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Commercialization Effort in Support of Electroslag-Casting Technology

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Fossil Energy Program

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COMMERCIALIZATION EFFORT IN SUPPORT OF ELECTROSLAG-CASTING TECHNOLOGY

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COMMERCIALIZATION EFFORT IN SUPPORT OF ELECTROSLAG-CASTING TECHNOLOGY*

V. K. Sikka

ABSTRACT

This report summarizes the results of an effort to revive interest in the electroslag casting (ESC) of components in the United States. The ESC process is an extension of a well established electroslag-remelting (ESR) process. Both processes use the electrode of a material that is continuously melted and cast in a water-cooled copper mold. For simple shapes, the mold can be movable, allowing the continuous casting of long lengths. In an effort to revive U.S. industies' interest in ESC, the following approaches were taken: (1) U.S. industries with prior experience in ESC or currently operating an ESR unit were contacted, followed up with telephone conversation, and/or sent copies of prior published reports on the topic, and, in some cases, personal visits were made; (2) with two companies, a potential interest in ESC was worked out by initially conducting ESR; and (3) to further strengthen the industrial interest, the newly developed iron-aluminide alloy, FA-129, was chosen as the material of choice for this study. The two industrial companies that worked with the Oak Ridge National Laboratory (ORNL) were Special Metals Corporation (New Hartford, New York) and Precision Rolled Products, Inc. (PRP) [Florham Park, New Jersey]. Even with its advantages, a survey of the industry indicated that ESC technology has a very limited chance of advancement in the United States. However, the processing of rounds and slabs by the ESR process is a well established commercial technology and will continue to expand.

1. INTRODUCTION

The electroslag-casting (ESC) technique is an extension of the electroslag-remelting (ESR) process. The ESC process[1,2] uses the electrode of a material that is continuously melted and cast in a water-cooled metal mold shown in Fig. 1. The

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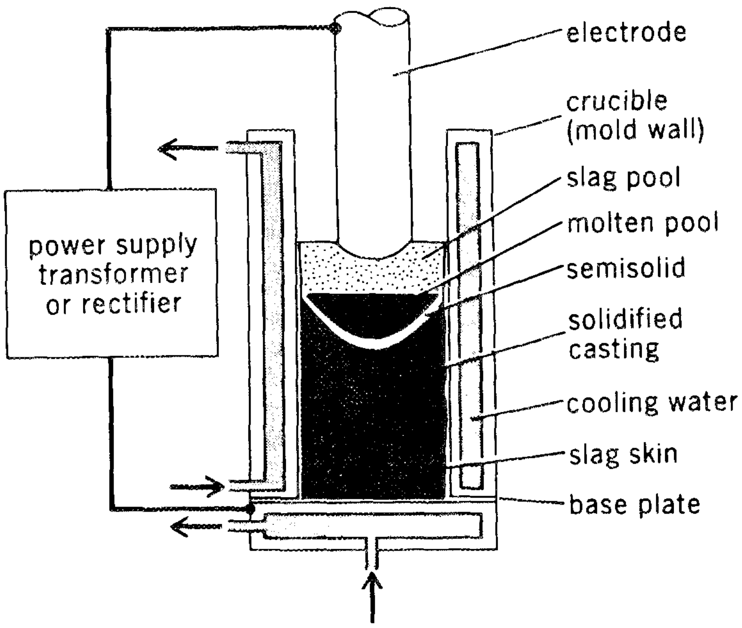

Fig. 1. Schematic diagram of ESC process.

electrode is melted through a layer of slag that provides I^2R energy through its resistance. The slag forms a thin layer between the mold and the molten pool and, thus, provides noncolumnar grains. The process requires about one-half the steps of the conventional sand-casting process shown in Fig. 2. The electroslag castings possess: (1) a smooth defect-free casting finish, (2) freedom from conventional casting defects, (3) more reproducible mechanical properties, and (4) properties comparable to those of forged products. The improvement[2] in the Charpy-impact properties of a 9Cr-1Mo steel by electroslag casting, as compared to sand casting, is shown in Fig. 3. One major disadvantage of the ESC process, often cited, is the cost of the metal mold. This cost can only be offset if a large number of parts of the same shape are produced. The ESC technology has been well established in several of the Soviet Union republics and European countries. The purpose of this task was to revive the interest in electroslag casting in the United States. To make it more interesting and different, a newly developed iron-aluminide alloy was chosen as the test material.

The purpose of this report is to summarize the results of industrial contacts in advancing the ESC technology and to present the results of work conducted on the iron-aluminide alloy.

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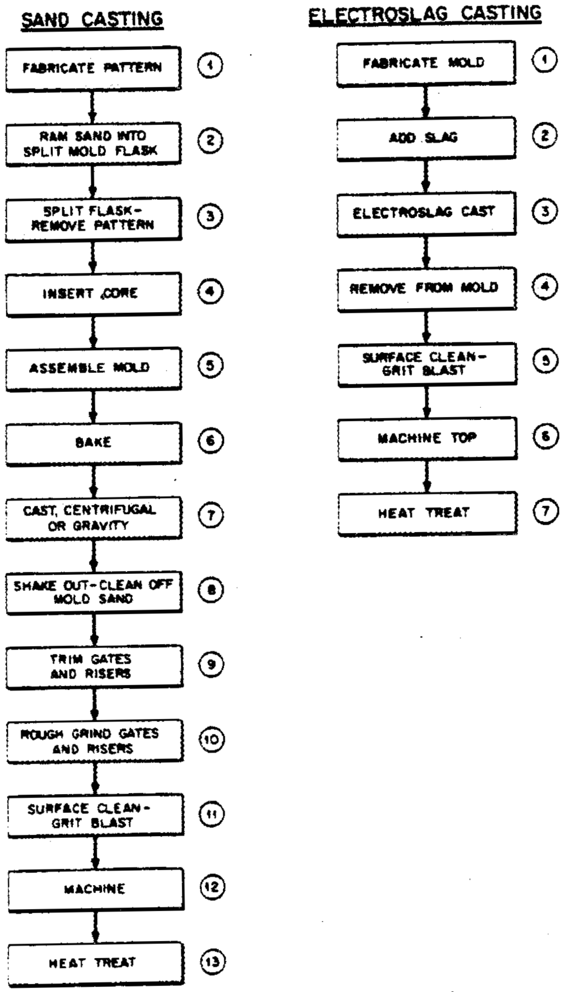

Fig. 2. ESC involves fewer process steps than does conventional sand casting.

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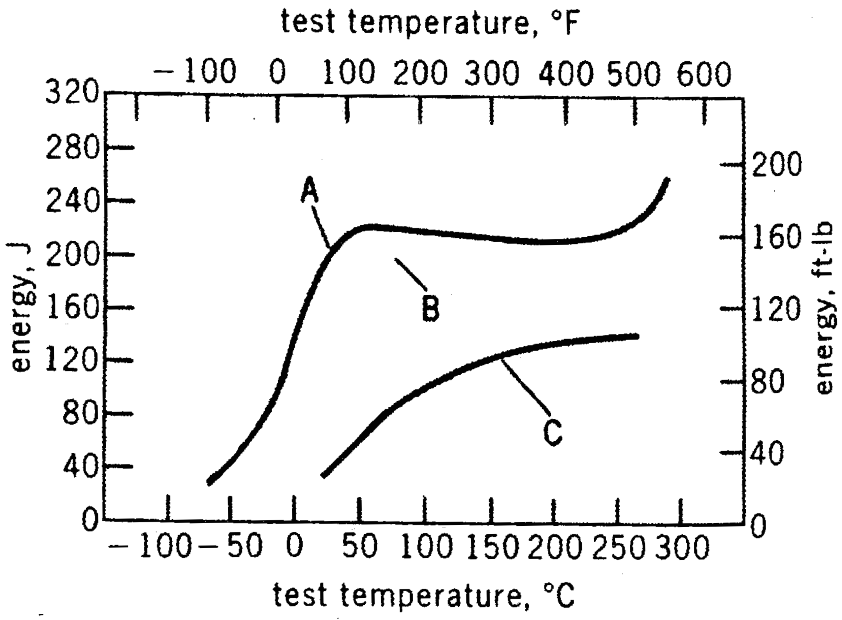

Fig. 3. Comparison of Charpy-impact energy data for the electroslag-cast valve body of 9Cr-1Mo steel with data for sand casting: A = ESC (transverse orientation), B = ESC (longitudinal orientation), and C = sand casting (all three orientations).

