Directional Solidification of Aluminum-Nickel Eutectic Alloys Using Electroslag Remelting

P. K. ROHATGI, A. K. BHUTANI, AND K. P. ABRAHAM

Attempts were made to produce directionally solidified, specifically grain aligned Al-6 wt pct Ni eutectic alloy using a laboratory scale ESR unit. For this purpose sand cast alloy electrodes were electroslag remelted under different mold conditions. The grain structure of the ingots obtained from these meltings showed that insulated silica molds gave the best vertical alignment of grains along the length of the ingot. The $NiAl_3$ fibers within the grains tended to fan out and there was only a preferred alignment of fibers along the growth direction under the conditions of our experiments. The ESR parameters most suitable for vertical alignment of eutectic grains have been identified. In some electroslag remelting trials ingots were grown on a seed ingot. This resulted in a fewer vertical grains compared to the case when no seed ingot was used. The sand cast specimen of the eutectic exhibited a maximum tensile strength of around 88.2 MN/m^2 (9.0 kg/mm^2) whereas conventional ESR using water cooled mold gave strength value of 98.0 MN/m^2 (10 kg/mm^2). The directionally solidified ESR material showed longitudinal tensile strength as high as 213.7 MN/m^2 (21.8 kg/mm^2) which could be further increased to 220.6 MN/m^2 (22.5 kg/mm^2) by using the seed ingot. The average growth rate was varied between 5 to 25 mm/min during electroslag remelting in this study. The flow stresses, tangent modulus and ultimate tensile strength of directionally solidified eutectic increased with increasing growth rates.

ALLOYS which freeze with a eutectic reaction can be directionally solidified to produce fibrous or lamellar composites in which one of the eutectic phase reinforces the other phase. Frequently the techniques generally used for directional solidification are similar to those used to grow single crystals. These involve either normal freezing, which is the Bridgeman or Stockbarger method, or zone melting. All these processes require very high purity starting materials and/or very low solidification rates. Moreover special experimental techniques are needed to grow eutectic composites of nearly ideal microstructures. These factors tend to render the production of directionally solidified eutectics relatively difficult and expensive on an industrial scale. There have also been some attempts[1,2] to study the properties of eutectic alloys where there is only a preferred alignment of fibers instead of perfect alignment.

This study explores the possible use of laboratory scale electroslag remelting equipment for growing directionally solidified composites from eutectic melts. The Al-Al_3Ni eutectic system was selected for this study, since this system has been studied quite extensively, for producing directionally solidified composites by the conventional techniques.

The ESR method of growing directionally solidified composites is likely to have the following advantages over the normal freezing or zone melting methods heretofore employed:

1) Very steep temperature gradients can be readily obtained due to the large superheat in the molten metal droplets and high slag temperatures.

2) Large diameter samples could be readily produced. The large thermal capacity of the system could make it relatively free from thermal fluctuations.

3) The possibility of some refinement of alloy droplet as it falls through the slag layer is an attractive feature. This may allow the use of relatively impure starting materials in some cases.

4) It may be possible to start with a mechanical mixture of the elements, which constitute the eutectic. It is not necessary to have it in the prealloyed form.

5) Electroslag remelting variables can be changed to readily get a large change of freezing rates.

6) Arrangement to withdraw the ingot can be readily made, to make the process continuous or semicontinuous.

7) It is also possible, that with modification of the mold, a far greater degree of directionality of solidification would be obtained.

In spite of these obvious advantages, the production of perfectly aligned ideal structures is not likely to be an easy task by the ESR technique, specially when the starting materials are not high purity.

The objectives of the present work were limited a) to observe the kind of directionality obtained during normal ESR, b) to evaluate the possible methods which can be used for improving the directionality of solidification, and c) to study the effect of improved directionality on mechanical properties.

In the present work alloy electrodes of the eutectic composition were electroslag refined under controlled conditions with a view to identify the conditions favorable for obtaining directionally solidified ingots, with near vertical alignment of grains and eutectic fibers. The mechanical properties of the ingots were measured after electroslag remelting.

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PREVIOUS WORK

Research on electroslag remelting has been concerned primarily with process development and studies on the refining action of the slag. Solidification process during ESR has received only limited attention. The following is a brief review of the work on directional solidification using electroslag remelting technique.

According to Duckworth and Hoyle[3] a high degree of control is possible in solidification process during ESR. Low power, highest voltage permissible, and a deep slag pool induce a thick skin on the mold and vertical freezing. The converse effect, radial solidification is produced by high currents and low voltages, high melt rates and shallow slag baths. Also, a high ratio of electrode diameter to ingot mold diameter helps to promote a desirable shallow metal pool.

Edwards and Spittle[4] using molds that were not water cooled showed that the solid-liquid interface was fairly flat during electroslag remelting of aluminum alloys. These authors performed experiments on a 25 kW experimental unit operated on AC. A high purity Al-Cu alloy was melted in a fused silica mold using LiCl-KCl slag of eutectic composition. They found that the average temperature throughout the bulk of the slag was uniform and the temperature gradient in the molten metal pool decreased as the solid-liquid interface approached. The following are some of the important conclusions drawn by them:

1) Very little natural stirring takes place in the metal pool.

2) Metal pool depth is proportional to the slag temperature and pool depth is determined to a major extent by heat transfer to the pool by the metal droplets which fall through the pool.

Sullivan *et al*[5] suggested that slag cover introduces an additional variable into the ingot solidification process. It acts as a thermal barrier which promotes unidirectional heat flow. It also tends to even out the thermal gradients from the center to outer edge of the mold leading to shallow pool, thus giving nearly vertical columnar grain structure. The most critical effect of the slag as it relates to the ingot structure is associated with the presence of a solid slag layer which comes in contact with the cylindrical head of molten alloy. This prevents accumulation of large superheats in total metal pool leading to a pool profile which is shallow.

Johnson and Hellawell[6] have directionally solidified lead-tin eutectic in transparent silica molds using the ESR technique. Within certain zones of the ingot produced, the eutectic structure was regular and the platelets aligned, similar to that which can be produced by conventional directional solidification.

