MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0354632 1

ORNL/TM-11796

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Properties of Large Heats of Fe_3Al-Based Alloys

V. K. Sikka
C. G. McKamey
C. R. Howell
R. H. Baldwin

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
CIRCULATION SECTION
4500N ROOM 175
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this report, send in name with report and the library will arrange a loan.

Fossil Energy Program

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-11796

Metals and Ceramics Division

PROPERTIES OF LARGE HEATS OF Fe_3Al-BASED ALLOYS

V. K. Sikka, C. G. McKamey, C. R. Howell, and R. H. Baldwin

Date Published - March 1991

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Prepared for the
U.S. DOE Fossil Energy AR&TD Materials Program
AA 15 10 10 0

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0354632 1

TABLE OF CONTENTS

LIST OF TABLES v
LIST OF FIGURES vii
ABSTRACT 1
INTRODUCTION 1
ALLOY NOMENCLATURE 2
SCALEUP OF ALLOYS 2
  FAS ALLOY 2
  FAL ALLOY 4
  FA-129 ALLOY 12
INTERACTION WITH INDUSTRY 30
SUMMARY AND CONCLUSIONS 31
FUTURE WORK 32
ACKNOWLEDGEMENTS 32
REFERENCES 33

LIST OF TABLES

Table 1. Nominal composition of tested Fe_3Al alloys 2

Table 2. Target and vendor analysis of vacuum-induction-melted heat of FAS alloy at Haynes International, Inc. 3

Table 3. Powder chemical composition and selected physical properties 4

Table 4. Target, vendor, and check analyses of vacuum-induction-melted and electroslag-remelted heats of FAL alloy at Haynes International, Inc. 9

Table 5. Chemical analysis of alloy FAL prepared by vacuum-induction melting and electroslag remelting at Carpenter Technology Corporation 11

Table 6. Target and vendor check analysis of vacuum-induction-melted ingots at Special Metals Corporation 17

LIST OF FIGURES

Fig. 1. Comparison of yield strength of Fe_3Al sheet produced from powder metallurgy (P/M) product and cast ingot 5

Fig.2. Comparison of ultimate tensile strength of sheet produced from powder metallurgy (P/M) product and cast ingot 5

Fig. 3. Comparison of total elongation of sheet produced from powder metallurgy (P/M) product and cast ingot........ 6

Fig. 4 Comparison of reduction of area of sheet produced from powder metallurgy (P/M) product and cast ingot 6

Fig. 5. Comparison of creep rupture strength of sheet produced from powder metallurgy (P/M) product and cast ingot........ 7

Fig. 6. Comparison of creep elongation of sheet produced from powder metallurgy (P/M) product and cast ingot........ 7

Fig. 7. Photograph of vacuum-induction-melted and electroslag-remelted ingots of iron aluminide FAL alloy processed at Haynes International. The ingots are 51-, 76-, and 102-mm-diam (2-, 3-, and 4-in.), respectively 8

Fig. 8. Photograph of a 203-mm-diam (8-in.) electroslag-remelted ingot of iron-aluminide FAL alloy prepared at Carpenter Technology Corporation 10

Fig.9. Photograph showing hot-forged and hot-forged and machined bars of iron-aluminide FAL alloy processed at Carpenter Technology Corporation. The starting material was an 203-mm-diam (8-in.) ingot prepared by vacuum-induction melting and electroslag remelting at Carpenter Technology Corporation 13

Fig. 10. Photograph of vacuum-induction-melted and vacuum-arc-remelted iron-aluminide FA-129 alloy ingots processed at Special Metals Corporation. The ingots are of 102- and 152-mm-diam (4- and 6-in.), respectively 14

Fig. 11. Photograph of vacuum-induction-melted and electroslag-remelted 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 (6-in.) diam........ 15

Fig. 12. Photograph showing bars fabricated from 102- and 152-mm-diam (4- and 6-in.) ingots of iron-aluminide FA-129 alloy at Special Metals Corporation. The bars were produced by hot-bar rolling 102- and 152-mm-diam (4- and 6-in.) vacuum-induction-melted and electroslag-remelted ingots produced at Special Metals Corporation 16

Fig. 13. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot center location. Magnification: 50× 20

Fig. 14. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot one-half radius location. Magnification: 50× 21

Fig. 15. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in an MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot edge location. Magnification: 50× 22

Fig. 16. Comparison of high magnification optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in an MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot one-half radius location. Magnification: 200× 23

Fig. 17. Optical micrographs of 6.35-mm-thick (0.25-in.) as-rolled plate fabricated from 102-mm-diam (4-in.) ingot of FA-129 alloy prepared by vacuum-induction melting at Special Metals Corporation. (*a*) and (*b*) are longitudinal and transverse sections near the plate edge, and (*c*) and (*d*) are longitudinal and transverse sections near the plate center. Note that the precipitate density is significantly higher near the edge than at the center of the plate 24

Fig. 18. Effect of cooling medium on 0.2% yield strength as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction melted ingot melted in a MgO crucible at Special Metals Corporation. Yield strength is not affected by either oil quenching (OQ) or air cooling (AC) 26

Fig. 19. Effect of cooling medium on 0.2% yield strength as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Full values of ultimate tensile strength were not achieved for specimens either oil quenched (OQ) or air cooled (AC). However, the air-cooled specimens values were even lower because of environmental effects 26

Fig. 20. Effect of cooling medium on total elongation as a function of test temperature for specimens from 0.76-mm-thick 0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Total elongation values are higher for oil-quenched (OQ) specimens than for air-cooled (AC) specimens for test temperatures <200°C 27

Fig. 21. Effect of cooling medium on reduction of area as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Reduction of area values are higher for oil-quenched (OQ) specimens than for air-cooled (AC) specimens for test temperatures <200°C 27

Fig. 22. Effect of cooling medium on creep behavior for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Oil quenching (OQ) is compared with air cooling (AC). Creep tests were conducted at 450°C and 379 MPa 28

Fig. 23. Effect of cooling medium on creep behavior for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Oil quenching (OQ) is compared with air cooling (AC). Creep tests were conducted at 650°C and 34.5 MPa 28

Fig. 24. Larson-Miller plot showing the status of creep testing of FAS and FAL alloys. Data on 403 and 304 stainless steels are included for comparison. Creep tests are for temperatures of 450 to 704°C. All tests are on cast and processed material except the Ametek material, which was produced from powder 29

Fig 25. Larson-Miller plot showing the status of creep testing of FA-129 alloy. Creep tests are on one experimental heat and two commercial heats. Test temperatures ranged from 450 to 704°C.. 29

PROPERTIES OF LARGE HEATS OF Fe_3Al-BASED ALLOYS*

V. K. Sikka, C. G. McKamey, C. R. Howell, and R. H. Baldwin

ABSTRACT

The scaleup of three Fe_3Al-based alloys at several commercial vendors is described. The scaleup processes examined the effect of crucible material (MgO versus Al_2O_3), melting practice, vacuum-induction melting, vacuum-arc remelting, electroslag remelting, and processing under commercial conditions. Each alloy is designed for a specific use: sulfidation resistance, room-temperature ductility, and high-temperature strength. One of the alloys was also scaled up through powder production by nitrogen-gas atomization. The scaled-up heats varied in size from 50 to 250 kg (100 to 500 lb). The ingot sizes varied from 38- to 203-mm (1 1/2- to 8-in.) diam. The scaleup processes occurred at Ametek Specialty Metal Products Division; Haynes International, Inc.; Carpenter Technology Corporation; Special Metals Corporation; and Precision Rolled Products, Inc. The processing of 102-mm-diam (4-in.) ingots at the Oak Ridge National Laboratory into plate and sheet is described in detail. Tensile and creep data on a large powder-metallurgy and cast-and-worked alloys are presented. Recommendations are made for future work on the heats scaled up in this study.

INTRODUCTION

The success[1] in increasing the room-temperature ductility of iron aluminides (Fe_3Al) has significantly increased the potential for their use in many applications. These applications include steam turbine parts, heating elements; automotive exhaust systems; components in sulfidizing environments; and components in highly oxidizing environments such as containment for molten salts, furnace furniture, and gas cleanup filters. To use iron aluminides in these applications, it is necessary to scale them up and to have property data on large heats. It is also necessary to prepare data packages to include these materials in ASTM standards, the ASME boiler and pressure vessel codes and piping codes. The purpose of this report is to present information on the scaleup of Fe_3Al-based alloys, processing of the scaled-up heats, property data, and interaction with industry.

*Research sponsored by the U.S. Department of Energy, Fossil Energy AR&TD Materials Program under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

ALLOY NOMENCLATURE

Three categories of (Fe_3Al) alloys are under investigation. The first composition has been maximized for sulfidation resistance and is designated as FAS. The second has been designed for maximum room-temperature tensile ductility and is designated as FAL. The third is being designed for maximum high-temperature strength and is designated as FA-129. The final designation of this alloy will be FAH. Nominal compositions of the three alloys are given in Table 1.

Table 1. Nominal composition of tested Fe_3Al alloys

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

SCALEUP OF ALLOYS

FAS ALLOY

The sulfidation-resistant alloy FAS has been produced by both casting and powder metallurgy. The scaleup in the cast form consisted of melting a nominal 50-kg (100-lb) heat of this composition at Haynes International. The alloy was processed by vacuum-induction melting (VIM) and cast into 38-mm-diam (1 1/2-in.) bar stock. The nominal and vendor analysis of the heat is shown in Table 2. The entire bar stock from this heat was supplied to Professor Donald E. Mikkola at Michigan Technological University for casting studies. The remelting and casting trials at Michigan Technological University indicated that the alloy had adequate fluidity for casting into shapes. A few test coupons from this material were cast by

Table 2. Target and vendor analysis of vacuum-induction-melted heat of FAS alloy at Haynes International, Inc.

Element	Composition (wt %) Heat 0020-0-0676	
	Target	Vendor
Al	15.90	15.77
Cr	2.20	2.20
B	0.01	0.015
Fe	Balance	Balance

remelting the material in air and supplied to a company* for testing in sulfidizing environments. If the initial results are favorable, more complex parts will be cast at Michigan Technological University and supplied to the same company for component testing under actual operating conditions.