2. RESULTS OF INDUSTRIAL CONTACTS

Several companies in the United States were contacted to establish the level of interest in the ESC technology. The discussion with each company is described below:

1. *Cameron Iron Works.* An earlier Fossil Energy-supported program[3,4] had helped set up ESC equipment in the research laboratory at Cameron Iron Works. Through this program, Cameron proved that the equipment worked satisfactorily, and they produced several alloy castings of a simple shape and also shapes that were rather complex. Cameron was contacted at the start of this program to see if the equipment was still functional and if they would be willing to work jointly with the Oak Ridge National Laboratory (ORNL) to further develop the ESC process. However, even after a personal visit, the research director at Cameron said that there was no interest and indicated that the equipment was still functional, even though the engineer and the operator who previously operated the equipment had left. Furthermore, the business interests at Cameron had changed, and, thus, even with additional funds from the Department of Energy (DOE) program, they were not willing to make electroslag castings.
2. *Carpenter Technology.* This company has been well known for taking a lead in establishing advanced manufacturing processes. Furthermore, they have several ESR units that, with minor changes, can be used for electroslag castings. Once again, an extensive discussion with Carpenter Technology resulted in the answer that it did not fit into their business plan. Under a subcontract with ORNL, Carpenter did process[5] a 203-mm-diam ingot of iron-aluminide alloy FAL by the ESR method (see Table 1 for alloy compositions).
3. *Universal Cyclops.* This company has several ESR units and, on initial contact, showed a lot of interest. As a result of their interest, a visit was made to their plant. Discussions with Universal Cyclops resulted in a lot of technical interest, and they indicated that they could process the rounds and slabs from the iron-aluminide alloy by the ESR method. ORNL was to provide the starting electrode and the funds to process the electrode by the ESR method. Even when ORNL readied the electrode, Universal Cyclops came back with a negative answer, saying there was no near-term expected interest in iron aluminides or electroslag castings.

Table 1. Nominal composition of Fe_3Al alloys

Element	Alloy (wt %)		
	FAS[a]	FAL[b]	FA-129[c]
Al	15.9	15.9	15.9
Cr	2.20	5.5	5.5
B	0.01	0.01	--
Zr	--	0.15	1.0
Nb	--	--	1.0
C	--	--	0.05
Fe	Balance	Balance	Balance

[a]Maximum sulfidation resistance.
[b]Maximum room-temperature tensile ductility.
[c]High-temperature strength with good room-temperature ductility.

4. *Haynes International.* Haynes has been well known for their large number of ESR units. They were quick to express their disinterest because their primary business is nickel base, and they were not interested in dealing with a new alloy. Even if Haynes became interested, it would be a round shape and strictly a one-time effort.
5. *Teledyne Alvac.* Teledyne Alvac is known for their ESR capabilities. When contacted, the response was negative. The reason cited was that they were only interested in making very large castings of rounds and slabs of well established alloys.
6. *Bhat Technology International, Inc.* Dr. Bhat was contacted to determine his input in establishing sources for ESC in the United States. He was extremely helpful in his discussions and even visited ORNL, Universal Cyclops, and Jessop Steel. The net result of these visits was the absence of any currently operating facility for ESC in the United States. Some rather complex ideas were presented for ESC work to be carried out overseas. .This did not fit into the overall scope of our interest.
7. *Special Metals Corporation.* Special Metals has been well known for working with new processes and alloys. When contacted, they agreed to compare the ESR rounds (152 mm diam) with rounds of the same size cast by vacuum-arc remelting (VAR).

This work was subcontracted by ORNL to Special Metals and resulted in good quality electroslag-cast rounds of iron-aluminide alloy FA-129. A report on this work was written by Special Metals,[6] and subsequent testing at ORNL has shown that further discussions could result in the making of shapes from iron-aluminide alloys as required. However, that did not materialize because of lack of interest.

8. *Precision Rolled Products*. Precision Rolled Products (PRP) was the most supportive of the idea of preparing the electrodes and ESR. They agreed to initially prepare the ESR rounds with subsequent possibilities for shapes. The contract with PRP, which was cost shared by them, resulted in the preparation of a 406-mm-diam ESR ingot of iron-aluminide alloy FA-129. It also resulted in the preparation of a 203-mm-thick by 965-mm-wide slab electrode for ESR. The details of these castings are described later in this report. The slab electrode was to be processed by ESR at Universal Cyclops. Although they supplied the mold to PRP to make the electrode, once it was prepared, Universal Cyclops refused to electroslag cast it. This refusal was based on not having any interest in processing new materials by the ESR method, and they had no future plans for ESC.

The conclusion from the industrial contacts was that even with its advantages, ESC technology has a very limited chance of advancement in the United States. However, the processing of rounds and slabs by the ESR method is a well established commercial technology and will continue to expand. U.S. industries are quite conservative in that they are not willing to take a chance on applying the well established ESR method to a new material such as iron aluminide.

3. ORNL PROJECT PLAN

Based on input from industrial contacts, ORNL developed the following plan for this project:

1. Let industry apply the ESR method to a new material such as iron aluminide. The justification was that the experience with the new alloy may move the industrial partner into a new business area.
2. Let industry initially cast the rounds and slabs to gain experience with applying the ESR method to the new material.
3. Once industry is satisfied with the new material and applying the ESR method to it, they will extend one or more of their ESR units for ESC.

4. ORNL will evaluate the basic mechanical properties of the ESR material and compare it with the same material prepared by other competing processes such as vacuum-induction melting (VIM) and VAR. The results of the comparisons were to be provided to industry.

4. SUBCONTRACT WITH SPECIAL METALS CORPORATION

4.1 MELTING AND CASTING

The melting and casting study at Special Metals Corporation had several objectives:

1. Check to see if any magnesium is picked up during the initial melting of the iron-aluminide alloy FA-129 in a magnesia crucible consisting of 74% MgO-24% Al_2O_3. This was to be accomplished by melting half of the total alloy in a 74% MgO-24% Al_2O_3 crucible and the other half in an Al_2O_3 crucible.
2. Investigate the differences in ingot quality of the ESR ingot, and compare them to the VAR and VIM electrodes.
3. Investigate the processing response of ESR, VAR, and VIM ingots into 25-mm-diam bar product.
4. Determine the mechanical properties of the ESR, VAR, and VIM ingots.

The schematic describing the melting and processing sequence used at Special Metals is presented in Fig. 4.

The melt stock for heats melted at Special Metals consisted of iron, electrolytic iron, carbon, spectrographic carbon, niobium, high-purity ferroniobium, chromium, high-purity chromium briquettes and aluminum, and virgin aluminum ingot. The VIM, VAR, and ESR ingots prepared at Special Metals are shown in Figs. 5 and 6. The chemical analysis of the VIM heats is compared with the specifications in Table 2 and shows that the use of an MgO crucible does produce higher magnesium levels than an Al_2O_3 crucible. Furthermore, the magnesium level of the alloy melted in an MgO crucible fell outside the range set for this study. The chemical analyses of the VAR and ESR ingots, along with the VIM electrode, are summarized in Table 3. This table shows that the VAR process reduces the magnesium content of the alloy from 20 to 10 ppm. The bottom of the ESR ingot also showed reduced magnesium content suggesting that the proper slag chemistry selection could reduce any magnesium picked

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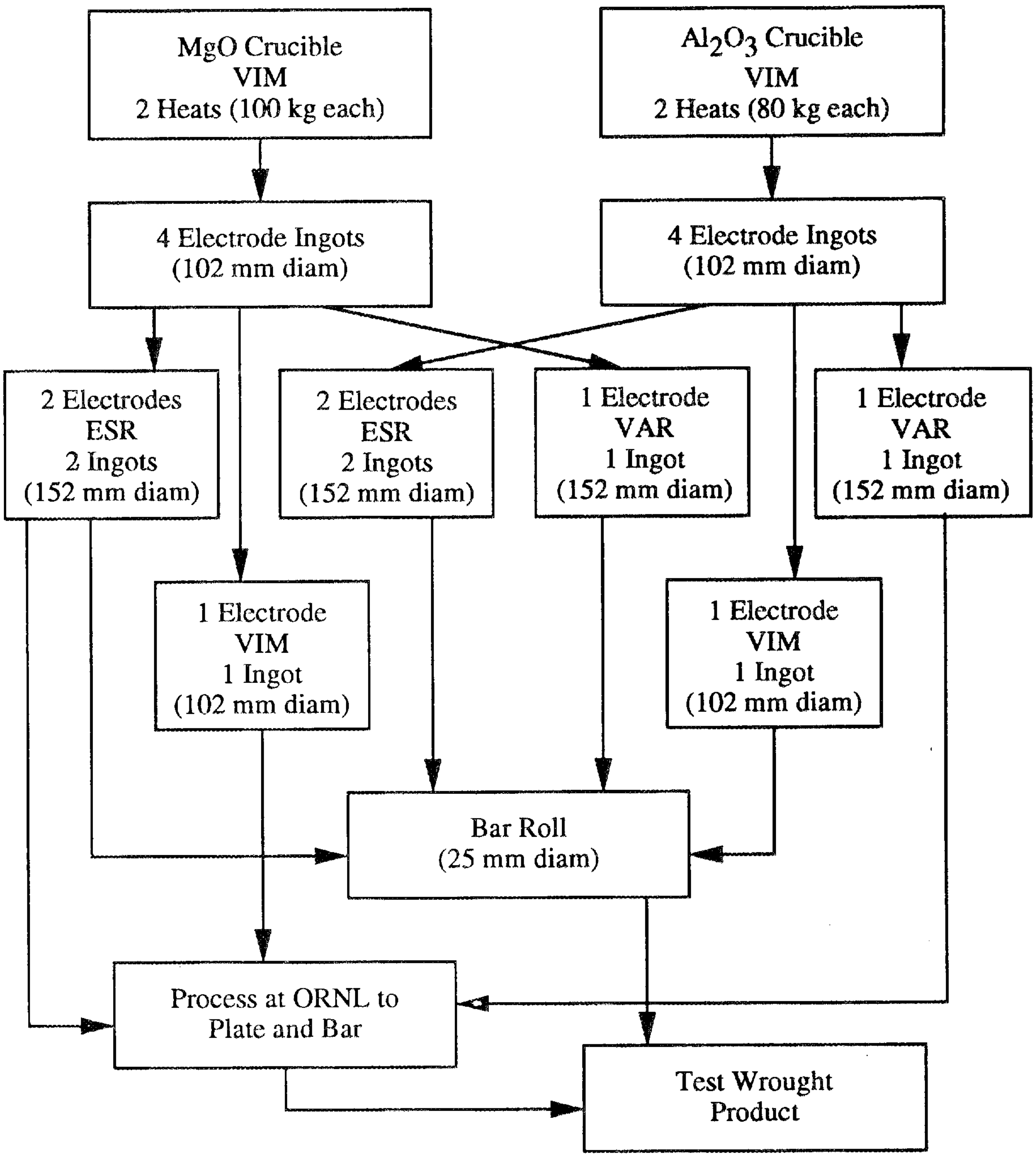

Fig. 4. Melting and processing schematic used for iron-aluminide alloy FA-129 at Special Metals Corporation.