The above literature review indicates that there has been some work on methods of promoting columnar grain growth during electroslag remelting. However this work has been mainly on steels and there has been no serious attempt to obtain perfectly aligned grains or single crystals by the ESR process. Specifically there has been no work reported on the electroslag remelting of aluminum base eutectic alloys including Al-Ni eutectic alloys. The literature indicates that there is a good possibility of obtaining conditions required for directional solidification of eutectics by controlling the ESR parameters.

EXPERIMENTAL PROCEDURE

Materials

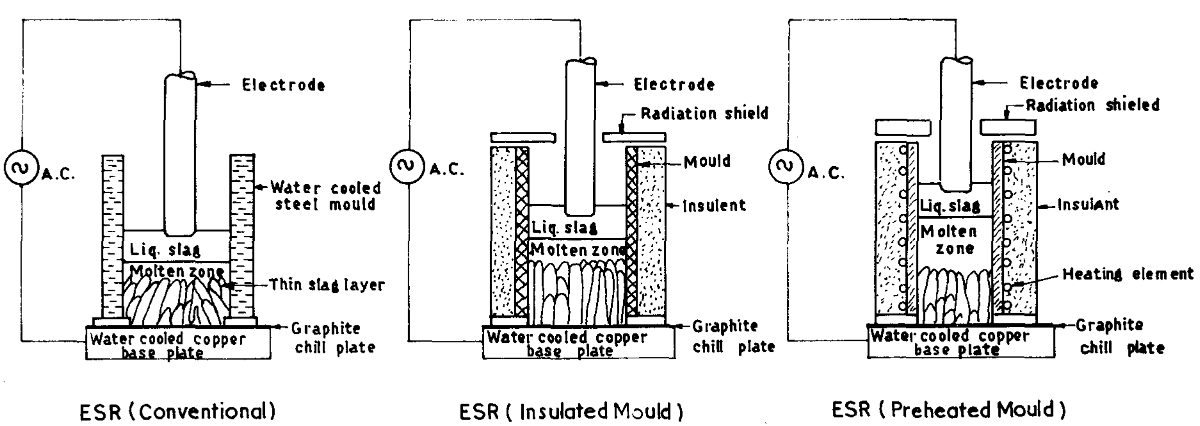
1) Commercial Aluminum a) 98.5 pct pure
   b) 99 pct pure
2) Commercial variety Nickel – 96.5 pct pure
3) Nickel shots – 99.99 pct pure

Slag Materials

Slag materials consisted of laboratory grade cryolite (Na_3AlF_6) and analytical grade potassium chloride (KCl) and lithium chloride (LiCl).

Preparation of Electrode from Impure Material

Preliminary studies were carried out using relatively impure materials. The first step was preparation of alloy electrodes in the form of rods. For this purpose aluminum rods with 5.8 to 6.4 wt pct nickel (96.5 pct pure) were made by air melting low purity Al (98.5 pct pure) and commercial variety nickel in clean graphite crucibles. An oil fired furnace was used for melting, and the melt was held at a temperature of about 900°C for half an hour to ensure com-



(*a*) (*b*) (*c*)

Fig. 1—Schematics of: (*a*) conventional ESR and (*b*) and (*c*) other possible ways of obtaining controlled grain growth by this technique.

plete mixing. Just before pouring at about 700°C, the melt was efficiently degassed using hexachloroethane pellets and then sand cast in the form of 2.0 to 3.8 cm diam rods.

Preparation of Electrodes from Purer Material

Some electrodes were also made with purer nickel shots (99.9 pct Ni) and 99 pct pure aluminum. A master alloy was initially made and subsequently used for the preparation of alloy rods of eutectic composition. The melting procedure was the same as described above. The alloy electrode was analyzed for uniformity of composition along the length, and the nickel content was found to be 6.02 pct. There was no appreciable fluctuation in the chemical composition along the length.

The experimental work was therefore carried out with the starting electrodes made of a) low purity eutectics and b) higher purity eutectics. It should be noted that the purity of the materials used in both cases is considerably lower than that used conventionally for directionally solidifying perfectly aligned eutectics. The present project as already stated was mainly to check the ability to align the eutectic grains using electroslag remelting technique.

Electrode

Most of the sand cast electrodes were dressed to a size range 1.8 to 3.5 cm in diam; some electrodes with diameter larger and smaller than this were also used for remelting. The electrodes after discarding the shrinkage pipe were generally 50 to 55 cm long.

Mold

Three types of molds were used in the present work:

1) Ordinary tapered steel molds with and without water cooling arrangement.

2) Preheated molds with provision for heating the side wall to 500°C.

3) Insulated molds.

Molds ranging in internal diameter from 3.6 to 6.5 cm were used for different experiments.

Slag

In majority of the experiments, the slag used was a mixed chloride-fluoride type containing 30 wt pct Na_3AlF_6 (cryolite) + 30 wt pct KCl (potassium chloride) + 40 wt pct NaCl (sodium chloride). This slag melts around 600°C and can be superheated to more than 1000°C depending upon the power input across the slag. Few initial melts were also carried out using low melting all chloride slag of eutectic composition. 45 wt pct LiCl (lithium chloride) + 55 wt pct KCl (potassium chloride). Prefused slag was used in all cases to avoid any moisture, which may lead to hydrogen pick-up, and porosity in the ingots. The slag was prefused around 700°C in graphite crucibles, and was crushed and stored in air tight containers before use.

Electroslag Remelting Procedure

The investigation was carried out on the laboratory scale electroslag remelting unit shown in the Fig. 1(*a*). Both solid and liquid slag starting techniques were adopted to initiate the melting operation. Limited work using water-cooled and non-water cooled steel molds, for melting this alloy, indicated that thick slag layer around water-cooled mold did not prevent radial heat loss from the mold to any large extent. Attempts were made to prevent radial heat flow using preheated and insulated molds (Fig. 1(*c*) and (*b*)). A fairly flat interface was visible when thin translucent silica tube was used. The insulated mold was supported on a 4 mm thick protecting graphite disc placed on top of the water-cooled base plate. The liquid metal pool, its depth, temperature and thermal gradients were adjusted by power input, rate of electrode feed, quantity and type of slag used and rate of water flow to the base plate during melting.

