#### EFFECTIVE ELECTROSLAG REMELTING OF SUPERALLOYS

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#### ABSTRACT

In order to take full advantage of electroslag remelting, it is necessary to optimize the most important properties, such as structure, chemical uniformity and inclusion control by careful choice of the remelt parameters, since these properties essentially determine the acceptability of the final part. The relationship between these properties and possible remelt variables such as melt mode, power level, slag chemistry and furnace atmosphere for various types of superalloy are reviewed and discussed. From the processing viewpoint, the differences between molten and solid slag starting are discussed as well as the effects of ingot structure and ingot surface on forgeability. The potential differences and similarities between the electroslag remelting process and the vacuum arc remelting process are considered and discussed.

In the past few years, electroslag remelting has gained tremendous popularity as a valuable processing technique for superalloys, tool steels and other high performance materials. The reasons for this are numerous and they will be discussed in this paper.

To set the stage, it is important that we review the history of electroslag remelting. An adequate review is given by Hoyle(1) in the book "Electroslag Refining." Table 1 depicts the historical development of the process. The gestation period was long and torturous going from principles written down in 1892 to actual research in 1935 to full scale production in a number of companies in the 1960's.

The growth of electroslag remelting furnaces is shown in Figure 1, not including Russian facilities. The number has grown from five in 1964 to approximately 65 in 1972. Of these 65 furnaces, approximately 10 are used for superalloys.

#### Equipment

Figure 2 is a general schematic diagram

showing electroslag versus a vacuum arc furnace. In general, all furnaces are somewhat similar to this. However, there are a number of variations. The mold can be short and movable resulting in a net ingot withdrawal system or the short mold can be stationary and the ingot can be withdrawn. Figure 3 demonstrates these concepts. The advantage of a withdrawal system is the simplicity of the mold and control of the post-solidification ingot cooling rate. Insulation or cooling can be applied to the portion of the ingot that has been withdrawn. Another variation is the electrical power supply. Most furnaces used for superalloy melting utilize single phase alternating current. However, a number of direct current vacuum arc furnaces have been converted to DC electroslag furnaces. DC furnaces do have advantages and disadvantages as will be discussed later in the paper.

Figure 4 shows a number of electrical variations that can and are being used to power electroslag remelting furnaces. The twin electrode configuration in the Armstrong setup is also known as the bi-filer technique. Superalloys known

# TABLE 1. HISTORY OF ELECTROSLAG MELTING

- 1. Basic principle described in book by Nickoloi Slavyanov in 1892.
- 2. First research done on small scale by Armstrong in 1928 on use of resistance-heated slag to aid melting.
- 3. First real definitive work done by Hopkins in 1935 and patent obtained in 1940.
- 4. Exploitation of ESR invention in late 1950's through Kellogg Company without great success.
- 5. Hopkins joined Firth-Sterling in 1959 and in 1962 exclusivity was lifted and a more open licensing policy was established.
- 6. Lectromelt took license in 1966 to build equipment.
- 7. Union Electric took license in 1966 to make steel.
- 8. In 1967, Stellite started melting solid solution superalloys in production and to date has melted 25 million pounds of HASTELLOY alloy X, and 50 million pounds total of superalloys and corrosion resistant alloys.

# TABLE 2. SUPERALLOYS MELTED BY ESR

# Solid Solution Alloys

- a. Nickel-base
  HASTELLOY alloys B, C, C-276, G, S, and X
  "Inconel" alloys 600, 601, 625, and 706
- b. Cobalt-base
  HAYNES\*alloys No. 25, 188 and 31
  HAYNES STELLITE\*alloy No. 6B

# Precipitation Strengthened Alloys

a. Nickel-base
"Inconel" alloys 718, 713, and IN-100
Rene' 41, 77, and 95
"Udimet" 700
"Astroloy"
Rolls-Royce C-263
AF2-1DA

<sup>\* &</sup>quot;Hastelloy", "Haynes", and "Haynes Stellite" are registered trade marks of Cabot Corporation.

to have been melted by ESR are shown in Table 2.

Another variation in electroslag furnaces is the starting technique. Either liquid slag starting is used or some version of a dry slag starting technique such as arcing against a mixture of slag and chips or slag, chips and exothermics, or resistance heating of a bar or coil that is surrounded by slag. Liquid slag starting has advantages because it gives a good butt end surface free of gas and is more reproducible than dry starting.

## ESR Parameters

Many investigators argue that ESR has an advantage over VAR because there are more parameters or degrees of freedom in the electroslag process. Conversely, one can argue that there are so many parameters that it is impossible to get reproducible control of the process. Table 3 presents an example of the degrees of freedom of ESR versus VAR. In molting of superalloys, the main parameters to control are:

- 1. Slag chemistry
- 2. Power input melt rate
- Electrode diameter/mold diameter

In melting superalloys, slag chemistries are usually based on the calcium fluoride, calcium oxide, alumina system. Calcium fluoride by itself is satisfactory except it does not possess high enough electrical resistivity to obtain good I2R heating. The addition of CaO is mainly for economical reasons, i.e., CaO is cheap and also for desulfurization. Up to 30% can be added to calcium fluoride without raising the melting point. The electrical resistance of the CaF2-CaO system is essentially the same as CaF2 thus, if higher resistance is needed, the addition of a third constituent such as Al<sub>2</sub>O<sub>3</sub> is made which effectively raises the electrical resistance without raising the melting point with additions up to 20%.