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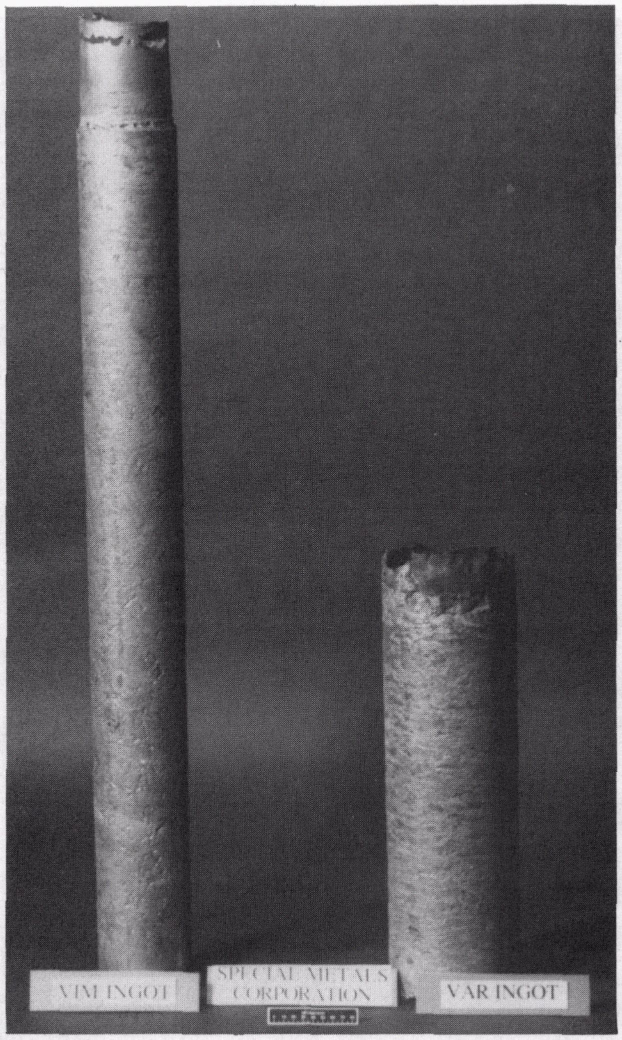

Fig. 5. Photograph of VIM and VAR iron-aluminide FA-129 alloy ingots processed at Special Metals Corporation. The ingots are 102 and 152 mm diam, respectively.

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Fig. 6. Photograph of VIM and ESR iron-aluminide FA-129 alloy ingots processed at Special Metals Corporation. One electrode was prepared using an MgO crucible and the other using an Al_2O_3 crucible. Both ingots are 152 mm diam.

Table 2. Results of chemical analysis of VIM heats of alloy FA-129 melted in MgO and Al_2O_3 crucibles at Special Metals Corporation

Element	ORNL specification (wt %)		Chemical analysis (wt %)			
			74% MgO, 24% Al_2O_3 crucible (100 kg/heat)		Al_2O_3 crucible (80 kg/heat)	
			Heat		Heat	
	Target	Range or limit	D5-3965	D5-3966	D5-3968	D5-3969
C	0.05	0.04 to 0.06	0.049	0.054	0.047	0.053
Mn	--	0.02 max	0.01	<0.01	<0.01	<0.01
P	--	0.005 max	N/A	N/A	N/A	N/A
S	--	0.005 max	0.001	0.0008	0.0016	0.0012
Si	--	0.20 max	<0.001	<0.01	<0.01	0.01
Ni	--	0.20 max	0.01	<0.01	<0.01	<0.01
B	--	0.005 max	<0.001	<0.001	<0.001	<0.001
Mg	--	0.0010 max	0.002	0.002	0.001	0.001
N	--	0.0050 max	0.0002	0.0001	0.0001	0.0001
O	--	0.0050 max	0.0016	0.0007	0.0015	0.0008
Al	15.9	15.5 to 16.5	16.33	16.30	16.29	16.42
Cr	5.5	5.0 to 6.0	5.28	5.31	5.31	5.34
Nb	1.0	0.9 to 1.1	0.98	1.00	0.99	1.00
Fe	Balance	Balance	Balance	Balance	Balance	Balance

Table 3. Effect of secondary melting processes on chemical analysis of alloy FA-129 (heat D5-3965) initially melted by VIM in an MgO crucible

Element	Weight percent				
	VIM chemistry	ESR ingot (top)	ESR ingot (bottom)	VAR ingot (middle)	VAR ingot (bottom)
C	0.049	0.052	0.051	0.057	0.049
Mn	0.01	<0.01	<0.01	<0.01	<0.01
P	N/A	N/A	N/A	N/A	N/A
S	0.001	0.0006	0.0004	0.0002	0.0001
Si	<0.01	<0.01	<0.01	<0.01	<0.01
Ni	0.01	<0.01	<0.01	<0.01	<0.01
B	<0.001	<0.001	<0.001	<0.001	<0.001
Mg	0.002	0.002	0.0005	0.001	0.001
N	0.0002	0.0002	0.0003	0.0010	0.0011
O	0.0016	0.0015	0.0013	0.0010	0.0011
Al	16.33	16.39	16.38	16.12	16.13
Cr	5.28	5.27	5.28	5.25	5.29
Nb	0.98	0.99	0.99	0.99	0.99
Fe	Balance	Balance	Balance	Balance	Balance

up during the VIM process using the MgO crucible. The VAR process also reduced the sulfur content by an order of magnitude. The ESR process reduced the sulfur to nearly half, but the effectiveness of this process in reducing impurities is a strong function of the slag selection. The vacuum in the VAR also helped in reducing the oxygen gas content. The ESR ingot showed much finer grain size and lesser volume fraction of porosity than the VIM ingot (see Fig. 7).

4.2 FABRICATION

The fabrication response of the VIM, VAR, and ESR ingots produced at Special Metals was investigated at Special Metals and ORNL. The fabrication at Special Metals consisted of hot-bar rolling at 1000°C followed by finish rolling at 800°C. No problems related to hot working were encountered on the 102- and 152-mm-diam ingots. The finished, centerless, ground, 25-mm-diam bars produced at Special Metals are shown in Fig. 8.

The detailed procedure used at ORNL for processing of VIM ingots into 0.76-mm-thick sheet for mechanical properties testing is described in a previous publication.[5] The VAR and ESR ingots were cut into 125-mm-long billets for hot extrusion into rectangular bar. All of the extrusions were carried out at 1000°C at a reduction ratio of 4.3:1. All of the extrusions were exceptionally good and pieces from the hot extruded bars were subsequently hot-bar rolled from a thickness of 51 to 37 mm. During this step, the VAR materials consistently performed better than the ESR materials. The ESR plates showed centerline delaminations. These delaminations were similar to those observed during the slab fabrication from a 200-mm-diam ESR ingot of iron-aluminide alloy FAL (see Table 1) produced at Carpenter Steel.[5] The scanning electron microscopy (SEM) analysis had shown significant enrichment of magnesium in the delaminated regions. Although not analyzed, the ESR process is known to result in more hydrogen in the alloy than the vacuum-melting processes. Since iron aluminides are sensitive[7-11] to hydrogen embrittlement, the ESR process possibly accentuates the delamination problem.