Approximate estimates of average rates of growth of the solid metal were obtained by dividing the total ingot height by total freezing time. The total freezing time was determined by adding the time during which the power is as on (or the melting time) and the time taken for the last liquid metal pool to solidify after the power was switched off. The latter was measured by inserting a thermocouple in the liquid metal pool below the slag surface. Generally the time taken for freezing of the last liquid was of the order of 1 to 2.5 min, the highest values obtained with preheated molds. The average growth rates varied between 0.5 to 2.5 cm/min, these rates are considerably higher than the rates commonly used[7] (0.6 to 19 cm/h) for growing directionally solidified $Al-Al_3Ni$ eutectics.

Directional Solidification Using Seeding Method

Another variable investigated in the present study was the use of a seed ingot during melting of purer eutectics. A transverse slice (10 mm thick and 5.5 cm diam) of an ingot, directionally solidified from a previous ESR run was used. This slice was cut from the upper portion of the ingot where a good degree of directionality was observed. The slice or the seed ingot was placed on the bottom chill, the mold was fixed on top of the seed ingot, and subsequently melted electrode was progressively grown on top of the seed ingot. A portion of the seed ingot initially melts before growing back. Again a transverse slice was cut from the ingot obtained from this experiment, from the same zone. This new slice was used as seed ingot for the next run. In other words a series of three ingots were grown 1) without any seed ingot, 2) with seed from ingot 1), and 3) with seed from ingot 2).

Electroslag Remelted Ingots

The majority of the ingots made by electroslag process were 3.6 to 5 cm in diam and 9 to 15 cm long, although a few initial ingots remelted in water-cooled steel molds and steel molds without cooling were in the range of 5.4 to 6.3 cm diam. The ingots of low purity eutectics, higher purity eutectics, and those made with seed ingot were examined macroscopically

Table I. ESR Parameters and Other Details of the Melting Operation

Heat No.	Slag Composition	Slag Wt., g	Current, Amp	Voltage, V	Average P.I., KVA	Electrode Diam (d) cm	Ingot Diam, (D), cm	Fill Ratio, d/D	Ingot Length, cm	Melting Time, min	Average G.R. mm/min	Mold Description
						1) Low Purity Eutectics						
1	A type	350	800-850	30-35	25.0	3.8	6.3	0.6	15.0	15.0	–	1.5 cm W.T., 6.5 cm ID water-cooled tapered steel mold.
2	A type	200	700-750	23-28	18.0	3.2	5.4	0.6	10.0	8.0	–	1 cm W.T., 5.7 cm ID tapered steel mold.
3	A type	300	200-250	20-25	5.0	2.8	4.4	0.64	15.0	18.0	5.0	1 cm W.T., 4.7 cm ID pre-heated graphite mold. Inside mold wall temp. = 500°C.
4	A type	150	120-150	15-20	2.5	1.8	3.6	0.50	12.5	10.0	10.0	6 mm W.T., 3.8 cm ID insulated silica mold.
5	B type	150	100-150	18-20	2.5	1.8	3.6	0.50	12.5	15.0	7.5	6 mm W.T., 3.8 cm ID insulated silica mold.
						2) Higher Purity Eutectic						
6	A type	200	500-550	18-20	10.0	3.3	4.8	0.70	15.0	6.0	5.25	6 mm W.T., 4.9 cm ID insulated silica mold.

Slag composition: i) 30 wt pct Na_3AlF_6 + 30 wt pct KCl = denoted as A type slag.
ii) 45 wt pct LiCl + 55 wt pct KCl = denoted as B type slag.
P.I.–Power Input, W.T. = Wall thickness, G.R. = Growth Rate, ID = Internal diam.

and microscopically and their mechanical properties were measured.

Specimen Preparation

Specimens from the ingots were prepared for macro- and microstructural studies in the following manner.

The entire ingot was cut in two halves in longitudinal direction, and one half after grinding was polished to secure a smooth surface. The polished surface was macroetched using fresh concentrated Kellers reagent for 15 to 30 s. Some transverse sections of the ingots grown on the seed ingots were also macroetched using the same procedure. The macroetched sections were photographed which revealed the grain size and orientation of the specimens. The other half of the ingot was used for preparing specimens for microscopic examination and mechanical testing.

Mechanical Testing Procedure

Standard tensile specimens (test section diam = 6.401 to 6.426 mm, gage length = 22.708 mm) from the cast and the directionally solidified ingots were tested to fracture in tension using Hounsfield Tensometer, the elongation was measured by the movement of the crosshead. In directionally solidified specimens, the tension axis of the specimen was parallel to ingot axis, that is parallel to the growth direction. Samples from directionally solidified ingots were taken from the central portion of the ingot.

RESULTS AND DISCUSSIONS

The details of all the ESR ingots including melting parameters are given in Table I. The superheat in the liquid metal pool below the slag layer varied anywhere from 300 to 400°C above the melting point of the alloy in the case of mixed chloride-fluoride slags (A type), and about 100 to 200°C in the case of all-chloride eutectic slags (B type).

Conditions at the Chill Face

Good contact of the chill with the ingot bottom is very important for directional heat flow. Irregular surfaces at the bottom of the ingots indicating poor heat flow were observed when solid slag starting technique was used. A thin slag layer was observed on the chill face and growth of the ingot frequently took place from this insulating slag layer. The slag layer can be reduced in thickness or eliminated by employing a high fill ratio (Electrode/ingot diam ratio) and by minimizing the arcing period by raising the power input to the system. In spite of this it was observed that for controlled columnar grain growth, conditions at the chill face were critical and solid slag starting technique was not suitable to achieve good columnar structure and alignment. This problem was completely overcome by use of liquid slag starting technique and by employing high fill ratio and average power input to the system. Long, directionally solidified, columnar grains, could be grown under these conditions. Low fill ratios and very low power inputs resulted in poor surface quality of ingot bottom and contact with the chill, even with liquid slag start.

Macrostructures of Ingots

The macrophotographs of longitudinal section of ingots prepared from low purity eutectics corresponding to heat numbers 1 to 5 (Table I) are shown in Figs. 2 and 3, and for purer eutectics in Fig. 4 corresponding to heat number 5 (Table I). The macrophotographs of the longitudinal section of ingot grown on seed ingot are shown in Fig. 5.

Macrostructures of Electroslag Remelted Ingots Made from Low Purity Electrodes

Solid slag starting technique was used in the growth of ingots made from low purity eutectics by ESR technique. In all the experiments a graphite starter plate (4 mm thick) was placed on the bottom chill on which the ingot solidified. The following describes the macrostructures of low purity eutectics.