TABLE 3. ESR PARAMETERS

<u>VAR</u>	ESR	<u>Parameter</u>
х	x x	Power AC DC Polyphase Armstrong
Х	X X	Electrodes Variable shape Change-over Multiple
Х	X X X	<u>Start</u> Arc Resistance Molten slag
Х	x x x	Special Techniques Continuous withdrawal Electromagnetic stirring Tubular ingots Composites Multiple ingots
Х	X	Slag refining Vacuum purification

With alloys containing reactive elements such as Zr and Ti, some producers add ZrO<sub>2</sub> and TiO<sub>2</sub> to the slag to get the benefit of mass action, i.e., Ti + 20→TiO<sub>2</sub> where the equilibrium constant

 $K = \frac{a_{TiO_2}}{a_{Ti}}$ 

In other words, the addition of TiO<sub>2</sub> to the slag retards the oxidation of the Ti by driving the reaction to the left. This is basically a naive approach and mechanistically is wrong in many cases. In summary, for effective electroslag remelting of superalloys to take place, the slag should have in general the following characteristics:

- 1. It should be essentially non-reactive with the alloy.
- 2. It should form a smooth layer upon solidification on the mold wall to provide a good ingot surface.

3. It should react with non-metallic inclusions in the melt to remove them from the metal.

4. It should possess enough electrical resistance to obtain efficient power utilization during melting.

5. It should be inexpensive.

The power input, amount of slag and the electrode diameter/mold diameter (fill ratio) control the pool shape and thus affect segregation. Increasing the fill ratio, slag volume and voltage independently or in concert lowers the pool depth and leads to less segregation.

## Refining Reactions

In applying the Electroslag remelting technique successfully to superalloys an understanding of the potential reactions and refining mechanisms is necessary. These may be divided for convenience into flotation or mechanical removal and chemical and electrochemical reactions. There has been a significant amount of work done in the past in an attempt to determine not only the mechanisms of inclusion removal but at which of the reaction zone or zones the electrode tip, the metal droplet, or the molten-metal-molten slag interface, inclusion removal takes place. Removal of inclusions by flotation could take place either in the droplet during transfer to the molten metal pool or after it becomes part of the metal pool. It has been concluded in the past that there is insufficient time for removal of inclusions from the droplet as it descends to the molten metal pool. One can approximate, using Stoke's law, as shown in Figure 5 the size of an inclusion which might be expected to float out from the molten metal pool during electroslag remelting. The appropriate Stoke's law equation is:

$$V_i = \frac{2g r^2 (\rho_m - \rho_{inc})}{9\eta}$$

where

Vi = the terminal velocity

g = acceleration due to
 gravity

r = radius of the inclusion

m = density of the molten
 metal

Pinc = density of the inclusion

For a typical melt rate of 1,000 lbs/hr for a 20" diameter ingot one would expect to lose inclusions having a radii greater than 8 microns by flotation. One must remember that Stoke's law assumes a spherical inclusion, and also no stirring and no surface tension effects.

Inclusion removal at the molten metal molten slag interface could also take
place as a droplet contacts the molten
metal. In the AC mode a vibratory
mechanism called the "electro capillary
effect" has been proposed (2) to account
for the elimination of inclusions. This
was suggested to be the result of a
change in the surface energy as the current direction reverses causing the
interface to vibrate and thus removing
the inclusions.

The importance of inclusion removal by the flotation mechanism has been pointed out by Medovar (4) and a number of other authors (5). They stress the importance of maintaining a flat, shallow pool in order to decrease the probability of inclusions being trapped by the growing dendrites.

The second site for inclusion removal is the electrode tip. During droplet formation the greatest surface to volume ratio is seen. This increases the probability of an inclusion coming into contact with the molten slag and thus being absorbed into it. Vachugov (6) and recently Loyd (7) has shown that about 50% of the inclusion reduction takes place at the electrode tip. In this case they were considering removal of silicate inclusions in mild steel. There is, however, some questions as to

the mechanism of inclusion removal at the electrode tip; that is, whether it is by dissolution of the inclusions into the molten metal and subsequent reaction with the slag or by absorption due to mechanical contact as mentioned previously. The former seems to be quite probable for a low melting point inclusion such as sulfides. It has been proposed however by Kay, et al (8) that in fact due to the high current density at the electrode tip sufficient temperatures are attained such that the dissolution of alumina inclusions occurs as shown in Figure 6. The inclusions in the electrode are much larger than in the region which has been molten indicating that dissolution takes place at the electrode tip. The current density in Kay's case was 223.9 amp/cm2 while the normal current density seen in the large scale production electrodesis about 10 amp/ cm2. Thus, the same reasoning of a high current density resulting in excessively high temperatures at the electrode tip may not apply to production ESR units.

The dissolution of oxide inclusions at the molten metal tip implies that the degree of inclusion removal of oxides as well as sulfides is the dependent upon chemical reactions through bulk diffusion. Thus the removal and redistribution of inclusions is controlled by the following slag metal reactions.

$$(M_x O_y)$$
 inc  $\stackrel{?}{\sim} x [M] + y [O]$ 
 $x [M] + y [O] \stackrel{?}{\sim} (M_s O_y)$  slag
and
 $(M_x S_y)$  inc  $\stackrel{?}{\sim} x [M] + S$ 
 $[S] + (O^-)$  slag  $\stackrel{?}{\sim} (S^-) + [O]$ 

As can be seen the removal of oxygen by dissolution may be inhibited by the introduction of oxygen as sulfur is removed.