The scaleup of FAS alloy also took place through the production of powder. Each scaled-up heat, weighing 250 kg (500 lb), was air-induction melted (AIM), and atomized by nitrogen gas. All atomization took place at Ametek Specialty Metal Products Division. Since the time of the first scaleup, Ametek has obtained an exclusive license from the Oak Ridge National Laboratory (ORNL) to produce iron-aluminide powders. The iron-aluminide powders are currently available for purchase from Ametek.

The FAS powder from the first scaled-up powder heat[2] was consolidated, processed, and tested at ORNL. Chemical analysis and powder characteristics for this heat are given in Table 3. The processing details follow Table 3.

A 76-mm-diam (3-in) mild steel can was filled with iron-aluminide powder. The can was then evacuated, sealed, and heated for 1 1/2 h at 1000°C and extruded through a 25-mm (1-in.) die to obtain an area reduction of 9:1. Optical microstructure of the as-extruded bar[2] showed full consolidation from the surface to the center of the bar. The grain size was 20 μm and uniform across the bar.

*The name of the company is not given because its agreement with ORNL is proprietary at present.

Table 3. Powder chemical composition[a] and selected physical properties
Apparent density = 3.75 g/cm^3; flow = 18 s/50 g

Composition R·M (wt %)[a]							
Alumium	Chromium	Boron	Oxygen	Nitrogen	Carbon	Sulfur	Iron
15.93	2.2	0.01	0.013	0.003	0.018	0.007	Bal.
Size Distribution R·M[b] (%)							
+80 (0)	-80+100 (0.6)	-100/+120 (20.8)	-120/+140 (29.6)	-140/+170 (12.4)	-170/+200 (32.5)	-200 (4.1)	

[a]Patent pending.
[b]U.S. standard mean size.

The steel can was removed from the extruded bar by a 10% HNO_3 solution. Two 76-mm-long (3-in.) sections of the bar were forged 50% at 1000°C, rolled 50% at 850°C, and finish rolled 50% at 650°C to 0.76-mm-thick (0.030-in.) sheet. These sheets were used to determine mechanical properties. A similar processing sequence was used to prepare sheet from a 76-mm-diam (3-in.) cast ingot of the same composition.

Tensile properties of powder-metallurgy-processed heats are compared with an AIM-processed and cast heat in Figs. 1 through 4. A similar comparison for creep data is presented in Figs. 5 and 6. These figures show that the scaled-up powder heat has tensile and creep properties similar to the laboratory-size cast and processed heat. Processing of a second scaled-up powder-metallurgy heat is currently under way. Data on this heat will be compared with the first heat to determine the heat-to-heat variability in properties. Tensile data on the nitrogen-atomized-powder heat was also compared with an argon-atomized powder heat in a previous publication.[2] In general, the heat produced from the nitrogen-atomized powder was found to be somewhat stronger in both tensile and creep properties than heats produced from argon-atomized powder. No nitrides were observed in the sheet fabricated from the nitrogen-atomized powder.

The powder is being considered for use in fabricating porous metal gas filters and for spray coatings to enhance the sulfidation resistance of other structural materials. Development of both applications is currently under way.

FAL ALLOY

The FAL alloy was scaled up at Haynes International, Inc., and Carpenter Technology Corporation. Three heats at Haynes weighed 50 kg (100 lb) each and were prepared by the

ORNL-DWG 90-17145

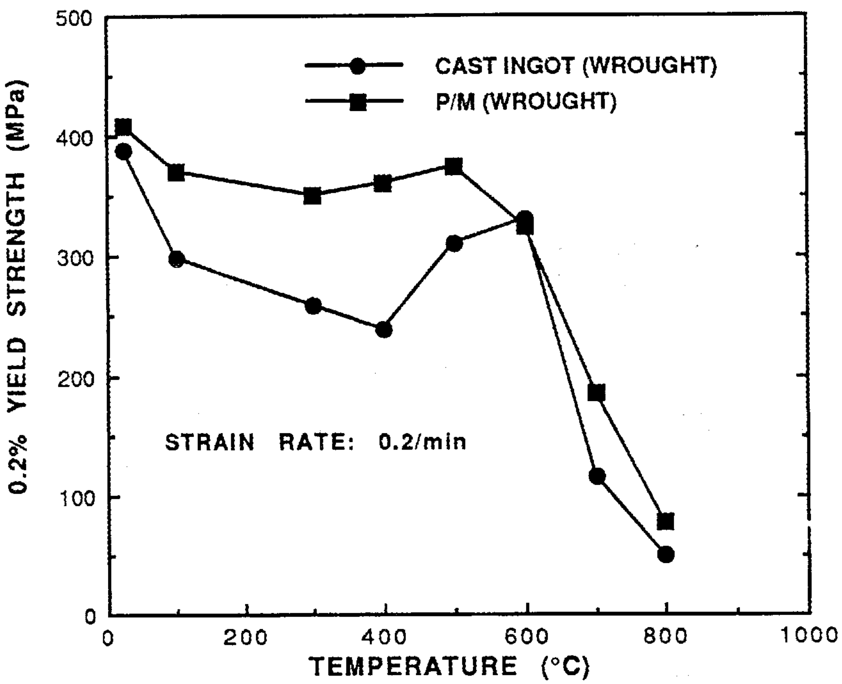


Fig. 1. Comparison of yield strength of Fe_3Al sheet produced from powder metallurgy (P/M) product and cast ingot.

ORNL-DWG 90-17146

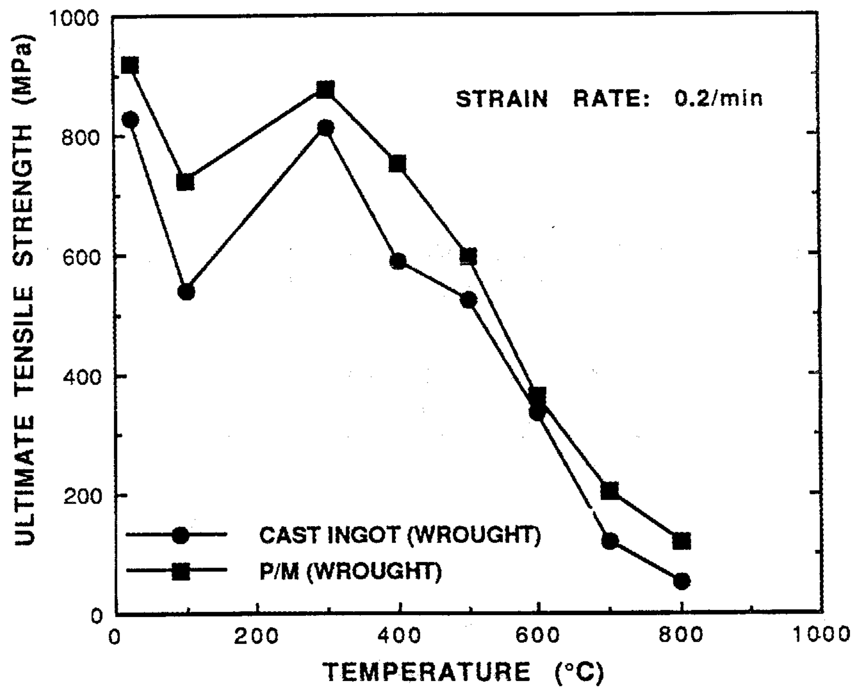


Fig. 2. Comparison of ultimate tensile strength of sheet produced from powder metallurgy (P/M) product and cast ingot.

ORNL-DWG 90-17147

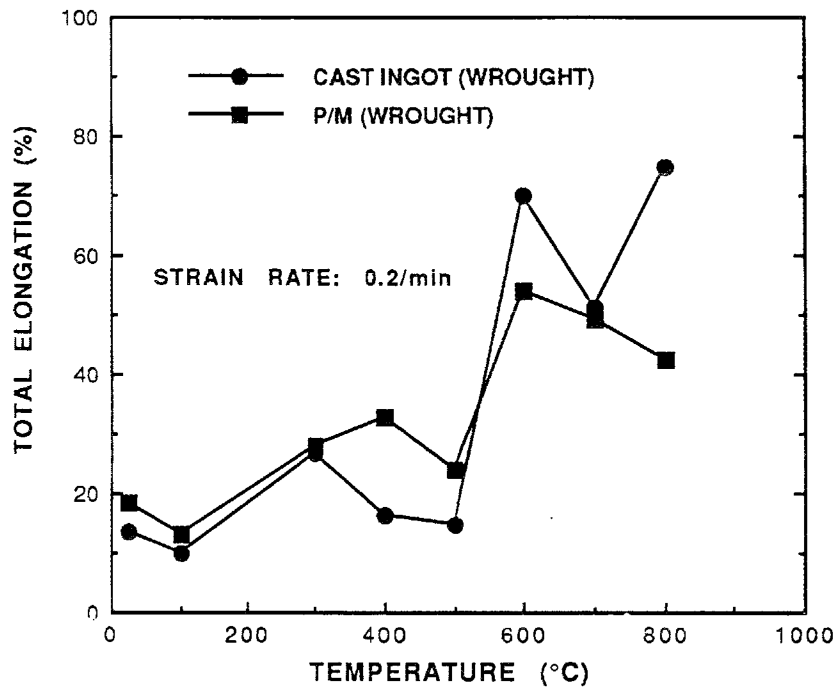


Fig. 3. Comparison of total elongation of sheet produced from powder metallurgy (P/M) product and cast ingot.