Figure 2(*a*) shows the macrophotograph of longitudinal section of an ingot which was electroslag remelted using a conventional ESR set up including a water-cooled steel mold. The macrostructure shows large equiaxed grains in the central portion of the ingot. The grains near the base plate and the mold wall were relatively more columnar and finer.

Figure 2(*b*) shows the macrostructures of the longi-

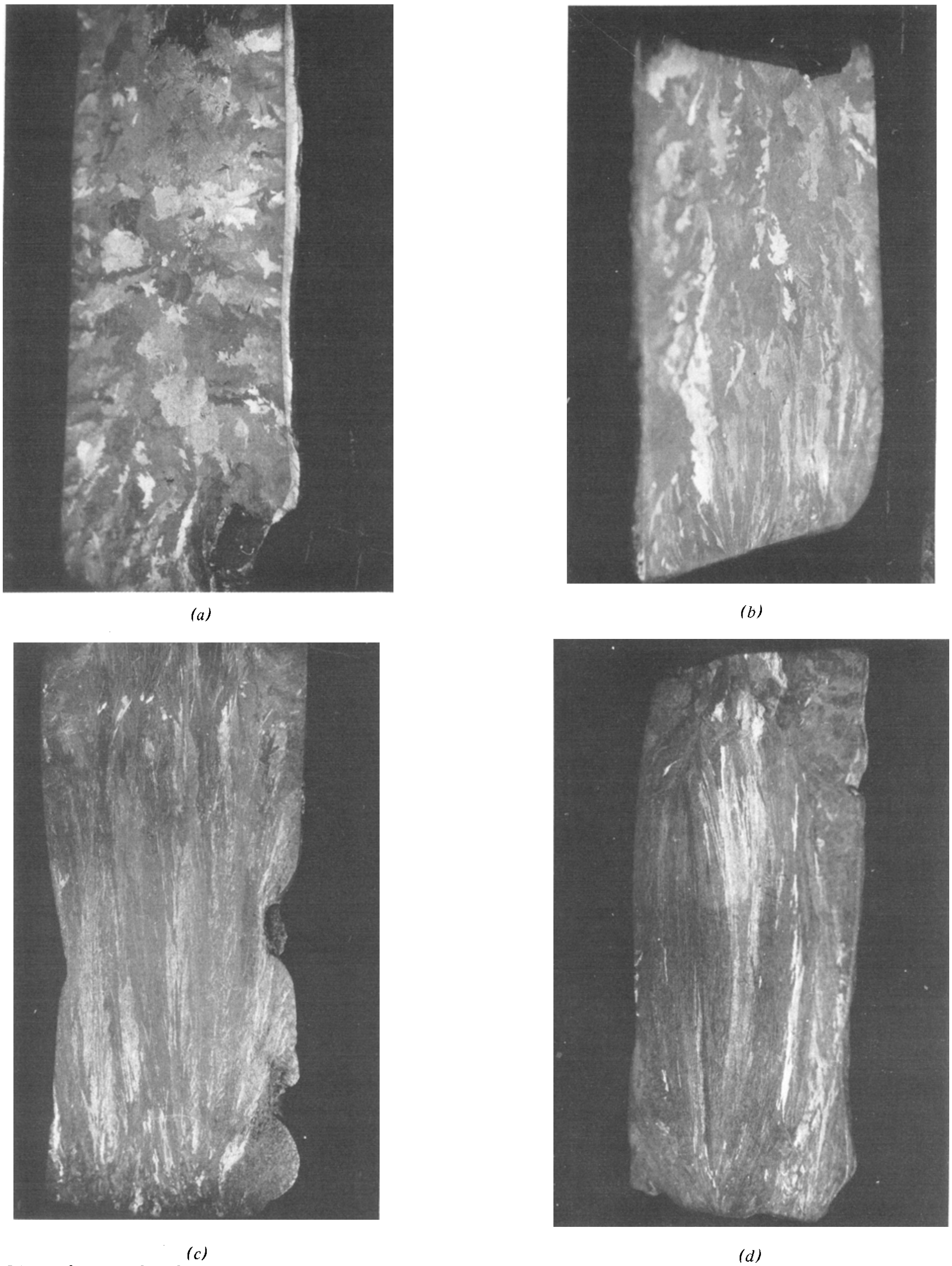


Fig. 2—Macrophotographs of longitudinal section of electroslag remelted ingots grown in: (*a*) water cooled steel mold, (*b*) steel mold which was not water cooled, (*c*) preheated graphite mold, and (*d*) insulated silica mold (low purity eutectic and A type slag).

tudinal section of the ingot grown in a mold which was not water-cooled. In this experiment, the grains were largely columnar as compared to Fig. 2(*a*) when water-

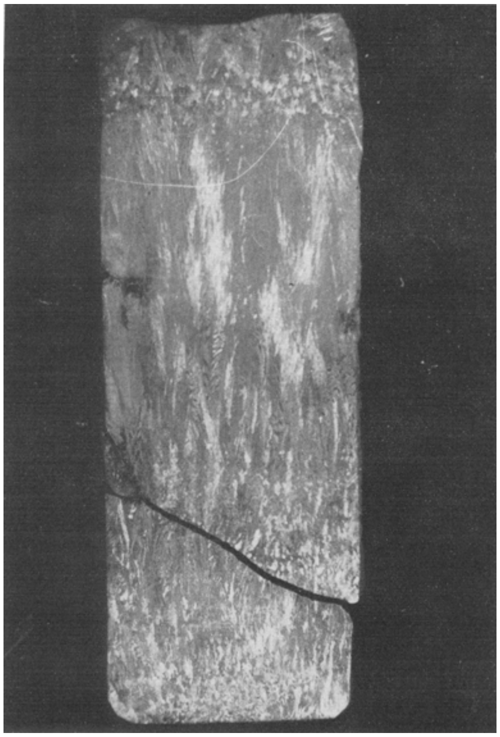


Fig. 3—Macrophotograph of longitudinal section of an electroslag remelted ingot grown in insulated silica mold (low purity eutectic and B type slag).