For steels it has been reported that sulfur losses from 40 to 85% can be realized with the use of basic slags. For superalloys where great pains are taken to insure a low sulfur content

in the electrode reductions of from 20-60% are still seen. Table 4 shows the initial and final sulfur contents for a number of superalloys which have been electroslag or vacuum arc remelted. It is noted that the sulfur levels in the ESR ingots are in general below the levels reported for the primary melt and the VAR ingots. Due to the low initial sulfur level of superalloys it is questionable whether the proposed reaction for the elimination of sulfur from the slag, thus maintaining a low sulfur activity in the slag, is of importance in this case. Even if total removal of sulfur from the ingot was accomplished there would be an insignificant increase in the activity of sulfur in the slag.

TABLE 4. SULFUR CONTENTS FOR SUPERALLOYS ELECTRO-SLAG REMELTED AND VACUUM ARC REMELTED

Alloy	Melt Mode	<u>s</u>
HAYNES STELLITE alloy No. 6B	Electrode ESR ingot VAR ingot	0.010 0.005 0.010
HASTELLOY alloy B	Electrode ESR ingot VAR ingot	0.002 0.002 0.002
HAYNES alloy No. 31	Electrode ESR ingot VAR ingot	0.008 0.007 0.009
Modified "Astroloy"	Electrode ESR ingot VAR ingot	0.005 0.003 0.005

During electroslag remelting there exists the possibility of losing easily oxidizable elements or the introduction of inclusions into the ingot by chemical reactions. In considering this it should be remembered however that it is desirable to lose elements such as silicon, titanium or aluminum during ESR if they were in the electrode initially as inclusions. However, the elimination of losses by oxidation of aluminum and titanium or other reactive elements from liquid solution during ESR is of prime

importance. The oxidation and subsequent loss of reactive elements is determined by the oxygen potential in the slag. Two of the most important variables affecting the slag's oxygen potential are: slag composition and the atmosphere above the slag. The presence of impurities in the slag which are easily reduced by the reactive elements in the superalloys will most certainly cause a loss of reactive elements. In addition, it is possible for elements which have more than one valence state to act as an oxygen pump by transferring the oxygen from the atmosphere to the molten metal interface as shown in the following equation for iron oxide:

$$2(\text{FeO}) + \text{O}_2 \rightleftarrows (\text{Fe}_2\text{O}_3)$$
  
Slag-Atmosphere Interface

Similar reactions can be proposed for the oxides of manganese or titanium in the electroslag remelting of superalloys. It is thus necessary to eliminate all impurity oxides from ESR slags which are to be used for melting superalloys. Another source of oxygen is surface oxidation of electrodes just above the slag bath. The use of an argon cover over the slag will eliminate electrode oxidation and reduce the po2 above the slag bath thus eliminating or minimizing the oxidation. It has been shown by Medovar (4) that the loss of reactive elements is essentially eliminated by employing an inert atmosphere.

In addition to this, the proper choice of the remelting flux can minimize elemental loss since the loss is controlled by the following reactions

$$x[M] + y [O] \stackrel{>}{\sim} (M_XO_V)$$

Thus if the activity of the oxide in the slag is increased by the addition of M $_{\rm O}$ , the thermodynamic driving force is lessened. At this time the theory of slags is not sufficiently developed

to enable accurate calculation of the appropriate activities.

In the foregoing discussions we have neglected potential electrochemical reactions, i.e., assumed that the remelting was accomplished using the AC mode and that no rectification occurred. Some electroslag remelting however is carried out using converted vacuum arc remelting units with DC power source and thus one must consider in this case the potential electrochemical reaction. Hoyle, et al (1), Medovar, et al (4), and Cameron (9) have reported that a significant amount of rectification takes place during AC ESR; therefore, even in this mode it is necessary to be aware of potential electrochemical reactions. Medovar, et al (4) has reported differences in degrees of refinement depending upon the melt mode use. They report that the greatest decrease in oxygen content is seen with reverse polarity, i.e. electrode positive and that the removal of sulfur is enhanced by the AC mode. Holzgruber (10) suggests that electrochemical effects due to current density considerations may become insignificant in production ESR units. He in fact, as shown in Figure 7, reports a reversal in the oxygen content of ESR ingots for decreasing melt mode as the size of the ingot increases. He ascribes this to the difference in current density and thus an insufficient EMF to induce electrochemical reactions. He concluded the reversal was due to the electrochemical reaction only taking place at the electrode tip for large diameter ingots with relatively small fill ratios. Electrochemical reactions such as the elimination of oxygen, however, depend upon the dissolution of the inclusions as discussed previously. It must be realized however that harmful reactions such as the introduction of oxygen into the ingot during electroslag remelting do not depend upon dissolution of inclusions and most in fact are enhanced if inclusions are formed.

The presence of electrochemical reactions and their effect in electroslag remelting has been demonstrated by Klein (11) for HASTELLOY alloy X. The material used

for the investigation had been previously electroslag remelted in the AC mode and was essentially inclusion free. Upon remelting in the AC mode no change in reactive elements or inclusion content was seen but for the DCSP mode a significant loss of aluminum and silicon and an increase in oxygen content of the ingot was observed as shown in Table 5. The loss of aluminum was a result of oxygen being deposited at the anode, the molten slag - molten pool interface, and then reacting with the aluminum and/or silicon in the molten metal by the following reaction:

$$(0^{-}) \stackrel{?}{\leftarrow} [0] + 2e \text{ anode}$$
  
2 [A1] + 3 [0]  $\stackrel{?}{\leftarrow} (Al_2 o_3)$ 

The inclusions thus formed are either dissolved into the slag thus resulting in a loss of aluminum or are trapped in

the molten metal pool resulting in an increase in the number of inclusions in the ingot as exhibited in Figure 8. In superalloys the presence of large amounts of deoxidents such as aluminum essentially eliminates the large over potential reported by Mitchell (12) for iron by keeping the oxygen activity at a very low level in the molten metal bath. This implies that the difference in melt rate and pool depth as reported for the DC SP modes may be a result of other reactions. One possible source is the oxidation of the species electrochemically plated out at the cathode by the oxygen in the air. This reaction taking place at the electrode tip could result in a very efficient use of the energy from this exothermic reaction and thus increase the melt rate. In addition the oxidation of aluminum in the molten metal bath also is highly exothermic and would contribute to the