ORNL-DWG 90-17148

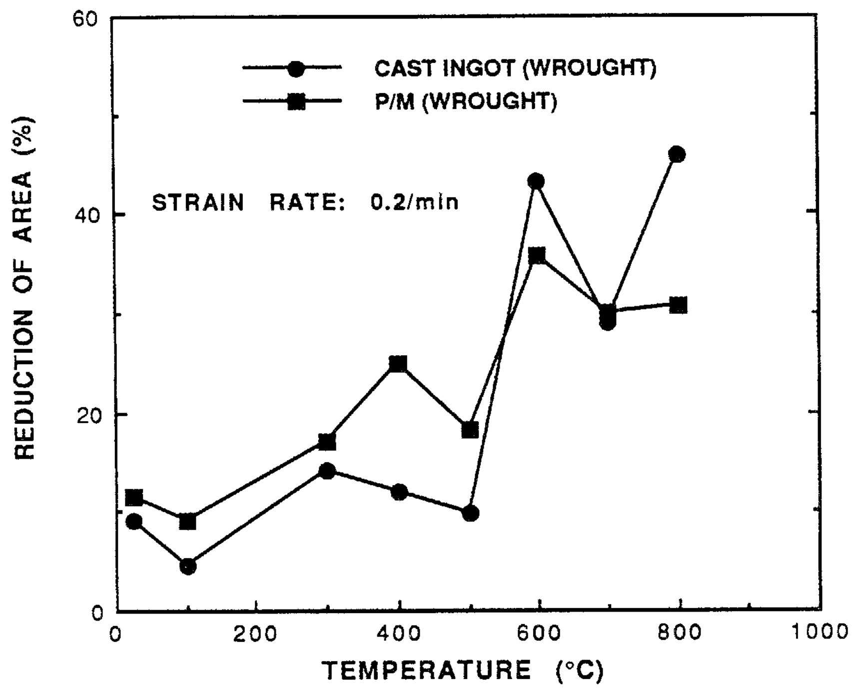


Fig. 4. Comparison of reduction of area of sheet produced from powder metallurgy (P/M) product and cast ingot.

ORNL-DWG 90-17149

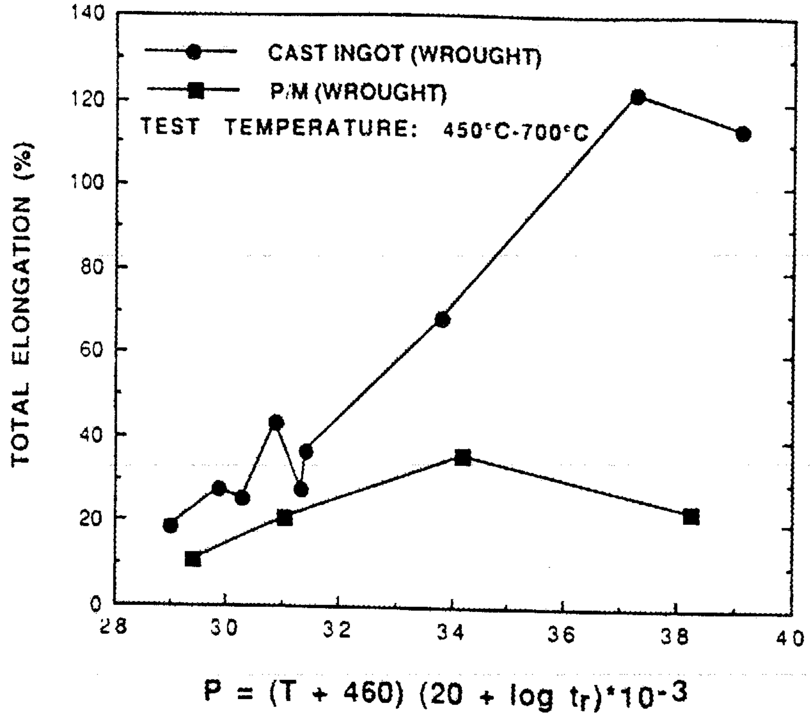


Fig. 5. Comparison of creep rupture strength of sheet produced from powder metallurgy (P/M) product and cast ingot.

ORNL-DWG 90-17150

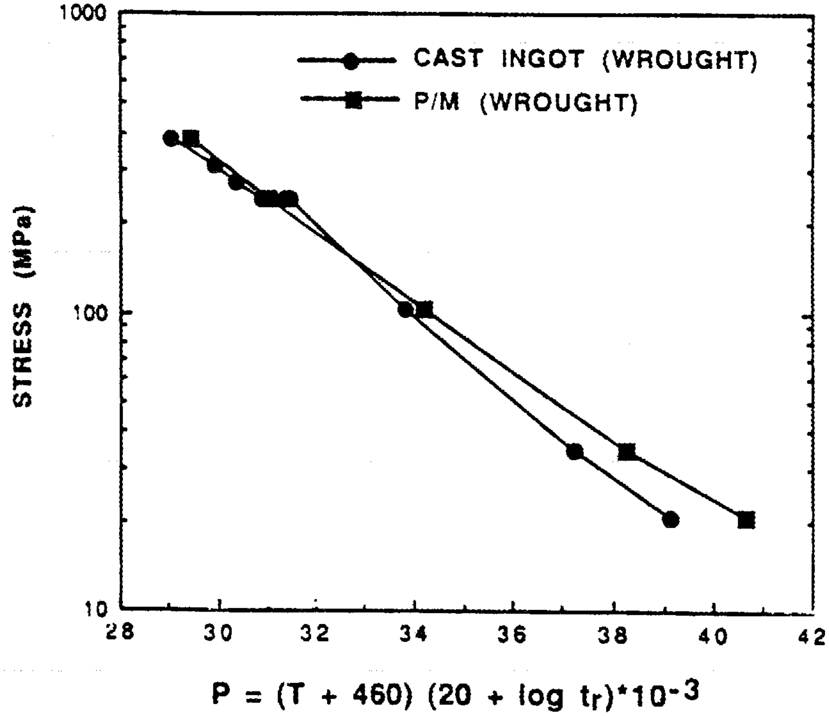


Fig. 6. Comparison of creep elongation of sheet produced from powder metallurgy (P/M) product and cast ingot

vacuum-induction-melting (VIM) process. These heats were cast into 38-mm-diam (1 1/2-in.) bars, 76-mm-diam (3-in.) ingots, and 76-mm-diam (3-in.) electrodes. The 38-mm-diam (1 1/2-in.) bars were to be processed by VAR at ORNL. The 76-mm-diam (3-in.) electrodes were processed by electroslag remelting (ESR) in 102-mm-diam (4-in.) ingots at Haynes. All of the heats from Haynes are shown in Fig. 7. The chemical compositions of these heats are given in Table 4.

The scaleup at Carpenter Technology consisted of processing a 152-mm-diam (6-in.) ingot from a 500-lb (250-kg) heat by the VIM process. The ingot was melted in a MgO crucible. The VIM electrode was processed by ESR into a 203-mm-diam (8-in.) ingot. This ingot is shown in Fig. 8. The chemical analyses of the ingot produced by VIM and ESR are presented in Table 5. The magnesium content of the ESR ingot increased to 30 ppm or more from a level of 10 ppm in the VIM electrode.

YP9508

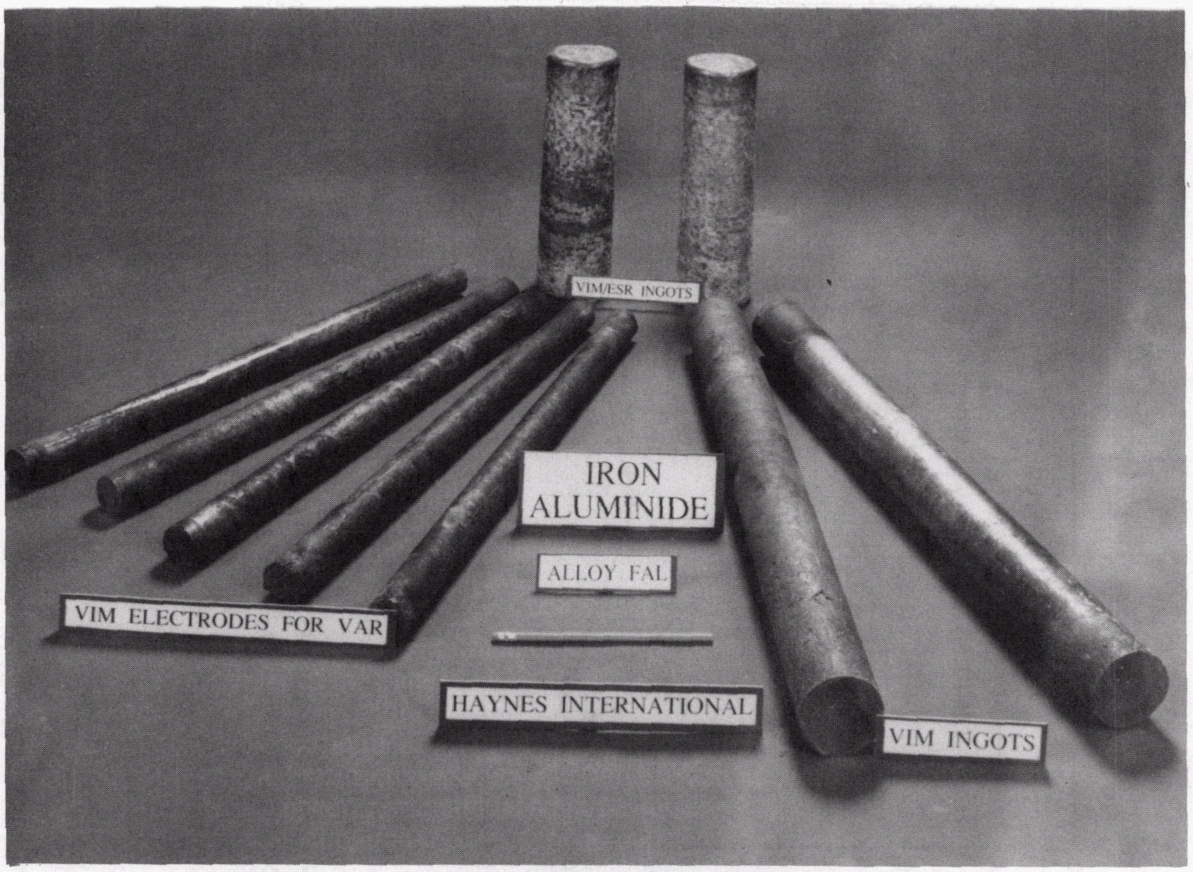


Fig. 7. Photograph of vacuum-induction-melted and electroslag-remelted ingots of iron-aluminide FAL alloy processed at Haynes International. The ingots are 51-, 76-, and 102-mm-diam (2-, 3-, and 4-in.), respectively.

Table 4. Target, vendor, and check analyses of vacuum-induction-melted and electroslag-remelted heats of FAL alloy at Haynes International, Inc.