4.3 MECHANICAL PROPERTIES

The 0.76-mm-thick sheet from the VIM ingot (heat D5-3966) produced at Special Metals was tensile and creep tested at ORNL. The results from the VIM

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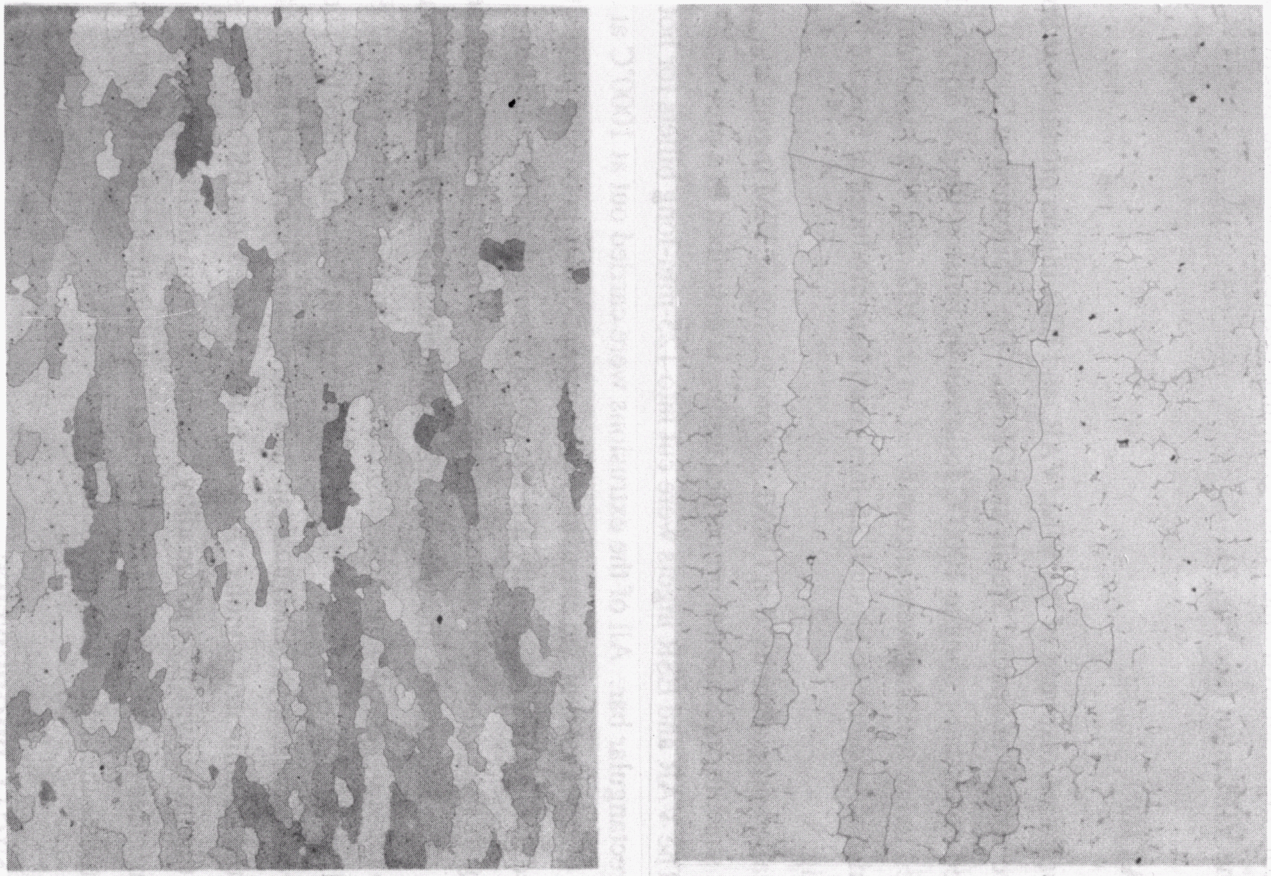

(*a*) (*b*)

Fig. 7. The ESR process produced finer grain structure and lesser volume fraction of porosity than the VIM process: (*a*) ESR ingot and (*b*) VIM ingot.

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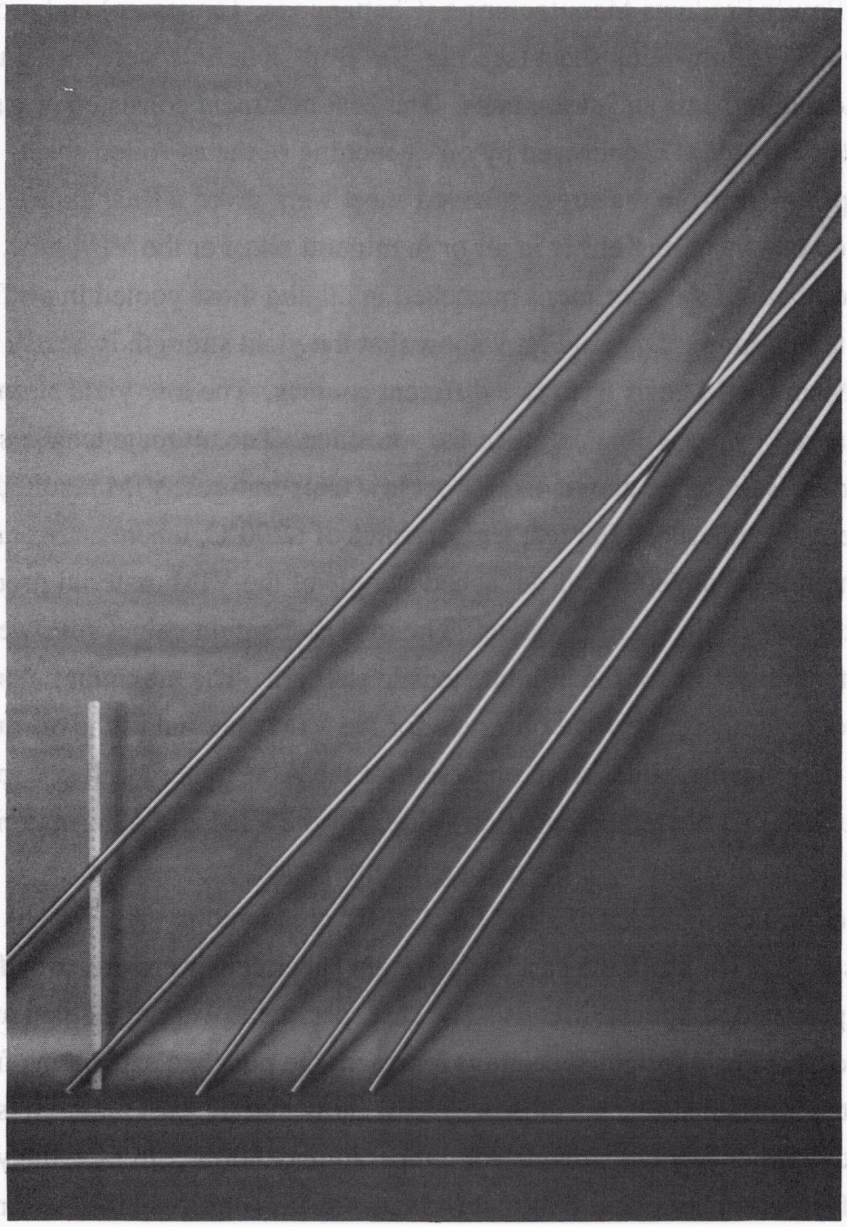

Fig. 8. Photograph showing 25-mm-diam bars fabricated by hot-bar rolling 102- and 152-mm-diam ingots of alloy FA-129 at Special Metals Corporation. The bars were produced from ingots prepared by VIM, VAR, and ESR.

material are compared with an 80-kg air-induction-melted (AIM) heat[12] (X3905) at ABB C-E Power Products Manufacturing (Chattanooga, Tennessee) and processed identically to 0.76-mm-thick sheet (see Fig. 9). Both materials were tested under identical heat treatments and strain rates. The heat treatment consisted of a stress-relief treatment for 1 h at 700°C followed by oil quenching of the as-rolled sheet. The punched specimens from the stress-relieved sheet were given a final anneal for 1 h at 700°C followed by cooling either in air or in mineral oil. For the VIM heat, data are presented on both of the specimens quenched in oil and those cooled in air from the annealing temperature. Data in Fig. 9 show that the yield strength is nearly the same for the AIM and VIM heats from two different sources. The low-yield strength at 400°C is caused by a possible defect in the specimen. The ultimate tensile strength for both materials is the same above 400°C. At low temperatures, VIM resulted in higher tensile-strength properties. For test temperatures of ≤200°C, where environmental embrittlement is possible, the oil-quenched sample of the VIM material produced the highest ultimate tensile strength values. The total elongation values followed the trend similar to that observed for the ultimate tensile strength. The maximum elongation values at room temperature were observed for the VIM material in the oil-quenched condition. The lowest values were observed for the AIM material. It is important to note that at ≥200°C, the total elongation values for the VIM and AIM materials are ≥20%, independent of the final quenching medium used.

The tensile properties of alloy FA-129 are compared in the wrought and cast conditions in Fig. 10. Both the cast and wrought specimens were prepared from the VIM heat prepared at Special Metals. The cast specimens were machined and tested by Special Metals. The wrought specimens represent the punched specimens from the 0.76-mm-thick rolled sheet. Results in Fig. 10 show that the cast material is significantly higher in yield strength for temperatures ≥800°C. In fact, the yield strength of the cast material at 800°C is the same as that observed for the wrought material at room temperature. No data on cast material were generated at test temperatures <650°C. The ultimate tensile strength of the cast material is also higher than the wrought material. The total elongation for the cast material is significantly lower. However, a total elongation value of ≥60% is observed for test temperatures ≥800°C. This value is much higher than needed for conventional hot working of material.