TABLE 5. RESULTS OF CHEMICAL ANALYSIS FOR SELECTED ELEMENTS A1, Si AND O COMPARED TO ELECTRODE VALUES OF 0.15, 0.45 AND 0.002 RESPECTIVELY

			Electrode Diameter					
			<u>4-3/</u>	4 Inches		6	-Inches	
Melt <u>Mode</u>	<u>Position</u>		10	14	Slag We: _18_	ight _ <u>10_</u>	14	18
AC	Butt End	Al Si O	0.14% 0.41 0.002	0.15 0.45 0.002	0.08 0.39 0.002	0.15 0.43 <0.002	0.10 0.42 0.002	0.13 0.45 0.003
	Hot Top	Al Si O	0.10 0.44 0.002	0.08 0.42 <0.002	0.08 0.21 0.002	0.10 0.42 0.003	0.11 0.43 0.002	0.11 0.42 0.003
DSCP	Butt End	Al Si O	<0.01 0.23 0.020	<0.01 0.025 0.019	0.03 0.21 0.007	0.07 0.39 0.004	0.11 0.27 0.004	0.11 0.39 0.002
	Hot Top	Al Si O	<0.01 0.20 0.014	<0.01 0.017 0.013	<0.01 0.23 0.009	0.05 0.36 0.003	0.06 0.35 0.005	0.08 0.38 0.002

heat input of the system and a deeper pool.

Thus it is extremely important in electroslag remelting to consider the possible electrochemical reactions and their resultant effects on the superalloy ingot. The choice of the improper remelt practice will result in an ingot of significantly inferior quality.

#### Hot Workability

One of the major reasons for the success of electroslag remelting is the improvement in the hot workability of the ESR ingot over that of VAR or direct forged ingots. This difference has been shown to be significant as illustrated in Figure 9 by Kelley (13) for "Udimet" alloy 700 in an investigation sponsored by the Air Force. A doubling of the hot working range over that of the direct forged or VAR ingot was seen. The test which has been used to measure hot workability with great success at Stellite is the Gleeble test. The Gleeble unit can be programmed such that the specimen being tested experiences the same thermal cycling as in forging. At the appropriate time a high strain rate tensile test is performed with the reduction in area of the sample being taken as a measure of its hot workability. A similar hot workability increase was seen by Pridgeon, et al (14) for a number of other alloys including HASTELLOY alloy B and F and the Gleeble curves are shown in Figures 10 and 11.

The increased hot workability as a result of electroslag remelting is due to a number of factors. In ESR the slag above the molten metal pool may absorb inclusions as previously discussed and thus one does not find the porous inclusion rich surface layer around the circumferance of the ingot as normally seen in VAR ingots. As a result, in general, VAR ingots must be ground to remove this layer before forging thus generating a significant amount of low grade grindings.

Kelley, et al (15) as seen in Figure 12, has shown for HASTELLOY alloy X that inclusions are more effectively removed in ESR than in VAR and moreover the remaining ones are significantly finer and more randomly disposed. For the ESR and VAR ingots 86.1% and 49.3%, respectively, had inclusion ratings of D 1/2 T or less. This result was significant at the  $\alpha$  = 0.01 confidence level.

Secondly, the pool shape of the ESR ingot is significantly shallower than that of a correspondingly VAR ingot resulting in a vertically oriented macrostructure which is more suitable for side forging. The result of pool depth measurements (14) for ESR and VAR experimental ingots with similar melt rates are given in Table 6 for HASTELLOY alloy B, F and HAYNES alloy No. 31. As can be seen the ESR ingot has a much shallower pool and thus a more vertically oriented macrostructure. The effect of slag weight, melt mode and fill ratio on pool depths in electroslag remelting was shown by Klein (11) as seen in Table 7. As can be seen increasing the slag weight results in decreasing the pool depth. An increase in fill ratio while not decreasing the total pool depth results in a much flatter pool with a more vertically oriented macrostructure. The shallowest pool is obtained using the DCRP melt mode while the DCSP results in the deepest with the AC mode being as expected inbetween.

The other two important factors effecting the hot workability of superalloys are the sulfur content and the chemical homogeneity, i.e., segregation. It is well known that the presence of sulfur can cause incipient melting and thus poor workability. The use of ESR results, in general, in lower sulfur contents which should result in better workability with corresponding increases in the Forge Shop recovery. It has also been shown that segregation is significantly reduced in electroslag remelting. By employing good remelting practice the massive segregation commonly known as "freckles" sometimes showed in vacuum arc remelted ingots are eliminated. This is especially important when remelting alloys which are quite prone to "freckle" formation such as "Inconel" alloy 718.