Element	Composition (wt %)							
	Heat 6-0-0627[a]			Heat 6-0-0629[b]		Heat 6-0-0630[c]		
	Target	Vendor analysis	Check analysis	Target	Vendor analysis	Target	Vendor analysis	Check analysis
Al	15.9	16.13	16.60	15.9	16.40	15.9	16.27	16.5
Cr	5.5	5.51	5.35	5.5	5.51	5.5	5.52	5.37
B	0.01	0.009	0.008	0.01	0.01	0.01	0.01	0.009
Zr	0.15	0.25	0.27	0.15	0.25	0.15	0.25	0.29
Fe	Bal.	Bal.		Bal.	Bal.	Bal.	Bal.	Bal.
C	—	0.006	0.015	—	0.006	—	0.024	0.011
Mn	—	—	0.02	—	—	—	—	0.02
P	—	—	0.001	—	—	—	—	0.002
S	—	—	0.001	—	—	—	—	0.002
Si	—	—	0.04	—	—	—	—	<0.01
Ni	—	—	0.09	—	—	—	—	0.05
Mo	—	—	0.01	—	—	—	—	0.01
Cb	—	—	<0.01	—	—	—	—	<0.01
Cu	—	—	0.01	—	—	—	—	0.01
N_2[d]	—	—	0.007	—	—	—	—	0.013
O_2[d]	—	—	0.015	—	—	—	—	0.020

[a]Electroslag-remelted 102-mm-diam (4-in.) ingots.
[b]Vacuum-induction-melted 76-mm-diam (3-in.) ingots.
[c]Vacuum-induction-melted 38-mm-diam (1.5-in.) ingots.
[d]Note that the nitrogen and oxygen contents of two of the three heats checked was much higher than typical values observed at the Oak Ridge National Laboratory and other vendors.

Fig. 8. Photograph of a 203-mm-diam (8-in.) electroslag-remelted ingot of iron-aluminide FAL alloy prepared at Carpenter Technology Corporation.

Table 5. Chemical analysis of alloy FAL prepared by vacuum-induction melting and electroslag remelting at Carpenter Technology Corporation

Element	Weight percent					
	Target	VIM[a]	ESR[a]		ESR[b]	
			Top	Bottom	Top	Bottom
Al	15.9	16.2	16.2	15.9	15.96	15.97
Cr	5.5	5.44	5.44	5.46	5.62	5.65
Zr	0.15	0.17	0.17	0.16	0.17	0.16
Nb		<0.01	<0.01	<0.01		
Mo		<0.01	<0.01	<0.01		
C		0.021	0.026	0.028	0.020	0.031
B	0.01	0.008	0.009	0.008	0.011	0.012
S		0.002	0.002	0.002	0.0006	0.0007
Si		0.03	0.04	0.08	0.03	0.08
Ni		0.01	0.01	0.01	<0.01	<0.01
Sn					0.001	<0.001
Mg		0.0010	0.002	0.004	0.006	0.011
As					<0.001	<0.001
Mn		0.030	0.030	0.030	0.01	0.01
P		0.002	0.004	0.004	<0.005	<0.005
N		<0.001	<0.001	<0.001	0.001	0.001
O		<0.001	<0.001	<0.001	<0.0005	<0.0005
Fe	Balance	Balance	Balance	Balance	Balance	Balance

[a]Chemical analysis performed for ORNL at Combustion Engineering, Chattanooga, Tennessee.
[b]Chemical analysis performed at Carpenter Technology Corporation, Reading, Pennsylvania.

The 203-mm-diam (8-in.) ESR ingot was hot forged at 1000°C at Carpenter Technology to a 127-mm-diam (5-in.) bar. The forging was conducted on a 4.55×10^5-kg (500-ton) forging press in Carpenter Technology's research laboratory. Some surface cracks were observed during hot forging. The forged bar was slow cooled and cut in half. One-half was machined to finish as 102-mm-diam (4-in.) bar. The second half of the forged bar was forged into a 51-mm-thick (2-in.) flat ingot. The forged and machined pieces from the Carpenter Technology heat are shown in Fig. 9.

Attempts were made to hot roll sections of the flat forged bar. However, sections alligatored during the first few rolling passes. Chemical analysis of chips taken from the alligatored section showed magnesium concentrations as high as 6 wt %. The pickup of magnesium during the ESR process was considered to be responsible for its segregation and observed alligatoring. Further processing of the 51-mm (2-in.) forged slab was halted at this point. A 152-mm-long (6-in.) section of the machined bar was cut for hot-extrusion trials. A mild steel nose was welded to this bar section, and the billet was hot extruded at 1000°C through a rectangular die with an opening size of 25 × 76 mm (1 × 3 in.). The extruded bar showed several surface cracks. These kinds of cracks have never been observed in any of the previous billets extruded at ORNL. Microstructural analyses are under way to determine the cause for surface cracking in the extrusion from Carpenter Technology's forged bar. No mechanical property data have yet been generated on Carpenter Technology's heat.

FA-129 ALLOY

Scaleup of the FA-129 alloy was performed at Special Metals Corporation. Two 165-kg (330-lb) heats each were prepared by the VIM process. One heat was melted in a MgO crucible and the other heat in an Al_2O_3 crucible. Two crucibles were used to determine the extent of magnesium pickup, if any, from the use of the MgO crucible. Each heat was cast into four 102-mm-diam (4-in.) ingots. One ingot from each heat was saved in the VIM condition. Two additional VIM ingots from each heat were processed by ESR into 152-mm-diam (6-in.) ingots. One VIM ingot each from the MgO and Al_2O_3 crucibles was also prepared by the VAR process into a 152-mm-diam (6-in.) ingot. The VIM and VAR ingots are shown in Fig. 10. The ESR ingots from the MgO-VIM ingots and the Al_2O_3-VIM ingots are shown in Fig. 11.

The VIM, VAR, and ESR ingots were processed into bar stock by hot-bar rolling at Special Metals Corporation. All of the ingots worked satisfactorily into bar stock under commercial bar-rolling conditions. The quality of the bars is shown in Fig. 12. Chemical analyses of the VIM ingots in MgO and Al_2O_3 crucibles are summarized in Table 6. The target composition of

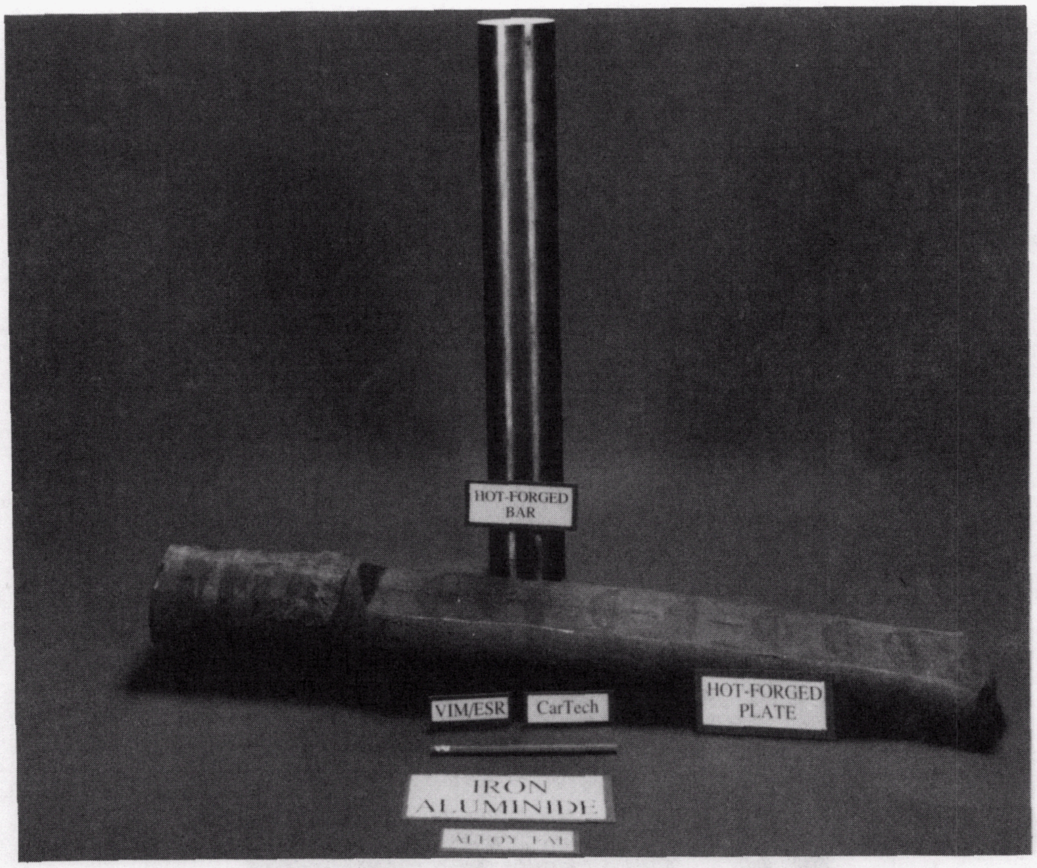


Fig. 9. Photograph showing hot-forged and hot-forged and machined bars of iron-aluminide FAL alloy processed at Carpenter Technology Corporation. The starting material was an 203-mm-diam (8-in.) ingot prepared by vacuum-induction melting and electroslag remelting at Carpenter Technology Corporation.