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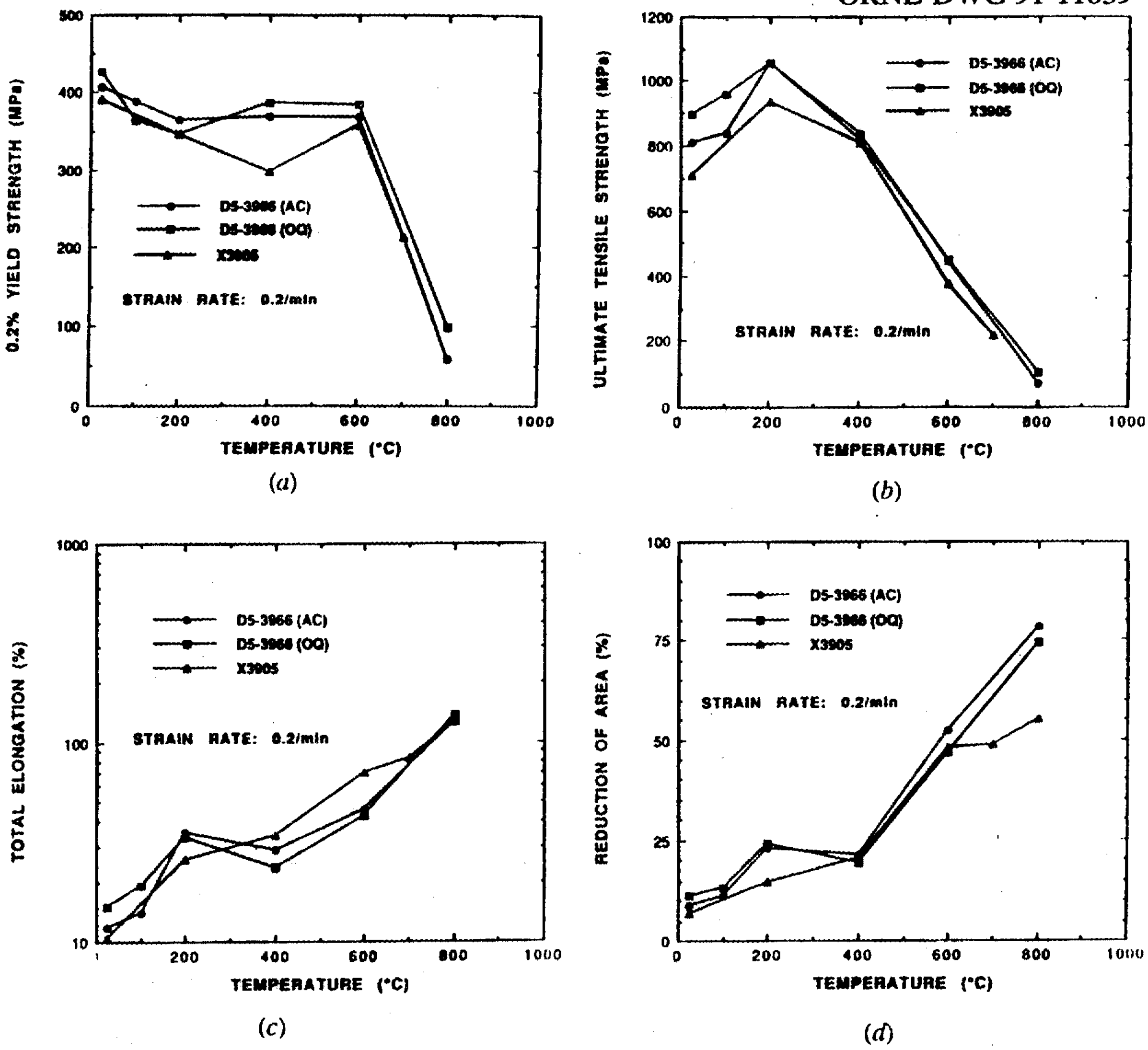

Fig. 9. Effect of test temperature on tensile properties of Fe_3Al alloy FA-129. Data are plotted for one each of VIM and AIM heats of 80-kg size: (*a*) 0.2% yield strength, (*b*) ultimate tensile strength, (*c*) total elongation, and (*d*) reduction of area. D5-3966 and X3905 are the heat numbers for the VIM and AIM heats, respectively.

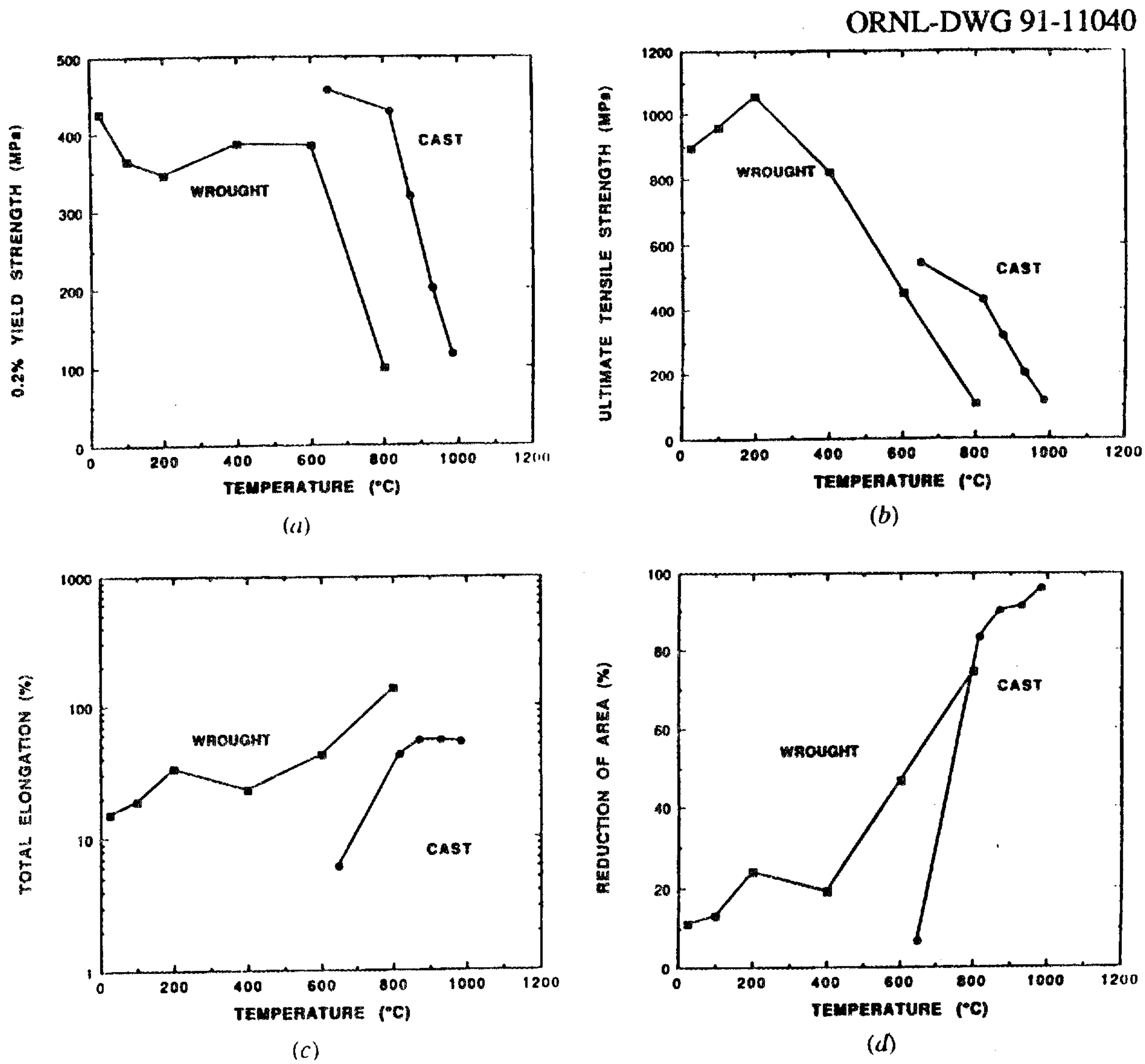

Fig. 10. Comparison of tensile properties of Fe_3Al Alloy FA-129 in the wrought and cast conditions: (*a*) 0.2% yield strength, (*b*) ultimate tensile strength, (*c*) total elongation, and (*d*) reduction of area. Both cast and wrought specimens were from VIM heat D5-3966.

5. SUBCONTRACT WITH PRECISION ROLLED PRODUCTS

5.1 ROUND CASTING

As part of PRP's cost-shared subcontract, they induction melted 2000 kg of the Fe_3Al-based alloy FA-129 (see Table 1). The molten metal was cast into a 330-mm-diam round electrode. The electrode was subsequently processed by the ESR method into a 406-mm-diam ingot shown in Fig. 11. After stripping the ingot from the mold, it was stress relieved for 8 h at 750°C. The ingot's surface finish was similar to that observed for most commercial iron- and nickel-based alloys. The surface finish of the ingot was acceptable for subsequent processing without requiring surface treatment, which is one of the advantages of the ESR method. The chemical analysis of the ESR ingot is compared with the target composition in Table 2. Based on the melting of this ingot, PRP indicated that the melting of iron aluminide was no different than many of the commercial alloys, and they would produce the alloy if customer requests were received. They also indicated that some work is needed in developing the proper slag system for a new material such as iron aluminide.