TABLE 6. POOL DEPTH AND COLUMNAR CRAIN GROWTH ANGLE MEASUREMENTS FOR ESR AND VAR INGOTS

	ESR		VAR		
Alloy	Pool Depth(1) Inches	Columnar Grain <sup>(2)</sup> Growth Angle <u>Degrees</u>	Pool Depth <u>Inches</u>	Columnar Grain Growth Angle Degrees	
HASTELLOY alloy B	2.7	23.0	3.3	43.0	
HASTELLOY alloy F	2.6	20.0	3.4	45.0	
HAYNES alloy No. 31	2.1	15.5	2.8 <sup>(3)</sup>	-	
HAYNES STELLITE alloy No. 6B	2.2	13.0	2.8(3)	-	

- (1) 30/32-inch was added to each ESR measurement to allow for the liquid alloy present below the bath surface next to the solidified slag layer.
- (2) Growth angle was measured as the angle between the direction of growth and the longitudinal axis of the ingot.
- (3) Depth was estimated from shrinkage defect in the top of the ingot. The columnar grain size was too small to obtain a good measurement of growth angle.

TABLE 7. POOL DEPTH MEASUREMENTS FOR 8-INCH DIAMETER "HASTELLOY" ALLOY X INGOTS

	,	Electrode Diameter 4-3/4 Inches 6-Inches					
<u>Melt</u>	<u>Position</u>	10 lb.	111	Slag W <u>18</u>	eight 10	114	18
AC	Center	2.38"	2.13	2.00	2.50	2.30	2.15
	Difference	1.01	0.96	0.90	1.10	1.03	0.93
DCSP	Center	3.09	2.28	2.88	4.78	4.43	4.06
	Difference	1.81	1.09	0.44	2.91	2.44	1.81
DCRP	Center				1.97	1.78	1.65
	Difference				0.97	0.92	0.88

In can be concluded from the above discussion that as a result of a combination of a number of favorable factors the hot workability of ESR ingots is superior to that of either the direct forged or VAR ingots.

## **Properties**

In order for the ESR material to be marketable its microstructure and properties must be superior or at least comparable to that produced from a VAR ingot. In selecting a processing technique for a particular type of material one considers not only the average property of the material produced from that ingot but also the reproducibility of that particular property of interest. i.e. standard deviations. The reproducibility of this particular property is a function of the inclusion level and the homogeneity of the ingot and its processing history. The superior chemical uniformity and reproducibility of the ingot as a result of the electroslag remelting compared to the VAR process was statistically shown by Kelley, et al (15). For a large number of production heats of HASTELLOY alloy X they determined the variation between the primary and remelt chemistries as shown in Table 8. For seven of the ten elements considered the material produced from the ESR ingot exhibited a smaller or equal deviation from ladle analysis than material produced from a corresponding VAR ingot. This greater chemical uniformity of the ESR ingot had a significant effect on the resultant mechanical properties as shown in Table 9. As is seen the average mechanical properties of the HASTELLOY alloy ESR material were greater than the corresponding VAR properties. Statistically the average ultimate tensile strength and reduction in area results are significantly different at greater than the  $\alpha = 0.01$  confidence level. While the other two properties are also reported higher, they are not statistically significant at the  $\alpha = 0.01$  level. Probably most important, however, is the standard deviation since most design criteria is based on the -3 olimit. The standard deviations in the mechanical properties of the ESR material are again

less than the standard deviations of the corresponding properties reported for the VAR material and all but that for the yield strength are significant at the  $\alpha$  = 0.01 confidence level.

Cook, et al (16) have reported chemical analysis and mechanical property data for a number of superalloys. It was the object of their investigation to prove the equivalence of the ESR produced material to that of VAR; thus a limited number of tests were run and for the alloys under study: HAYNES alloys No. 600, 625, 750 and L605 (HAYNES alloy No. 25) their results show that the ESR superalloy is at least equivalent to the VAR vacuum-arc remelted material.

A comparison of the mechanical properties of "Astroloy" from material produced by ESR and VAR is shown in Table 9. The properties of this alloy like in Cook's investigation are essentially equivalent. The same is true for the stress rupture properties shown in Table 10.

#### Summary

It has been shown that to successfully apply the electroslag remelting technique to superalloys an understanding of potential reactions and a knowledge of the processing parameters is necessary. Among the most important considerations are:

- Effect of slag chemistry on retention of oxidizable elements.
- 2. Role of electrochemical processes in inclusion control.
- Control of atmospheres above slag to minimize oxygen potential.

If the proper choice of electroslag remelting conditions is made the resultant ingot has been shown to have superior workability and product superior or at least equivalent mechanical properties to material produced by vacuum arc remelting.

TABLE 8. DEVIATION OF BILLET FROM LADLE ANALYSIS

	Analysis	ESI		VAR	-
Element	Error	<u>ā (%)</u>	od (%)	<u>ā</u> (%)	σ <sub>d</sub> (%)
Cr	0.27	0.05	0.20	0.09	0.24
Fe	0.27	<u>0.09</u> *	0.18	0.03	0.13
Мо	0.15	-0.01	0.06	0.02	0.07
Co	0.07	0.02	0.06	0.02(5)	0.07
Si	0.04	-0.011*	0.02(5)	0.007	0.03
C	0.01	0.000	0.01	-0.002	0.01
Mn	0.04	0.010	0.04	-0.002	0.02
W	0.04	<u>-0.020</u> *	0.03(5)	<u>-0.016</u> *	0.03
S	0.003	0.0000	0.000(6)	0.0002	0.001(5)
P	0.004	0.0002	0.002	0.0008	0.003
n		3	33	5	7