YP9509

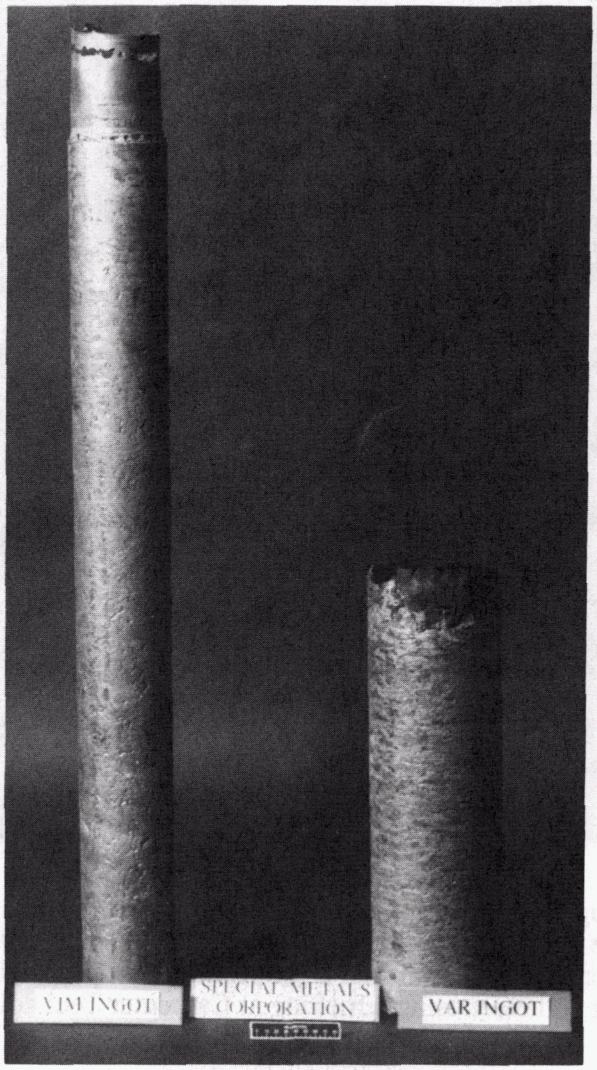


Fig. 10. Photograph of vacuum-induction-melted and vacuum-arc-remelted iron-aluminide FA-129 alloy ingots processed at Special Metals Corporation. The ingots are of 102- and 152-mm-diam (4- and 6-in.), respectively.

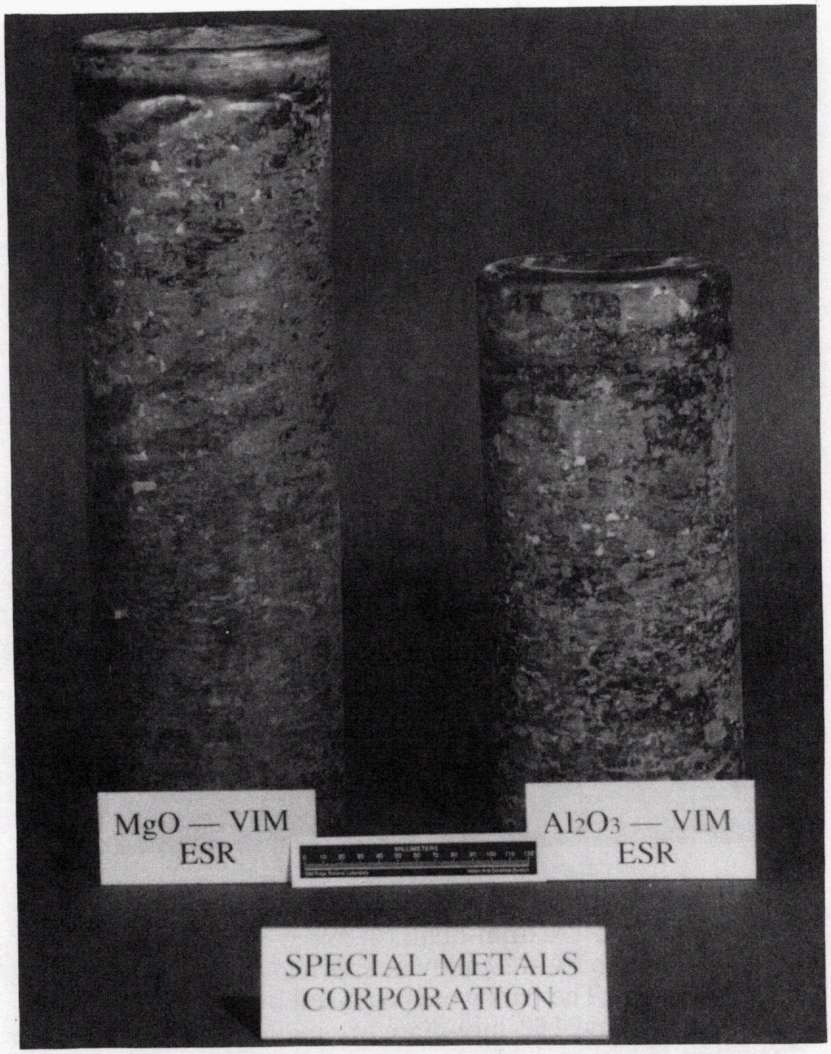


Fig. 11. Photograph of vacuum-induction-melted and electroslag-remelted iron-aluminide FA-129 alloy ingots processed at Special Metals Corporation. One electrode was prepared using an MgO crucible and the other using an Al_2O_3 crucible. Both ingots are 152-mm (6-in.) diam.

YP113737

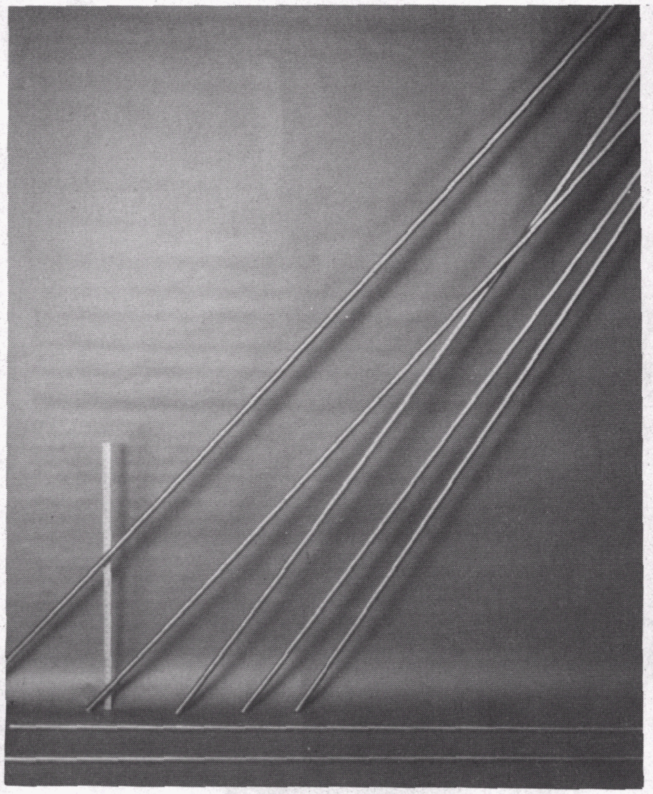


Fig. 12. Photograph showing bars fabricated from 102- and 152-mm-diam (4- and 6-in.) ingots of iron-aluminide FA-129 alloy at Special Metals Corporation. The bars were produced by hot-bar rolling 102- and 152-mm-diam (4- and 6-in.) vacuum-induction-melted and electroslag-remelted ingots produced at Special Metals Corporation.

Table 6. Target and vendor check analysis of vacuum-induction-melted ingots at Special Metals Corporation

Element	Ingot analysis (wt %)				
	Target	Heat[a]		Heat[b]	
		D53965	D53966	D53968	D53969
Al	15.9	16.33	16.30	16.29	16.42
Cr	5.5	5.28	5.31	5.31	5.34
Nb	1.0	0.98	1.00	0.99	1.00
C	0.05	0.049	0.054	0.047	0.055
Fe	Balance	Balance	Balance	Balance	Balance
Mn		0.01	<0.01	<0.01	<0.01
Si		<0.01	<0.01	<0.01	<0.01
Ni		0.01	<0.01	<0.01	<0.01
Co		<0.01	<0.01	<0.01	<0.01
Mo		<0.01	<0.01	<0.01	<0.01
W		<0.01	<0.01	<0.01	<0.01
V		<0.01	<0.01	<0.01	<0.01
Ti		<0.01	<0.01	<0.01	<0.01
B		<0.001	<0.001	<0.001	<0.001
Zr		<0.01	<0.01	<0.01	<0.01
S		0.0010	0.0008	0.0016	0.0010
Cu		0.01	0.01	<0.01	<0.01
Ta		<0.01	0.01	<0.01	<0.01
Hf		<0.01	<0.01	<0.01	<0.01
Ag		<0.0005	<0.0005	<0.0005	<0.0005
Pb		<0.0005	<0.0005	<0.0005	<0.0005
Bi		<0.00005	<0.00005	<0.00005	<0.00005
O		0.0016	0.0007	0.0015	0.0008
N		0.0002	0.0001	0.0001	0.0001
Mg		0.0020	0.0020	0.0010	0.0010
Sn		<0.0020	<0.0020	<0.0020	<0.0020
Cd		<0.0050	<0.0050	<0.0020	<0.0050
Zn		<0.0020	<0.0020	<0.0020	<0.0020
Sb		<0.0020	<0.0020	<0.0020	<0.0020
Ca		<0.0100	<0.0100	<0.0100	<0.0100

[a]Vacuum-induction-melted ingots prepared using an MgO crucible. The MgO-crucible-melted ingots contain twice as much magnesium as the Al_2O_3-crucible-melted ingots as a result of chemical reaction with the MgO crucible.

[b]Vacuum-induction-melted ingots prepared using an Al_2O_3 crucible.

the FA-129 alloy is also included for comparison. The chemical analyses of the ESR ingots are not completed at the present time. Some general observations can be made about the VIM process in MgO and Al_2O_3 crucibles : (1) major elements of the alloy were met well, (2) magnesium content of the heat melted in the MgO crucible was twice that of the ingot melted in the Al_2O_3 crucible, (3) oxygen content was extremely low in both heats, (4) nitrogen content was even lower than the oxygen content, and (5) overall residual-element content was extremely low. The main point to note is that the magnesium content of the ingot melted in the MgO crucible is twice that of the ingot melted in the Al_2O_3 crucible although the starting material was the same. The magnesium content of the heat melted in the MgO crucible at Special Metals Corporation is between the amount observed for the VIM and ESR ingots of FAL alloy prepared at Carpenter Technology.

The following detailed procedure was used at ORNL to process and section the 102-mm-diam (4-in.) MgO-melted FA-129 ingot from Special Metals Corporation.