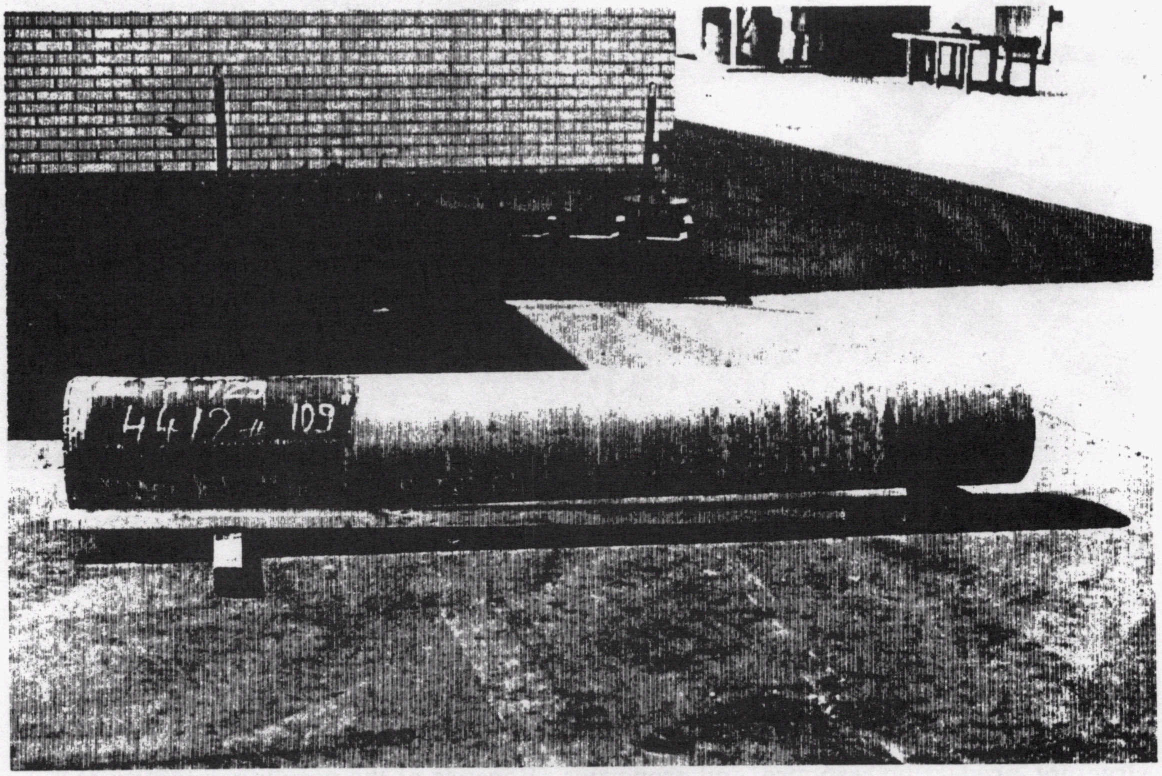

Fig. 11. A 406-mm-diam ingot of alloy FA-129 prepared by VIM and ESR at PRP. *Source:* Precision Rolled Products, Inc., Florham Park, New Jersey.

5.2 SLAB CASTING

Subsequent to the VIM and ESR processing of the round ingot, PRP prepared a second 3000-kg heat of iron-aluminide alloy FA-129 by the VIM process. The heat was cast into a rectangular slab mold measuring 203 by 965 mm. The slab was removed from the mold, slow cooled, and stress relieved for 8 h at 750°C. The slab is shown in Fig. 12. As expected, the quality of the VIM slab was not as good as the ESR ingot. Note, however, that this was only the electrode that was to be subsequently electroslag cast. The ESC of the slab was to be carried out at Universal Cyclops. However, after the preparation of the electrode, they decided against doing so. Thus, the slab will remain in the VIM condition.

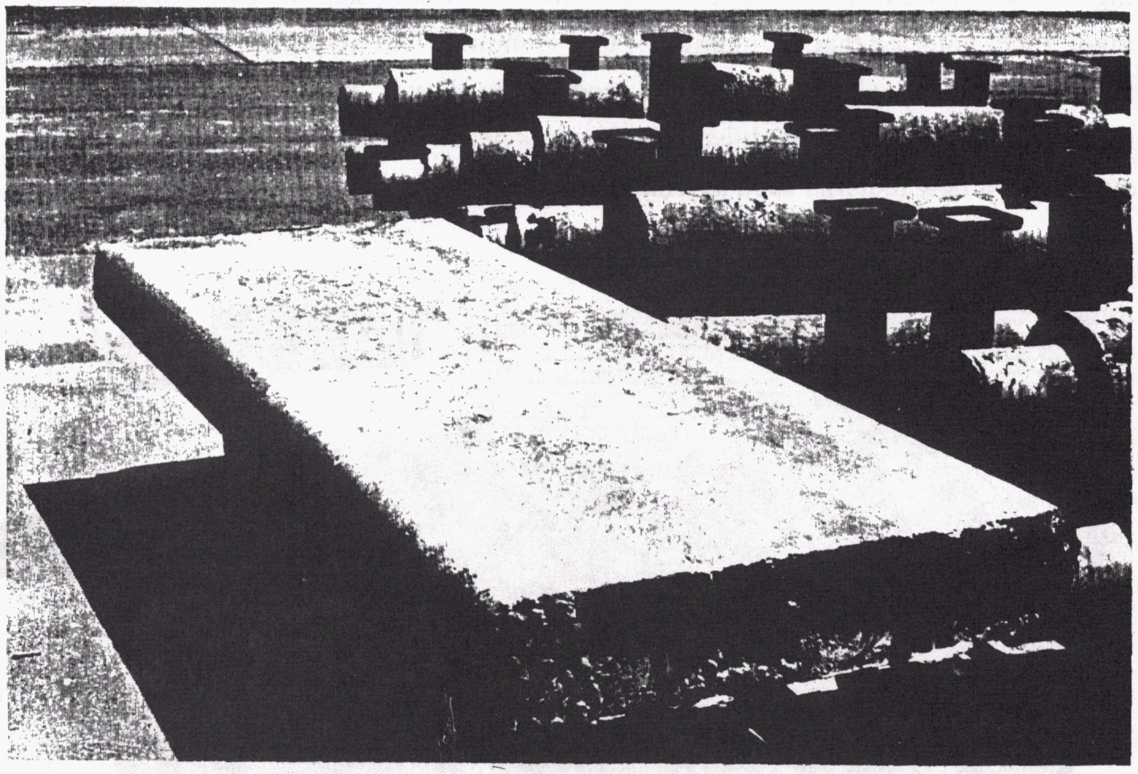

Fig. 12. A 203- by 965-mm slab of alloy FA-129 prepared by VIM at PRP. *Source:* Precision Rolled Products, Inc., Florham Park, New Jersey.

5.3 CUTTING OF PRP CASTINGS

The 406-mm-diam ESR ingot from PRP was sectioned to study its macrostructure, processing response, and properties. Because of the very low ductility of alloy FA-129 in the as-cast condition, ORNL recommended that the ingot be cut by using a slow-speed band saw rather than a high-speed abrasive wheel, which is a common industry practice. PRP subcontracted the band-saw cutting to another vendor who found the ingot to be extremely difficult to cut. In spite of the slow-cutting response, two slices were sectioned from near the top of the 406-mm-diam ESR ingot. The sectioned pieces showed evidence of cracks near the center of both slices. The cracking could have been caused either from the solidification process or from the cutting process. Subsequent crack-free cutting of the slices at ORNL suggests that the cracks may be related to the solidification process. The macro- and microstructures of the ESR ingot sections are shown in Fig. 13. The macrostructure is very similar to that observed for other commercial alloys, and the microstructure is very similar to that observed for the 102-mm-diam ingots of iron-aluminide alloy FA-129 (ref. 5).

Since Universal Cyclops declined to process the slab electrode by the ESR method, it was decided to section it in the VIM condition. The size of the slab was larger than any of the sectioning equipment available at ORNL. The initial cut in the slab was made by plasma arc followed by abrasive-wheel cutting into smaller pieces. No cracks or large porosity were observed in the sections cut from the slab. Three $330 \times 152 \times 203$-mm sections of the slab were sent to Allegheny Ludlum for hot-rolling trials. This work was to be carried out by Allegheny Ludlum at their expense and the results shared with ORNL. The work has been completed, and a letter report is expected from them.