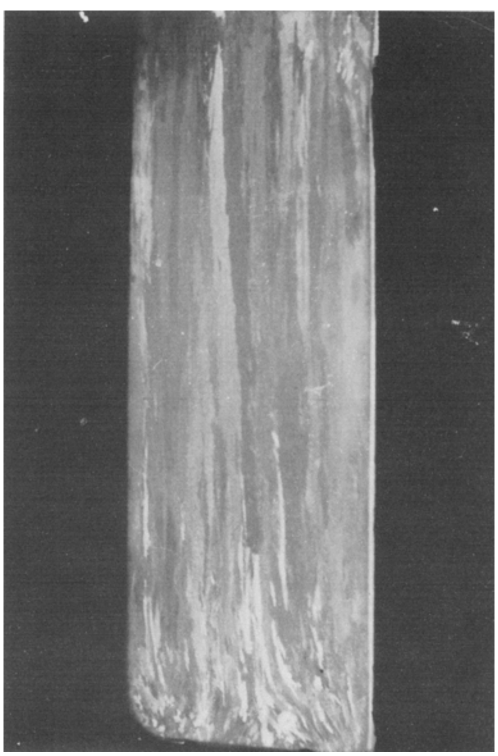


Fig. 4—Macrophotograph of longitudinal section of an electroslag remelted ingot grown in insulated silica mold under optimum conditions (higher purity eutectic and A type slag).

cooled steel mold was used and specially the columnar grain growth in the proximity of the chill was better.

Figure 2(*c*) is the macrophotograph of the ingot grown in a preheated graphite mold. The macrostructure shows columnar grains fanning out from the chill and extending over large lengths of the ingot. In this case there is hardly any evidence of the grain growth from the mold walls. Due to preheating of the mold, the slag superheat temperature was quite high and the rate of melting was very fast; however the rate of solidification was rather slow.

Figure 2(*d*) is the macrophotograph of an ESR ingot grown in an insulated silica mold. Long columnar grain growth took place which had some tendency to fan out. There is some evidence of grains growing from the mold walls near the periphery of the ingot.

All the macrostructures described above relate to the use of mixed chloride-fluoride (A type) slags. Figure 3 is the macrophotograph of ingot which was produced by carrying out melting in a silica mold using all chloride (B type) slag. The slag could be melted relatively easily even at low power inputs and arcing time was short which resulted in good ingot bottom surface quality and contact with the chill. This led to a much finer grain structure near the chill surface, as compared to the structure when A type slag was used. This ingot made using low melting B type slag also shows transverse bands near the bottom of the ingot, apparently due to low superheat and instantaneous freezing of small volumes of liquid as they were generated. A distinct transverse band is also observed near the top of the ingot characterizing the end of ESR operation. These bands were not observed when using A type of slag because large quantity of liquid metal pool with high gradient and superheat existed, this large liquid metal pool did not freeze at a rate drastically different from the base ingot. While melting, a red glow was visible outside the silica tube in the hot zone and this glow indicated that small, almost flat, liquid metal pool advanced as the electrode melted when using B type slags and true ESR conditions prevailed. However with A type slags large quantity of liquid metal accumulated at the bottom and solidification process started only at a later stage during melting.

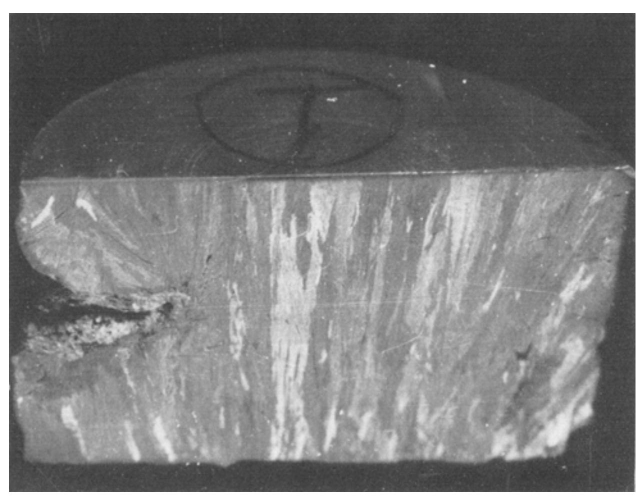


Fig. 5—Longitudinal section macrostructure of an ESR ingot grown on seed ingot (higher purity eutectic and A type slag).

In view of the above, it was decided to use insulated silica molds, a high fill ratio, average power inputs and disproportionately large volumes of A type high melting slag in subsequent experiments. Preheated molds were not used because of very high rates of melting in these molds. Preheated molds also led to frequent arcing between the electrode and the slag and unstable melting conditions. An additional disadvantage was that they led to very deep liquid metal pools with very low thermal gradients; this condition is undesirable for directional solidification of eutectics.

Macrostructure of Electroslag Remelted Ingots Made from Higher Purity Electrodes

After standardization of conditions for good directional growth using low purity electrode, further experiments for growth of aligned grains were carried out using higher purity electrode and liquid slag starting technique. Insulated silica mold was used in this experiment. As is clear from Fig. 4 it was possible to align grains along the length of the ingot. The grains extended almost the whole length of the ingot and had relatively less tendency to fan out under the optimum conditions. This experiment gave by far the best alignment of grains.

Macrostructure of High Purity Eutectics Grown by Seeding Method

It is expected that increasing the diameter of the grains (and therefore reducing the number of columnar grains) will lead to a better alignment of $NiAl_3$ fibers and an increased strength of the composite. The lesser the number of grains, lesser will be the chance of fanning of fibers near the grain boundaries.

In an attempt to reduce the number of grains, in the ingot, limited experiments were carried out using seed ingots from a previous ESR run at the bottom of the mold. This seed ingot partially melted under the liquid slag, and further growth took place on the already existing coarse grains (Fig. 5) the grain boundaries in the unmelted seed are frequently extended into the freshly growing ESR ingot. This eliminated the nucleation of a very large number of randomly oriented grains at the bottom of the ingot, and resulted in larger grains.

A gradual increase in the grain size was observed using seed ingots by comparing the macrophotographs of the transverse sections from the same points of identically grown ingots. A seed ingot taken from the first ingot section was used to grow a second ingot, and the seed ingot from the second ingot was used to grow a third ingot. The progressive increase in the grain size suggests that if single composite crystals of Al-Al_3Ni eutectic with perfectly aligned $NiAl_3$ fibers, were used as seed ingot, one would get very large grains with improved alignment of $NiAl_3$ fibers in ESR melted ingots. As will be shown in the section describing mechanical properties, the highest ultimate tensile strength value in the direction of grains was obtained with the use of seed ingot implying better alignment of fibers in fewer grains.