1. Source:	Special Metals Corporation
2. Melt Type:	Vacuum induction
3. Heat Size:	165 kg (330 lb)
4. Ingot Type and Size:	Round ingot 102-mm diam × 203-mm long (4-in. × 34-in.) with small hot-top
5. Cutting Plan:	Cut hot-top, 13-mm-thick (1/2-in.) slice, 203-mm-long (8-in.) billet, 203-mm-long (8-in.) billet, 13-mm-thick (1/2-in.) slice, 203-mm-long (8-in.) billet, and 203-mm-long (8-in.) billet
6. Cutting Method:	Bandsaw without lubricant
7. Homogenization Treatment:	Billets 1 and 2 from top of the ingot were heated in air at 1150°C for 64 h. The billets were transferred to an air furnace at 700°C for 1 h followed by air cooling. The 700°C step was used to minimize the cooling stresses from 1150°C. One 13-mm-thick (1/2-in.) slice from each billet was sectioned with a bandsaw for metallography.
8. Preextrusion Preparation:	Carbon steel noses were TIG welded to each billet using IN82 filler wire. This was done by an ORNL shop welder.
9. Extrusion:	Billets were heated in air at 1000°C for 2 h and extruded through a rectangular die of 25 mm × 76 mm (1 in. × 3 in.) to a reduction ratio of 4.3:1. The K-factor for these extrusions were 32 and 31 tons, respectively. Each extrusion had a slight twist but an excellent surface quality.

10. Cutting of Extrusions:	After cutting the mild steel nose section, each extrusion was bandsaw cut into nearly 203-mm-long (8-in.) pieces. The pieces were marked 1, 2, and 3, respectively.
11. Rolling:	Each piece was hot rolled at 800°C from a thickness of 25 mm to 13 mm (1 in. to 1/2 in.). The rolling passes were 15% each with reheating times of 10 min each. Each piece was cut into two pieces for subsequent rolling at 650°C. The 650°C rolling reduced the thickness from 13 mm to 6.35 mm (1/2 in. to 1/4 in.). The 6.35-mm-thick (1/4-in.) pieces ended up with some curvature. Each piece was cut into two and rolled at 650°C with zero reductions. This flattened the pieces. One piece was cut in order to get chemistry and metallography specimens. One of the 6.35-mm-thick (1/4-in.) pieces was rolled at 650°C to a thickness of 0.76 mm (0.030 in.). No cracking was observed during any of the rolling steps.
12. Chemical Analysis:	One specimen has been sent to MQS Inspection, Inc. in Cincinnati, Ohio, for chemical analysis.

Optical micrographs of the 102-mm-diam (4-in.) VIM ingot are shown in Figs. 13 through 16 in the as-cast and after homogenization at 1150°C for 64 h. These figures represent the specimen locations of ingot center, half radius, and ingot edge. The cast microstructure contained precipitates, which remained unchanged in size and distribution by the homogenization heat treatment. The 1150°C treatment for 64 h seems to have produced some increase in grain size. Photomicrographs of a 6.35-mm-thick (0.25-in.) as-rolled plate fabricated from a 102-mm-diam (4-in.) ingot of FA-129 prepared by the VIM process at Special Metals Corporation are presented in Fig. 17. The micrographs were taken from near the edge and the center of the plate thickness in both longitudinal and transverse directions. Both orientations showed a higher density of precipitates near the plate edge than the plate center. Reasons for such a difference may be the dissolution and renucleation of precipitates at many sites near the billet edge because of faster cooling at the edge from the homogenization temperature of 1150°C. The slower cooling of the billet center may have caused less nucleation and, thus, less precipitate coarsening at the plate center. Very poor thermal conductivity of Fe_3Al-based alloys may have exaggerated the precipitate size difference between the plate edge and center.

One 203-mm-long (8-in.) section of the 102-mm-diam (4-in.) VIM ingot was sent to Precision Rolled Products for bar rolling in their production mill. The bar was heated to 1000°C and bar rolled to 10-mm (0.4-in.) diam with intermediate grinding to remove surface defects. The bars are finished at a size of 102-mm-diam (4-in.). No problems were encountered in bar rolling the 102-mm-diam (4-in.) ingots in the commercial mill at Precision Rolled Products. However, the finished bars were too brittle to straighten at room temperature

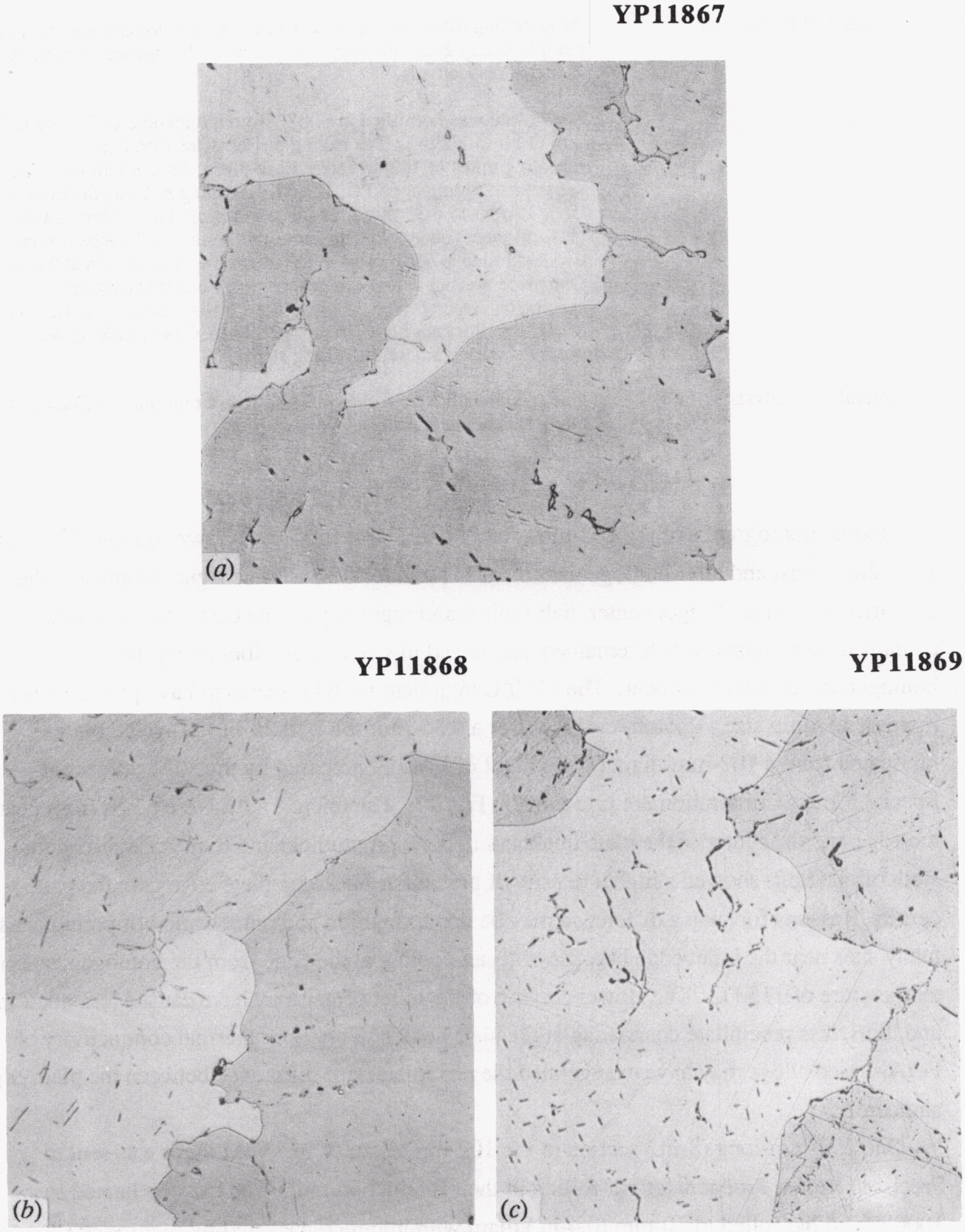
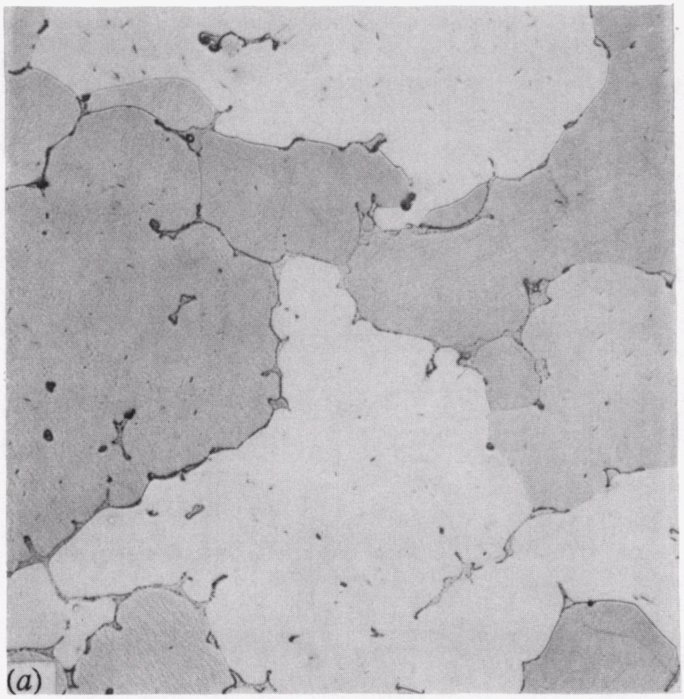
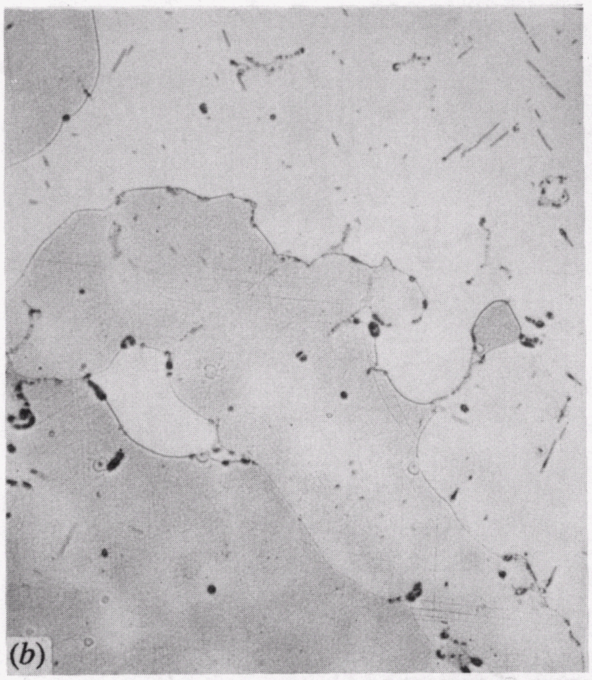


Fig. 13. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. (a) As-cast, (b) and (c) homogenized for 64 h at 1150°C at ingot center location. Magnification: 50×.