 $<sup>\</sup>bar{d}$  = Billet Minus Ladle Analysis

<sup>\*</sup>  $\bar{d} \neq 0(\alpha = 0.01 \text{ for yes decision})$ 

TABLE 9. HOT ROLLED BAR ROOM TEMPERATURE TENSILE TEST RESULTS (CODED DATA)

	U.T. (ksi		0	.2% Y.S (ksi)	• ·	Elong _(%)	-	R. (%*	
ESR $\overline{X}$ (n = 107) $\sigma$	+ 0.4			- 0.34 2.0		+ 2.5 2.9		+ 0. 2.	
$VAR \overline{X} $ $(n = 101)\sigma$	- 0.6 3.4			- 0.88 2.3		+ 1.9 4.7		- 0. 3.	
S.M. $\overline{X}$ (n = 104) $\sigma$	+ 0.2 3.3	•		+ 1.22 2.9		- 4.4 3.4		- O.	
<u>Tests</u>		Sig.	<u>a</u>	Sig.	<u>a</u>	Sig.	<u>α</u>	Sig.	<u>a</u>
$\overline{X}$ (ESR) vs. $\overline{X}$ (ESR) vs. $\underline{\sigma}$ (ESR) vs. $\underline{\sigma}$ (ESR)	VAR) S.M.) S.M.) S.M.)	Yes Yes No Yes Yes No	0.01 0.01 0.05 0.01 0.02 0.05	No No Yes Yes Yes Yes	0.05 0.05 0.01 0.01 0.01	No Yes Yes Yes Yes	0.005 0.01 0.05 0.01 0.01	Yes Yes Yes Yes No Yes	0.01 0.01 0.01 0.01 0.05 0.05

<sup>\*</sup> Data transformed to normalize distribution

TABLE 10. COMPARISON OF TENSILE PROPERTIES OF ESR AND VAR "ASTROLOY"

	Temp.	U.T.S. (psi)	0.2% Y.S. (psi)	Elong. (%)	R.A. (%)
ESR	RT	206,500	149,600	21.8	21.2
VAR	RT	207,300	150,100	22.1	22.5
ESR	1400	162,500	127,500	19. <sup>)</sup>	32.9
VAR	1400	158,000	124,700	17.4	28.0

TABLE 11. STRESS RUPTURE PROPERTIES OF ESR AND VAR "ASTROLOY"

	Temp.	Stress (psi)	Life <u>(hours)</u>	Elong.
ESR	1400	85,000	40.4	23.2
VAR	1400	85,000	41.6	21.0

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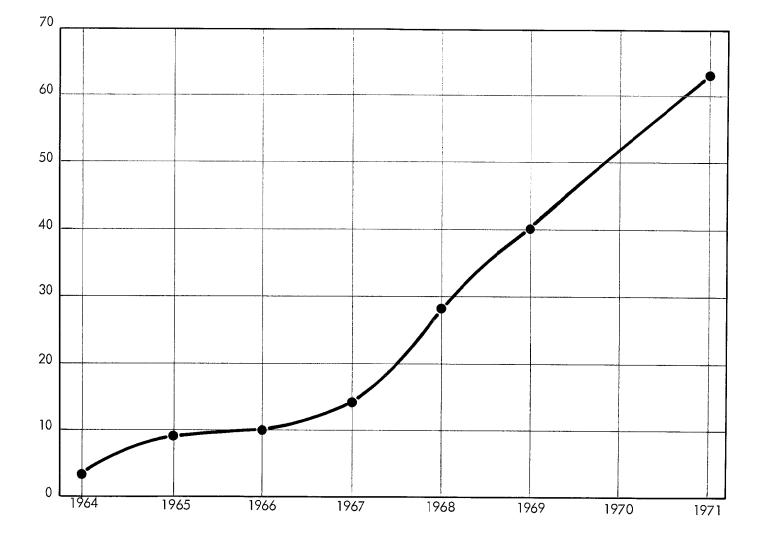


Figure 1. Growth of ESR furnaces throughout the world excluding Russia. (1)

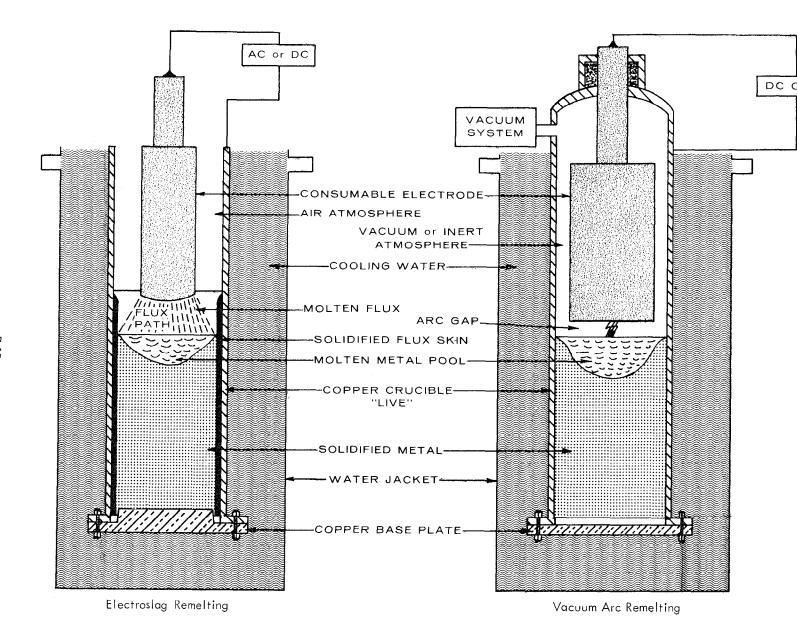


Figure 2. Comparison of ESR and VAR furnaces.