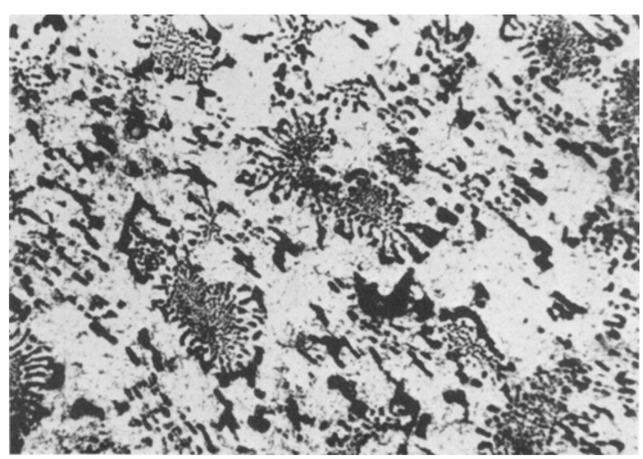
Microstructures

A microstructural examination of the longitudinal Fig. 6(*a*) and transverse sections Fig. 6(*b*) of the higher purity eutectic ingot (corresponding to Fig. 5) shows that within the grains there was partial alignment of $NiAl_3$ fibers which had some tendency to fan out. The $NiAl_3$ fibers at the colony boundaries were coarse and had irregular plate type morphology. The regions between the colonies were predominantly α-aluminum. In general, the alignment of $NiAl_3$ fibers was poorer in the ingots made from low purity electrode material. This apparently was due to more extensive breakdown of the solid-liquid interface in the presence of impurities. In low purity eutectics the angle of misorientation between fibers varied from 5 to 20 deg within the eutectic colony depending upon the growth rate and the impurity.

Mechanical Properties

Majority of the samples were prepared with their lengths parallel to the length of the ingot, and the

(*a*)



(*b*)

Fig. 6—Microstructures of higher purity eutectic ingot (corresponding to Fig. 5): (*a*) longitudinal direction, (*b*) transverse direction. Magnification 174 times.

properties of these bars will be referred to as longitudinal properties. Limited number of samples were prepared with their lengths perpendicular to the length of the ingot and the properties of these bars will be referred to as transverse properties since the direction of grain boundaries and fibers is at angles close to 90 deg to the tensile axis.

Tensile Strength Results

i) Eutectics Made From Low Impurity Materials. The sand cast samples exhibited an average tensile

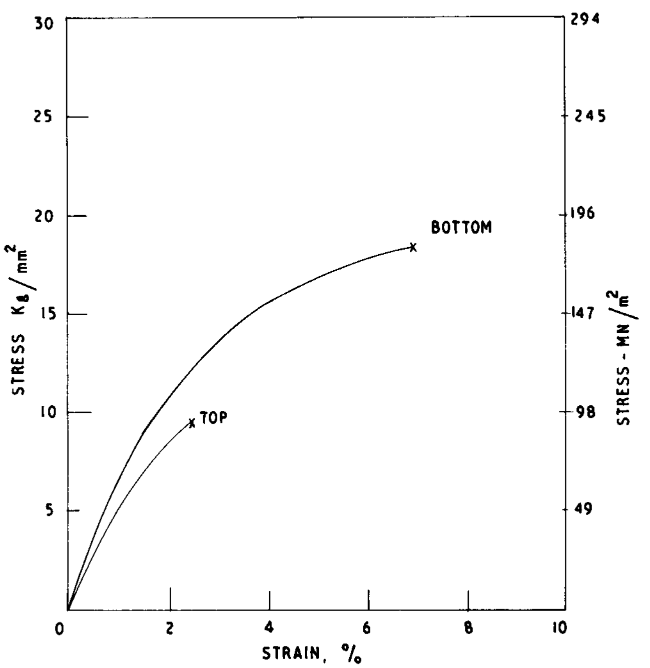


Fig. 7—Stress-strain behavior of Al-Al_3Ni eutectic specimen from two different portions of an electroslag remelted ingot.

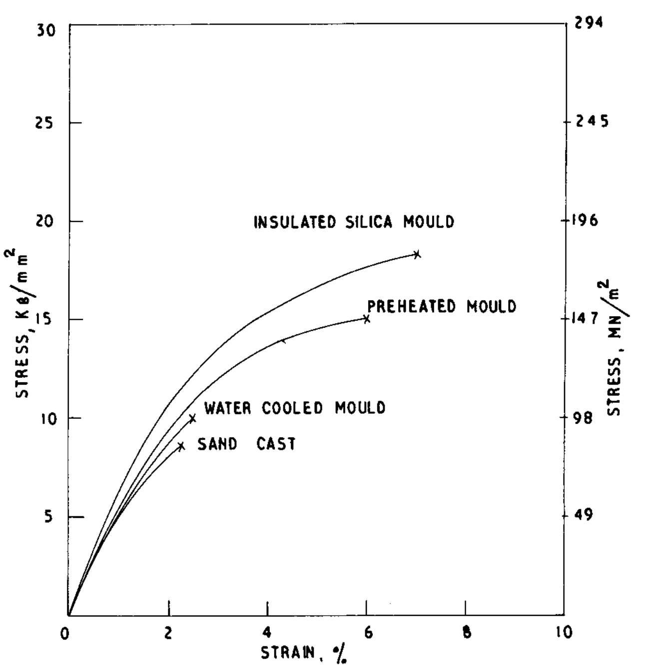


Fig. 8—Stress-strain behavior of electroslag remelted Al-Al_3Ni specimens under different mold conditions.