YP11864



YP11865



YP11866

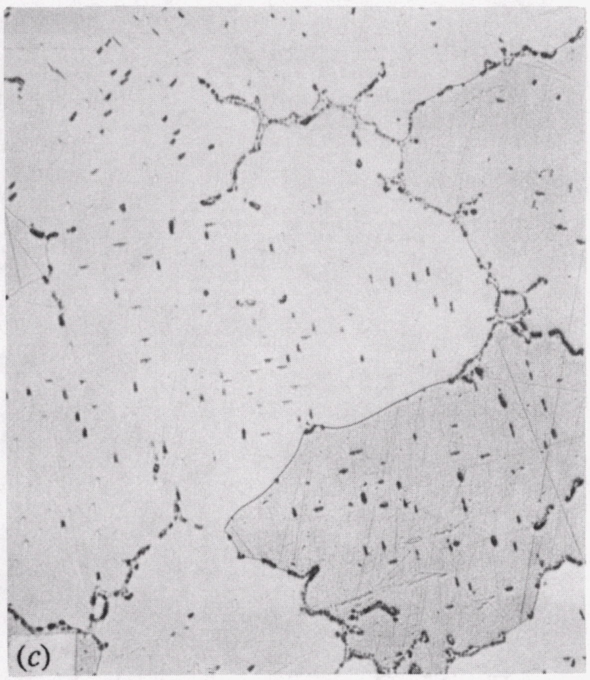


Fig. 14. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot one-half radius location. Magnification: 50×.

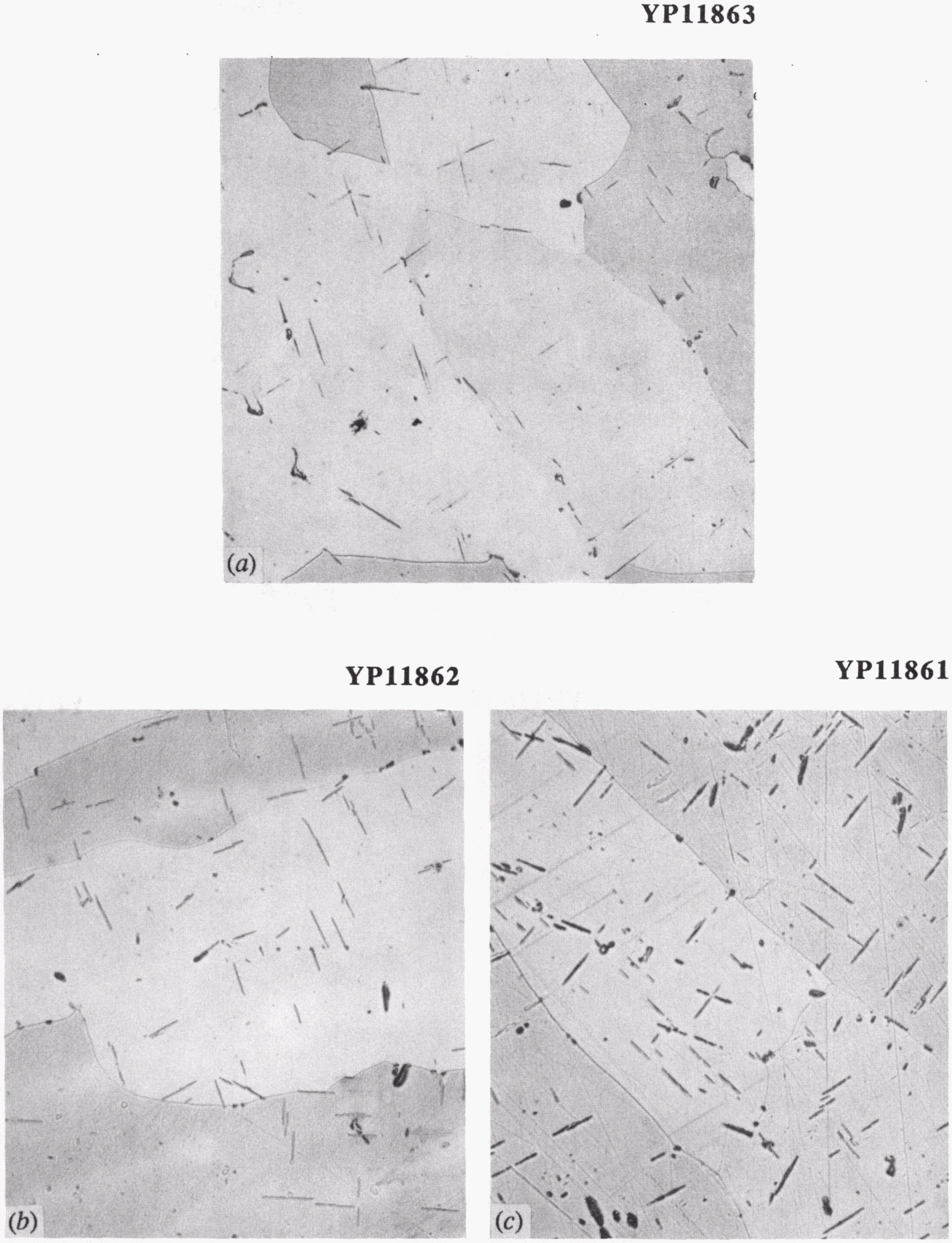
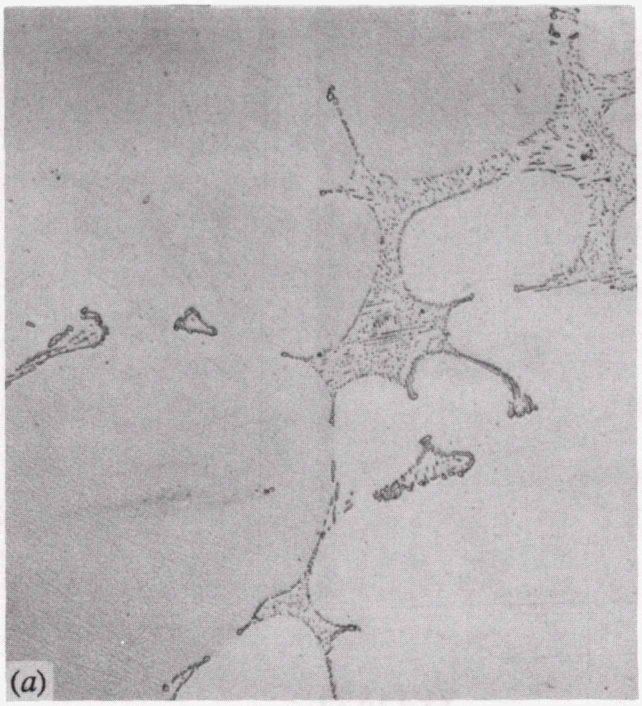
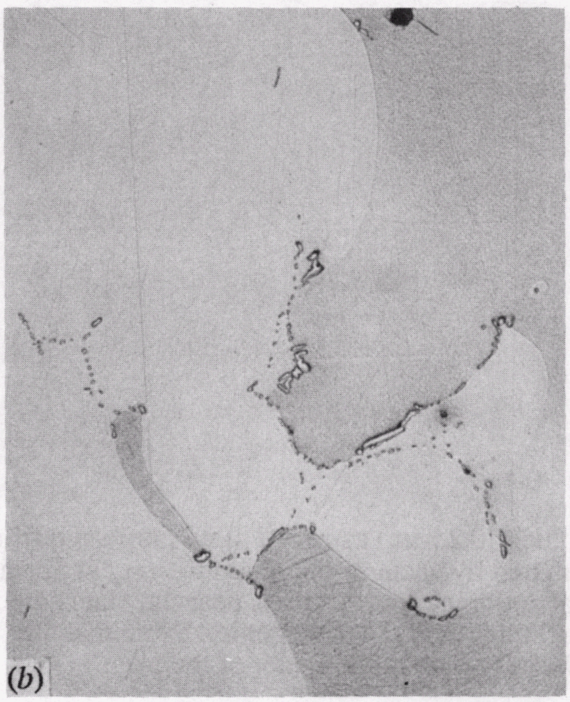


Fig. 15. Comparison of optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in an MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot edge location. Magnification: 50×.

YP11854



YP11855



YP11856

Fig. 16. Comparison of high magnification optical microstructure of as-cast and homogenized sections of 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in an MgO crucible at Special Metals Corporation. (*a*) As-cast, (*b*) and (*c*) homogenized for 64 h at 1150°C at ingot one-half radius location. Magnification: 200×.