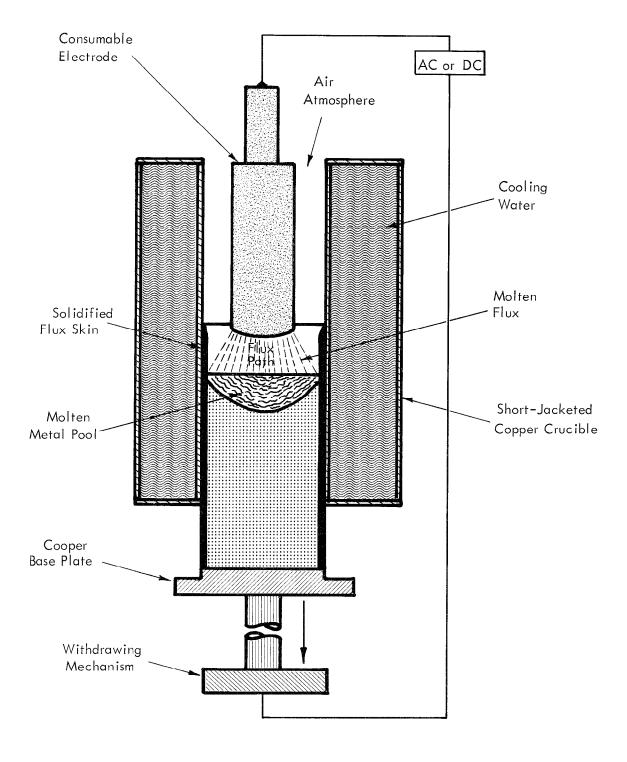
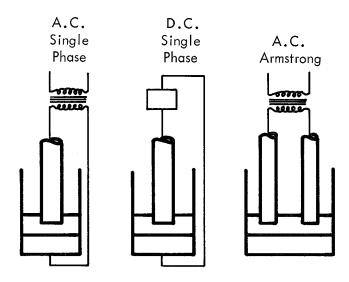


Figure 3. Electroslag Remelting using withdrawable ingot mechanism.



A.C. Three Phase

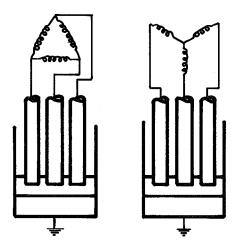


Figure 4. Power supplies for electroslag refining.

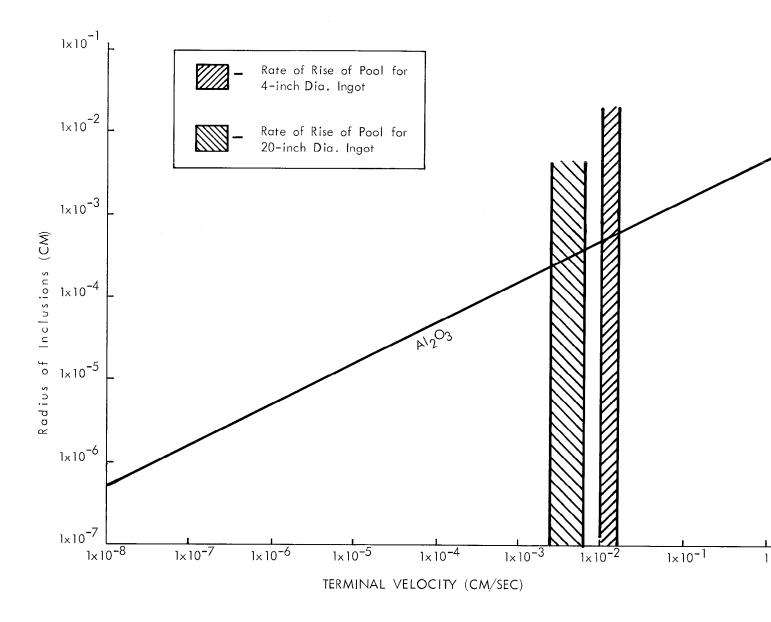


Figure 5. Stoke's Law Calculation for Al<sub>2</sub>O<sub>3</sub> inclusions in superalloys

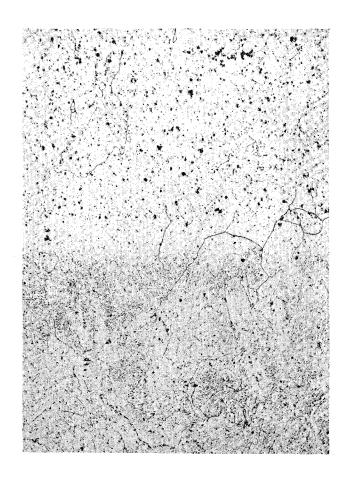


Figure 6. Dissolution and reprecipitation of inclusions at the electrode tip.