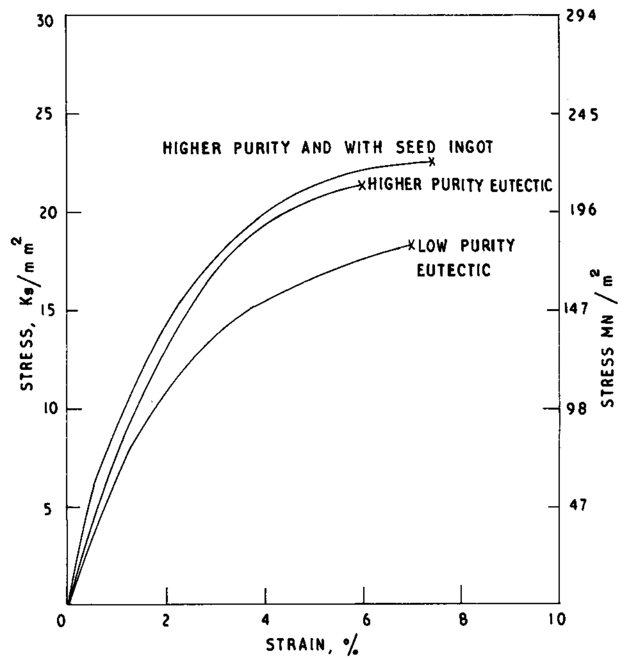


Fig. 9—Effect of purity on stress-strain behavior of electroslag remelted Al-Al_3Ni eutectic specimens.

strength of 35.8 MN/m^2 (3.65 kg/mm^2) and total elongation of 2 pct or even less. The low average tensile strength and low elongation values (2 pct or less) in case of sand cast specimens are mainly due to coarse structure and the macroporosity in the cast rods. Some alloys after directional solidification using electroslag remelting displayed tensile strengths as high as 181.4 MN/m^2 (18.5 kg/mm^2) in the longitudinal direction, and a corresponding total elongation of 7 pct. The bottom portions of the ingots showed the highest strength and elongation values and these are used in this paper for comparison purposes. The strength values were lower in the middle and the top portions (Fig. 7). This apparently is due to the highest solidification rate in the bottom portions of the ingot. Figure 8 shows the tensile strength behavior under conventional electroslag remelting and under different mold conditions. Insulated silica mold appears to be the best choice because ingots grown in this mold gave the highest properties.

ii) Eutectics Made From Higher Purity Materials. The two sand cast specimens exhibited ultimate tensile strength of 52.25 MN/m^2 (5.33 kg/mm^2) and 88.14 MN/m^2 (8.99 kg/mm^2) and total elongation values of 1.6 and 2.1 pct respectively. Electroslag remelted samples showed tensile strengths as high as 213.7 MN/m^2 (21.8 kg/mm^2) with a corresponding elongation of 7 pct under the same conditions. Sand cast samples showed a very coarse fracture surface with most of the facets at angles close to 90 deg to the tensile axis. The electroslag remelted ingots showed fine planar fracture surfaces which were inclined at 25 to 50 deg from the tensile axis. Eutectic ingots made from purer material have shown higher average tensile strengths after electroslag remelting compared to those made from low purity eutectics (Fig. 9). This is due to more regular and aligned structures obtained in ESR eutectics made from purer material. Strength obtained in ESR eutectics made from purer material was further increased when a seed ingot was used as chill (Fig. 9).

Both the tensile strength and elongation of electroslag remelted ingot in the longitudinal direction (21.5 kg/mm^2, 6 pct) were considerably higher than in the transverse direction (9 kg/mm^2, 4 pct). This again is an indirect measure of the alignment of grains and the fibers along the length of the electroslag remelted ingot, and the influence of this alignment on the mechanical properties.

Figure 10 shows that the tensile strength and pct

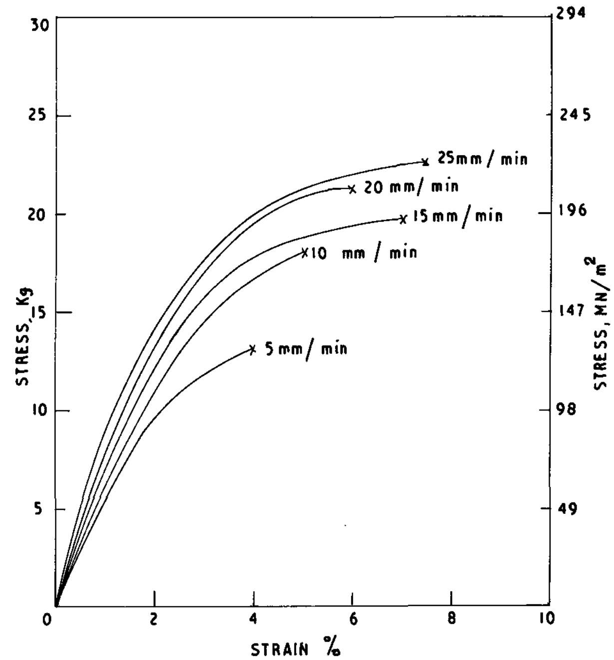


Fig. 10—Effect of average growth rate during electroslag remelting on stress-strain behavior of Al-Al_3Ni eutectic specimens.

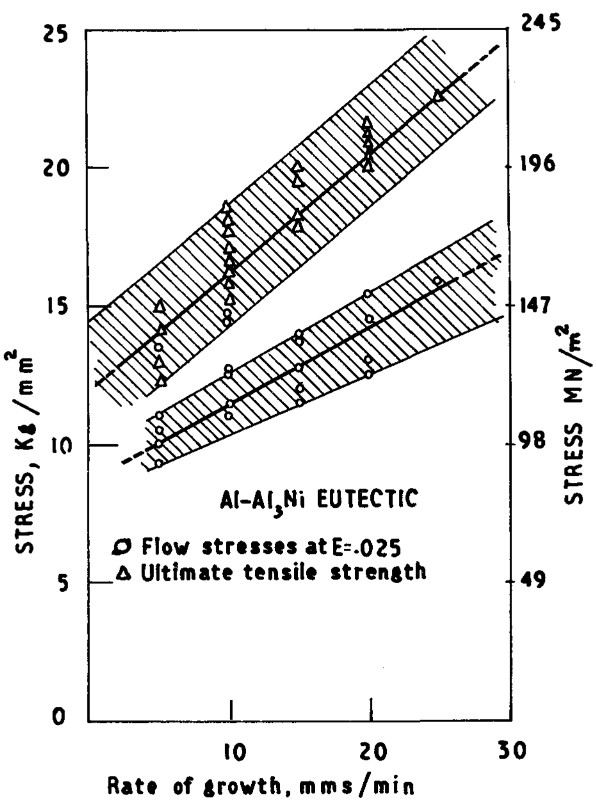


Fig. 11—Variation of ultimate tensile strength (U.T.S.) and flow stresses (at 2.5 pct strain) with average rate of growth of Al-Al_3Ni eutectic specimens during electroslag remelting.