5.4 PROCESSING OF 406-MM-DIAM ESR INGOT INTO SHEET

A 28-mm-thick piece from the section representing the top of the 406-mm-diam ESR ingot was processed into 0.76-mm-thick sheet at ORNL. The processing steps, temperatures, and percent reductions are shown schematically in Fig. 14. The forging steps were at 1000°C followed by rolling steps at 800 and 650°C, respectively. No problems were encountered in the preparation of the sheet. The processing steps used for the section from the 406-mm-diam ESR ingot are the same as those previously used for the 102-mm-diam ingots.[5]

5.5 MECHANICAL PROPERTIES

The 0.76-mm-thick, as-rolled sheet was stress relieved for 1 h at 700°C followed by oil quenching. The stress-relieved sheet was punched into specimens for tensile and

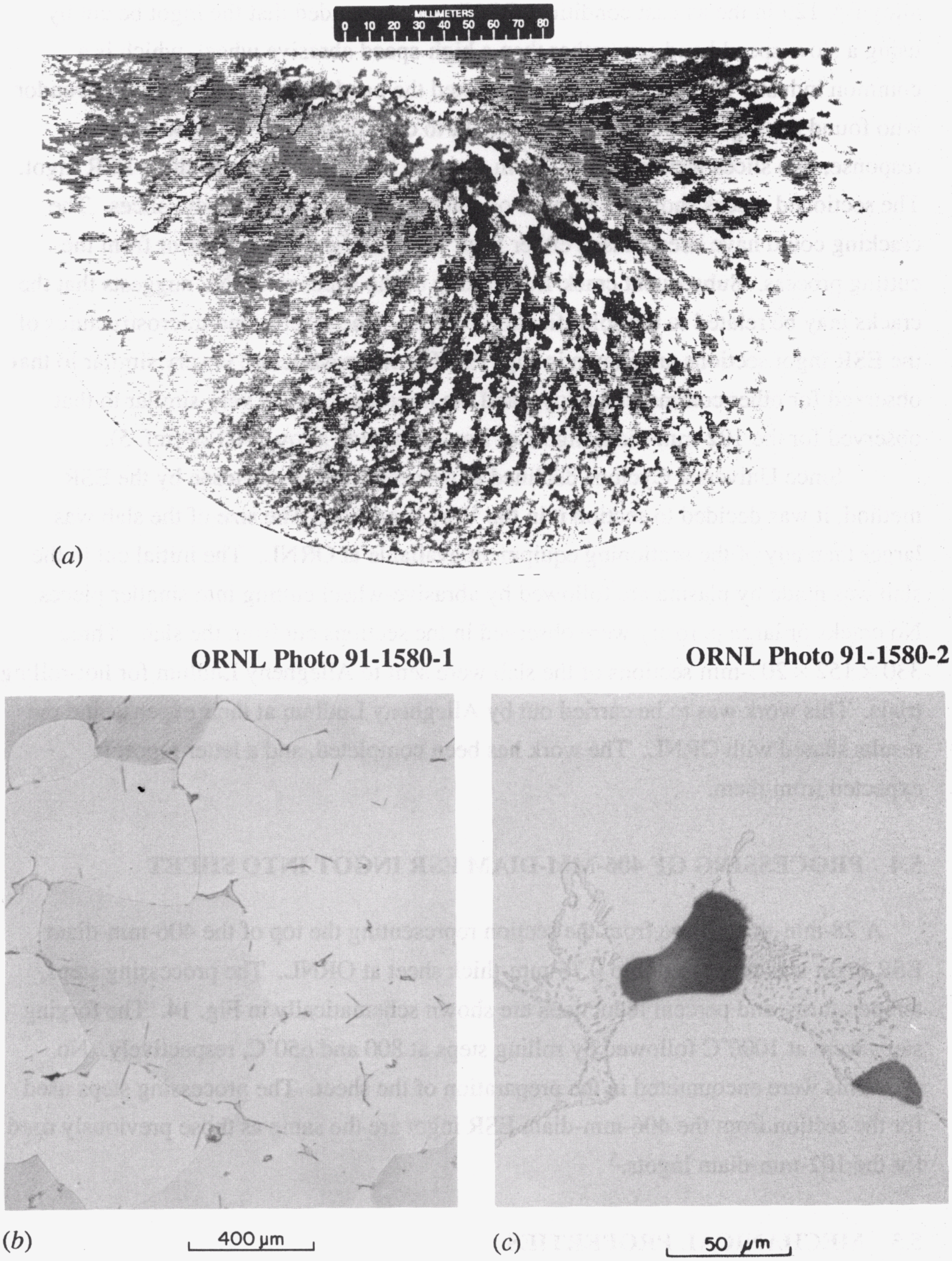

Fig. 13. Optical macrostructure (*a*) and microstructures (*b*,*c*) of a section taken from near the top of the 406-mm-diam ESR ingot of FA-129 showing (*b*) grain size and second-phase distribution at low magnification and (*c*) eutectic and porosity at high magnification.

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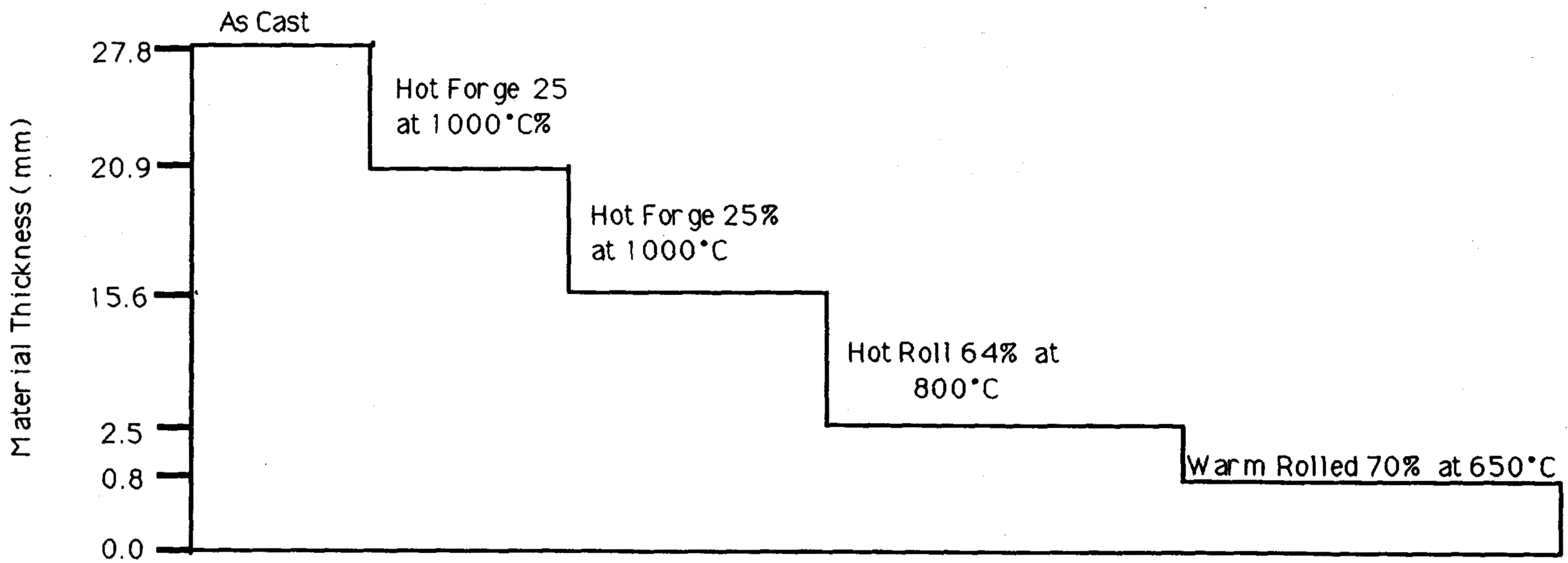

Fig. 14. Schematic showing the steps used for processing a section taken from near the top of the 406-mm-diam ESR ingot of FA-129.

creep testing. In order to remove the work from the die-punching operation, all of the specimens were given a final anneal for 1 h at 700°C followed by oil quenching prior to testing. Tensile tests on these specimens were conducted in the temperature range of room temperature to 800°C. Data from these tests are plotted in Figs. 15 and 16 and compared with the results on 102-mm-diam ingots processed by VIM at Special Metals Corporation. Data in Figs. 15 and 16 show the following:

1. The yield strength of the 406-mm-diam ESR ingot is similar to that of the 102-mm-diam VIM ingot up to 400°C. At higher temperatures, specimens from the ESR ingot are weakened.
2. The ultimate tensile strength of the 406-mm-diam ESR ingot is lower than the 102-mm-diam VIM ingot. At higher temperatures, the tensile strength data are identical.
3. At room temperature, total elongation of the ESR and VIM ingots is the same. At temperatures over room temperature up to 400°C, the ductility values for the ESR ingot are lower. Above 400°C, total elongation values for the ESR ingot are higher than for the VIM ingot.
4. Reduction of area values show trends similar to that observed for total elongation.

6. SUMMARY AND CONCLUSIONS

This report summarizes the results of an effort to revive interest in ESC of components in the United States. The ESC process is an extension of the well established ESR process. Both processes use the electrode of a material that is continuously melted and cast in a water-cooled copper mold. For simple shapes, the mold can be movable, allowing the continuous casting of long lengths. In an effort to revive U.S. industies' interest in ESC, the following approaches were taken: (1) U.S. industries with prior experience in ESC or currently operating an ESR unit were contacted, followed up with telephone conversation, and/or sent copies of prior published reports on the topic, and, in some cases, personal visits were made; (2) with two companies, a potential interest in ESC was worked out by initially conducting ESR; and (3) to further strengthen the industrial interest, the newly developed iron-aluminide alloy, FA-129, was chosen as the material of choice for this study. The two industrial companies that worked with ORNL were Special Metals Corporation and PRP . The following observations are possible from this study:

