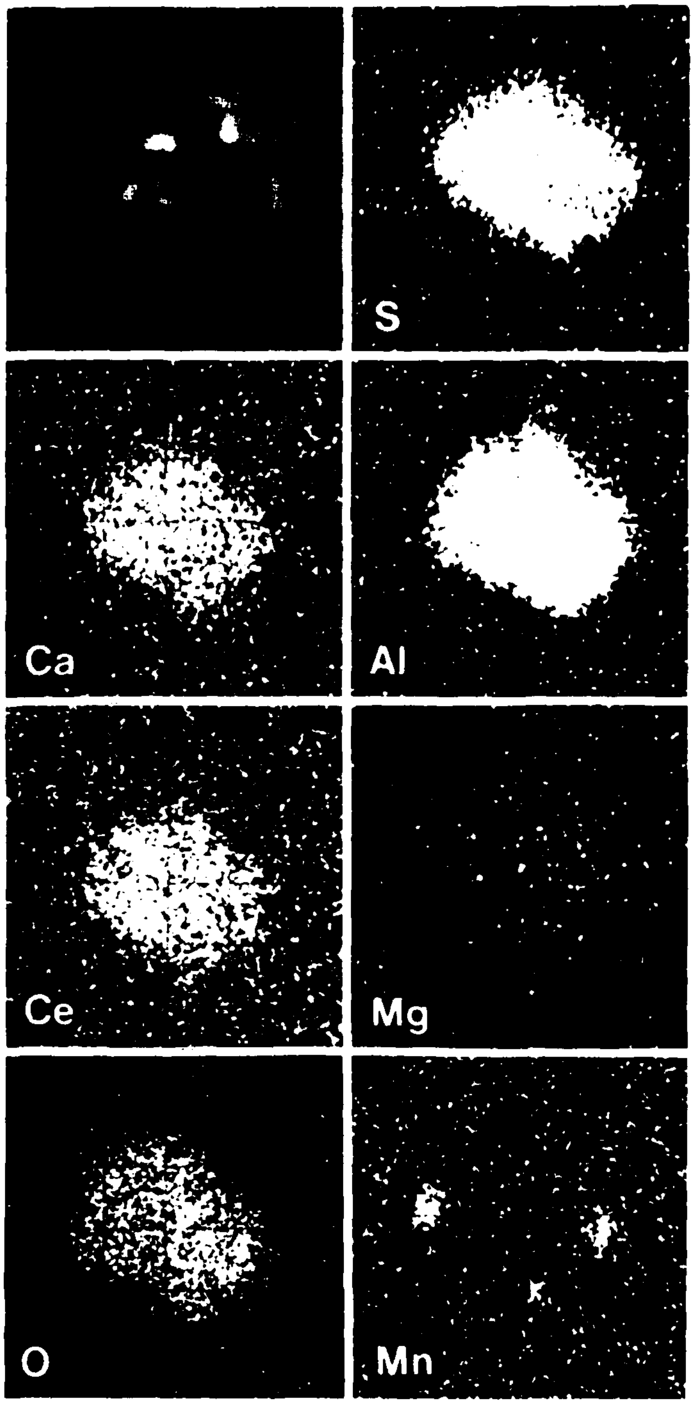

FIGURE 6 X-Ray microprobe image of a modified calcium cerium sulphide/aluminate inclusion typical of the majority of fine inclusions found in ESR steels remelted with slags containing RE oxides. X4500.

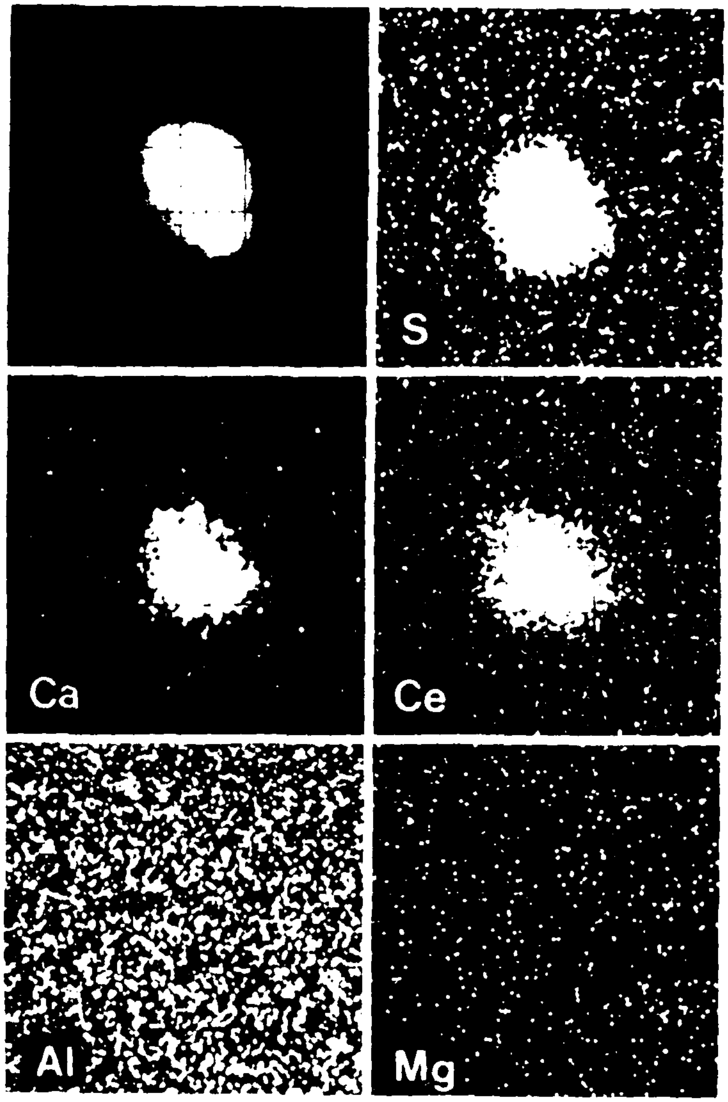

FIGURE 7 X-Ray microprobe images of a modified sulphide containing both calcium and cerium found in steels remelted under slags containing RE oxides. X4500.

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