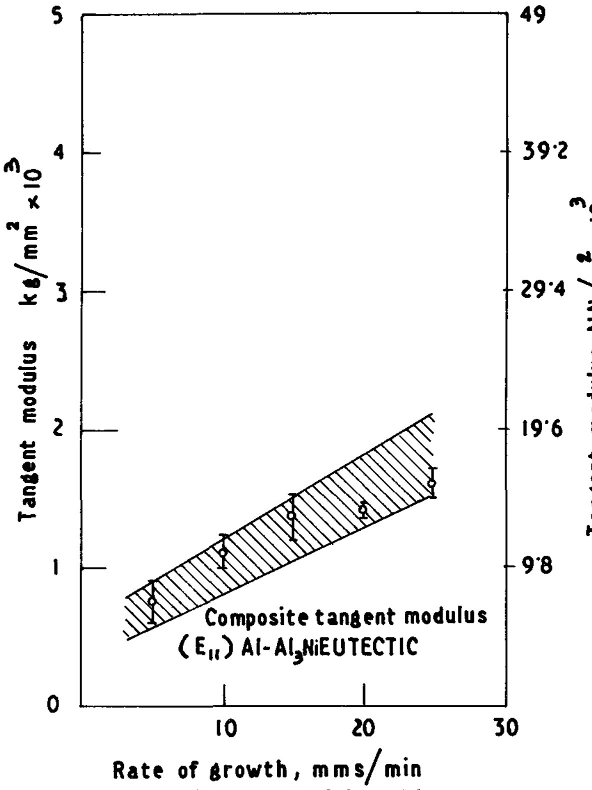


Fig. 12—Variation of tangent modulus with average rate of growth of Al-Al_3Ni eutectic specimens during electroslag remelting.

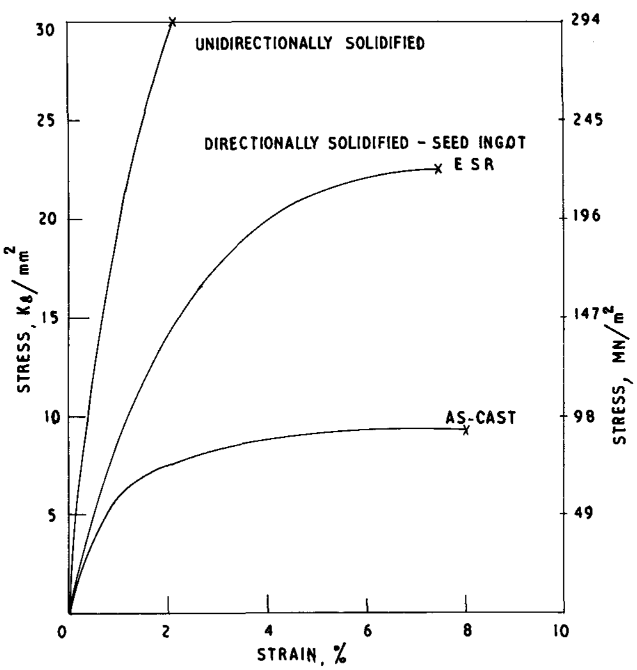


Fig. 13—Comparison of stress-strain behavior, Al-Al_3Ni eutectic containing perfectly directionally aligned fibers[7] with the behavior of electroslag remelted Al-Al_3Ni eutectic specimen with best alignment of grains.

elongation of the electroslag remelted ingots (along the direction of growth) increases with an increase in the average growth rate of the ingot. This apparently is mainly due to a decrease in average fiber diameter and average interfiber spacing.

The UTS of electroslag remelted ingots increased with the average growth rate (Fig. 11). Figure 11 and Figure 12 shows that the flow stresses and tangent modulus of the electroslag remelted ingots also increased with the increase in the average growth rate of the ingots. The flow stresses were computed at a composite strain of 2.5 pct ($\epsilon = 0.025$) and tangent modulii were computed from the average slope of the stress-strain curve between assumed yield points of $\epsilon_y = 0.001$ and $\epsilon = 0.0025$. These results are in line with the results of Lawson and Kerr[8] where the eutectic melts were solidified at faster growth rates (2.54 to 10.72 cm/min) compared to those used in the present study (0.5 to 2.5 cm/min).

Figure 13 compares the stress-strain curves for the perfectly directionally aligned $Al\text{-}Al_3Ni$ eutectic[7] and the best electroslag remelted ingot made in the present study. The ultimate tensile strength and the modulus of the electroslag remelted ingot with best alignment of grain is lower than the directionally solidified eutectic with perfectly aligned fibers, however the pct elongation of electroslag remelted ingot is higher.

CONCLUSIONS

1) Using ESR technique it is possible to align the grains of Al-6 wt pct Ni eutectic alloys along the length of the ingot.

2) The conditions most conducive to the alignment of grains along the length of electroslag remelted ingot are: a) use of very large volumes of a mixed chloride-fluoride (A type) slag, b) liquid slag starting technique, c) a high fill ratio, d) average power inputs, e) use of insulated silica molds and, f) the use of purer electrodes. Alignment of grains and mechanical properties could be further improved by the use of a seed ingot as a chill for starting the electroslag remelting process, under such conditions this seed ingot partially melts during ESR.

3) Under optimum conditions with good alignment of grains, tensile strengths as high as 213.7 MN/m^2 (21.8 kg/mm^2) with a total elongation of 7 pct could be obtained along the length of the ESR ingot without using any seed. Whereas the tensile strength of the sand cast material was 88.2 MN/m^2 (9.0 kg/mm^2)[7] and electroslag remelted polycrystalline solidified ingots was 98.0 MN/m^2 (10 kg/mm^2). When a seed ingot was used tensile strength as high as 220.6 MN/m^2 (22.5 kg/mm^2) were obtained along the length of ESR ingots.

4) In general the ultimate tensile strength, the flow stresses and the tangent modulus of the electroslag remelted ingot increased with the average rate of growth during ESR.

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