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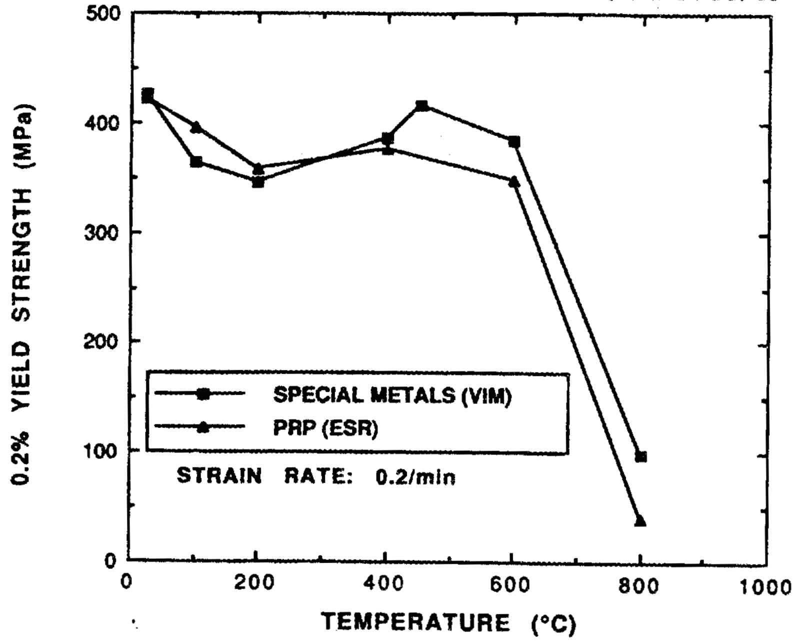

(*a*)

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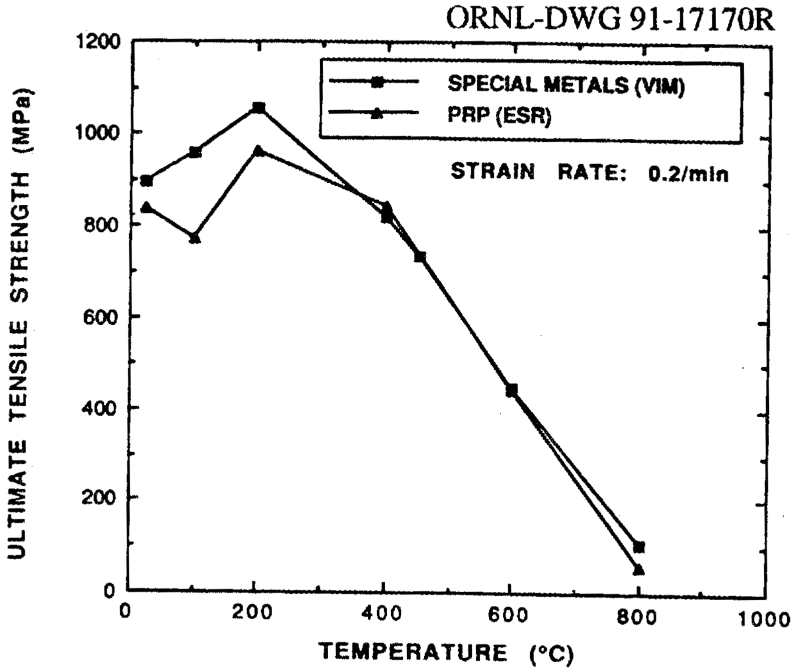
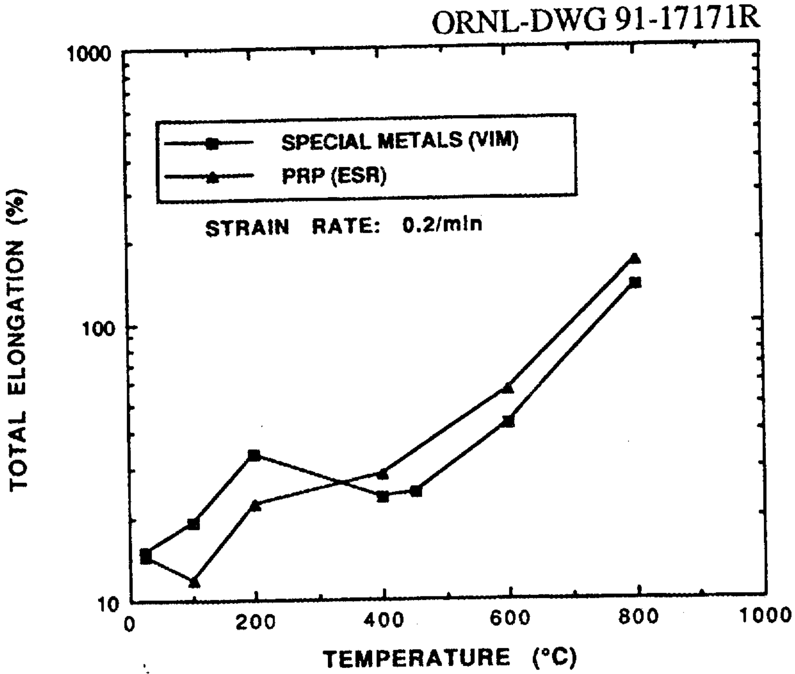
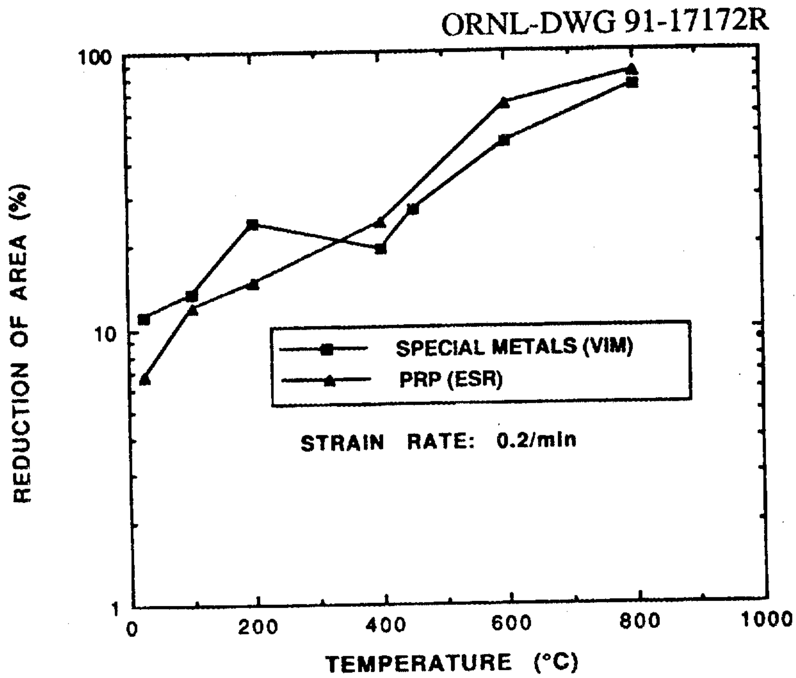


(*b*)

Fig. 15. Tensile properties of specimens from a 0.76-mm-thick sheet rolled from a section of the 406-mm-diam ESR ingot of alloy FA-129. Data on the 406-mm-diam ingot are compared with the previously developed data on a 102-mm-diam ingot of the same alloy: (*a*) yield strength and (*b*) ultimate tensile strength.



(*a*)



(*b*)

Fig. 16. Tensile properties of specimens from a 0.76-mm-thick sheet rolled from a section of the 406-mm-diam ESR ingot of alloy FA-129. Data on the 406-mm-diam ingot are compared with the previously developed data on a 102-mm-diam ingot of the same alloy: (*a*) total elongation and (*b*) reduction of area.

1. Even with its advantages, ESC technology has a very limited chance of advancement in the United States. However, the processing of rounds and slabs by the ESR process is a well established commercial technology and will continue to expand.
2. Two studies were conducted by commercial vendors in support of the present program. The commercial vendors were Special Metals Corporation and PRP.
3. Special Metals Corporation prepared the electrodes of iron-aluminide alloy FA-129 by the VIM process. One set of electrodes was prepared in an MgO-Al_2O_3 crucible and the other half in an Al_2O_3 crucible. The electrodes from each melt crucible were remelted into 152-mm-diam ingots by the VAR and ESR processes. The quality of the ESR ingots was excellent, similar to that of the VAR ingots.
4. One each of the VIM, VAR, and ESR ingots was hot-bar rolled to yield a 25-mm-diam bar stock at Special Metals Corporation. The quality of the finished bars of alloy FA-129 was excellent, irrespective of the melting practice.
5. The processing trials at ORNL of the FA-129 ingots prepared at Special Metals Corporation revealed that the ESR ingots did not respond well as the VAR ingots. The extruded sheet bars from the ESR ingots showed centerline cracking. The hydrogen pick-up during ESR melting is considered a possible cause for the centerline cracking.
6. As part of PRP's cost-shared subcontract, one 2000- and one 3000-kg heat of alloy FA-129 were processed by VIM at PRP. The 2000-kg heat was cast into a 330-mm-diam round electrode, and the 3000-kg heat was cast into a 244 × 965 × 203-mm slab electrode. The 330-mm-diam round electrode was processed by ESR into a 406-mm-diam round ingot. The surface quality of the ESR ingot was excellent. However, when the ingot was cut, it contained cracks. The exact reason for the cracks could not be established. The slab electrode was not remelted because the vendor who was expected to conduct the remelting backed out of the initial commitment.
7. Part of the 406-mm-diam ESR ingot was processed into a 0.76-mm-thick sheet and tested. Tensile properties of the sheet from the 406-mm-diam ESR ingot compared favorably with the sheet processed from the 102-mm-diam VIM ingot melted at Special Metals Corporation.
8. Besides the subcontract with two companies and the use of newly developed iron-aluminide material for the studies, no interest could be generated in commercialization of ESC technology in the United States.

7. ACKNOWLEDGMENTS

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