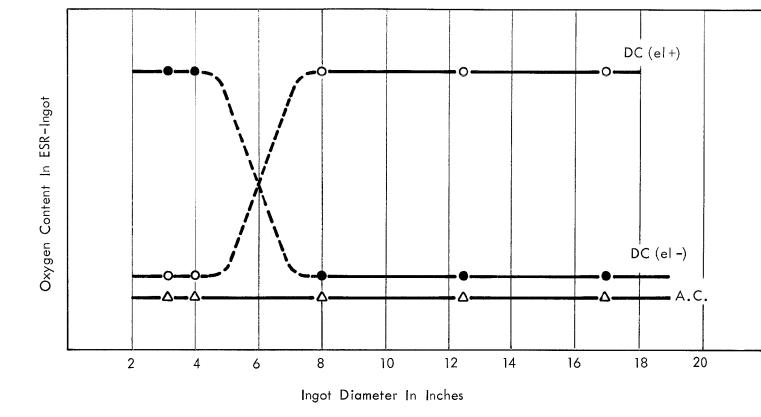
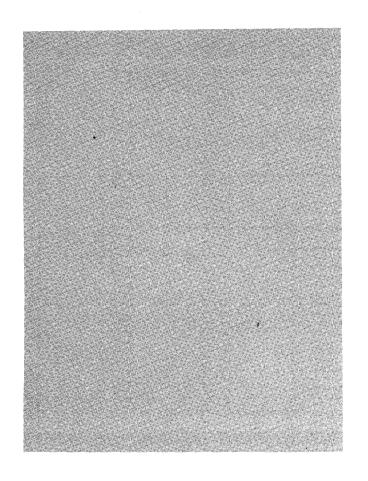
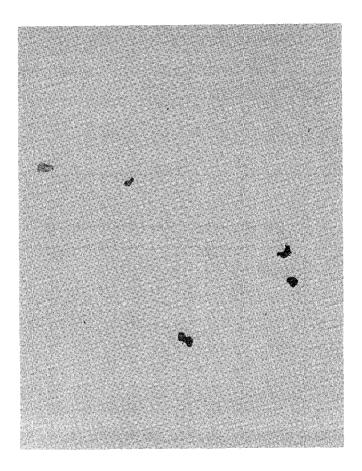


Figure 7. Oxygen content of electroslag remelted ingots as a function of ingot size and melt mode.





(a) (b)

Figure 8. Effect of Melt Mode on Inclusion Content of  ${\sf HASTELLOY}^{\circledR} \ {\sf alloy} \ {\sf X} \ ({\sf 500X}) \ ({\sf a}) \ {\sf AC} \ {\sf Mode} \ \ ({\sf b}) \ {\sf DCSP} \ {\sf Mode}$ 

Figure 9. Gleeble Hot Ductility of U-700 Alloy.

Figure 10. Gleeble Hot Ductility of HASTELLOY® alloy B

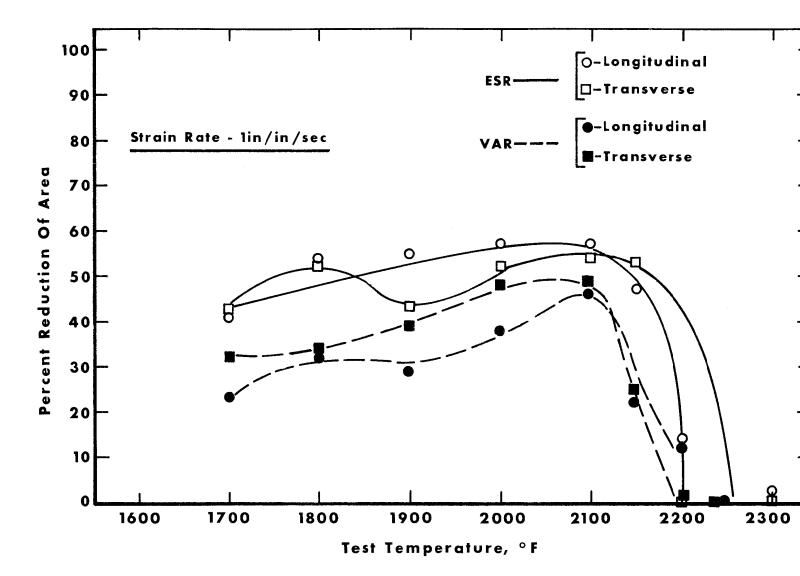


Figure 11. Gleeble Hot Ductility of HASTELLOY® alloy F

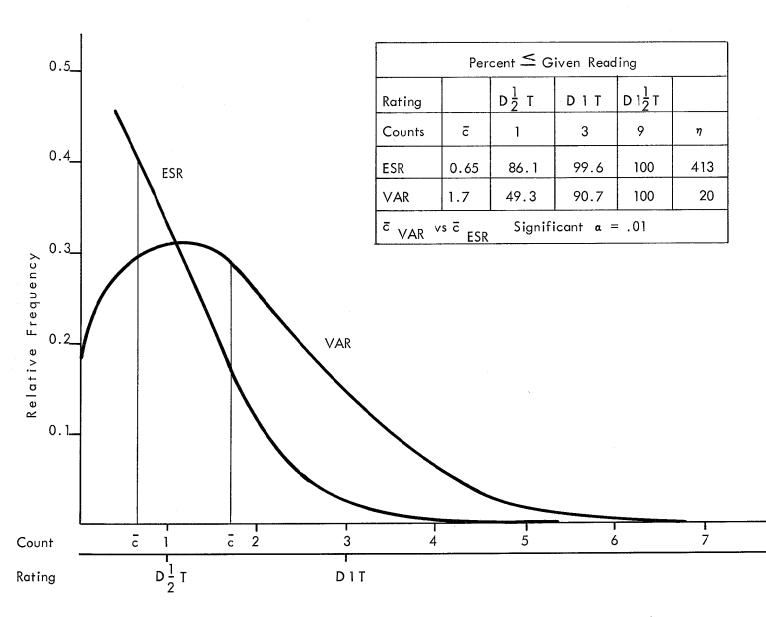


Figure 12. Distribution of oxide inclusion ratings for 0.040-0.080-inches sheet.