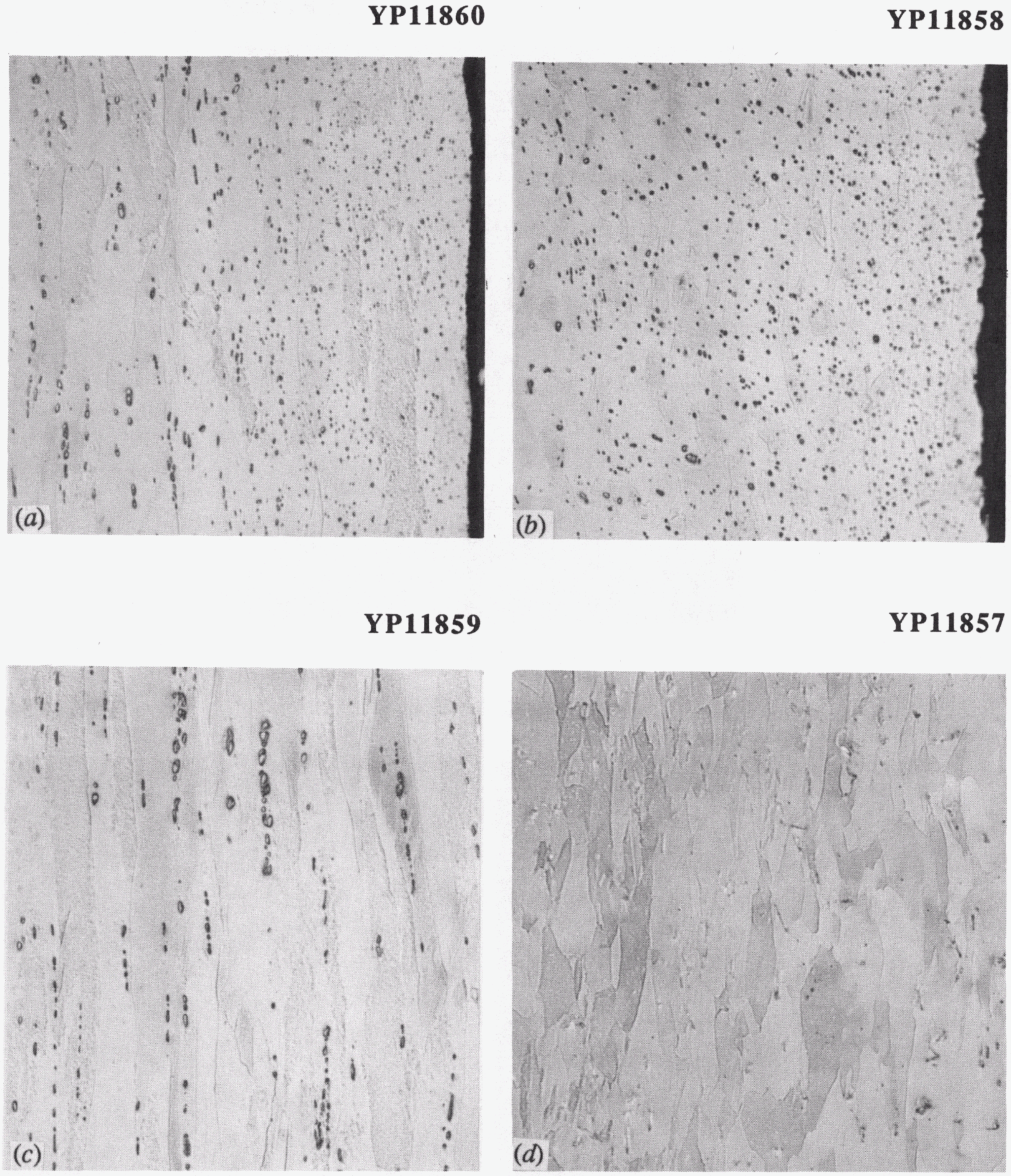


Fig. 17. Optical micrographs of 6.35-mm-thick (0.25-in.) as-rolled plate fabricated from 102-mm-diam (4-in.) ingot of FA-129 alloy prepared by vacuum-induction melting at Special Metals Corporation. (*a*) and (*b*) are longitudinal and transverse sections near the plate edge, and (*c*) and (*d*) are longitudinal and transverse sections near the plate center. Note that the precipitate density is significantly higher near the edge than at the center of the plate.

without cracking. The bars would have been more ductile if intermediate processing was carried out at 800 and 650°C rather than 1000°C. However, these steps were left out, thereby yielding a coarse-grained, low-ductility structure. Precision Rolled Products has agreed to process another ingot through their bar mill to improve the room-temperature ductility. The 0.76-mm-thick (0.030-in.) sheet produced from the VIM ingot melted in the MgO crucible was punched into specimens for tensile and creep testing. The sheet was stress relieved at 700°C for 1 h, followed by oil quenching. One set of punched specimens were given a 1-h anneal at 700°C, followed by oil quenching. The other batch was given a 1-h anneal, followed by air cooling. Tensile tests from room temperature to 800°C on oil-quenched and air-cooled specimens are plotted in Figs. 18 through 21. Most of the tensile tests were conducted in air. The air-cooled specimens and a few oil-quenched specimens were also tested in vacuum. All of the tensile tests were conducted at a strain rate of 3.3×10^{-3} s. Results of the vacuum testing are also included in Figs. 18 through 21. These figures confirm the results[1] on laboratory and scaled-up AIM heats. For air testing, oil quenching produced higher ductility than air-cooled specimens for temperatures up to 100°C. Above 100°C, tensile properties were independent of the final quenching media. It is believed that oil quenching provides a barrier between the specimens and the humidity in air and produces minimum effect associated with hydrogen embrittlement from the reaction of aluminum with moisture. At temperatures >100°C, either hydrogen diffuses away from the surface or diffuses too fast through the specimen for any difference to be caused by the cooling medium. Furthermore, the oil on the surface of the oil-cooled specimen burns off at >100°C and, thus, the surfaces from the two cooling mediums are expected to behave identically. This result is confirmed by the same behavior of air- and oil-cooled specimens during creep testing between 450 to 650°C (Figs. 22 and 23). The testing in vacuum of air- and oil-quenched specimens shows a significant improvement in ductility in the test temperature region where oil was effective. The higher improvement in ductility for oil-quenched specimens, as compared to air-cooling specimens, is possibly the result of a difference in fraction of the B2 phase retained by oil quenching versus air cooling. Transmission electron microscopy and X-ray analysis will be conducted to verify this possibility.

The overall status of creep testing on experimental and commercial heats of iron-aluminide alloys FAS, FAL, and FA-129 is presented in Figs. 24 and 25. The creep test temperature ranges from 450 to 704°C, and test times have exceeded 5000 h. The average behavior of 304 and 403 stainless steels are included for comparison. The iron-aluminide alloys currently in the

ORNL-DWG 90-17152

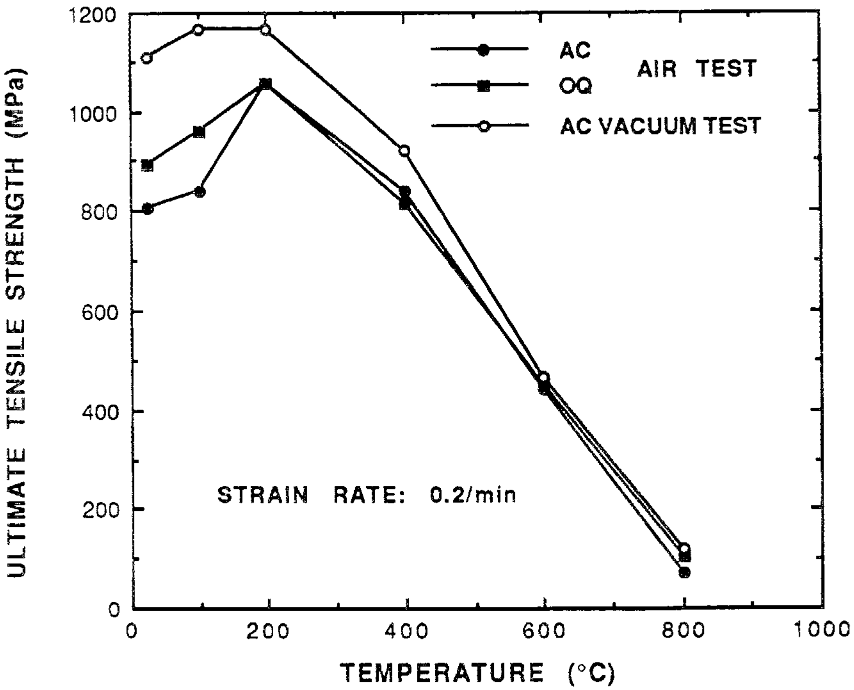


Fig. 18. Effect of cooling medium on 0.2% yield strength as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction melted ingot melted in a MgO crucible at Special Metals Corporation. Yield strength is not affected by either oil quenching (OQ) or air cooling (AC).

ORNL-DWG 90-17151

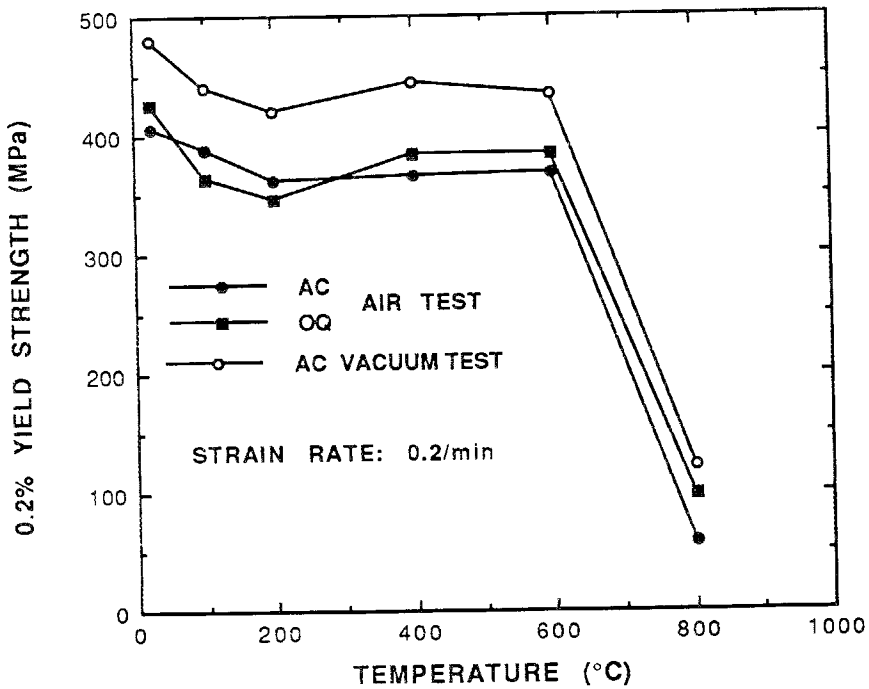


Fig. 19. Effect of cooling medium on 0.2% yield strength as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Full values of ultimate tensile strength were not achieved for specimens either oil quenched (OQ) or air cooled (AC). However, the air-cooled specimens values were even lower because of environmental effects.

ORNL-DWG 90-17153

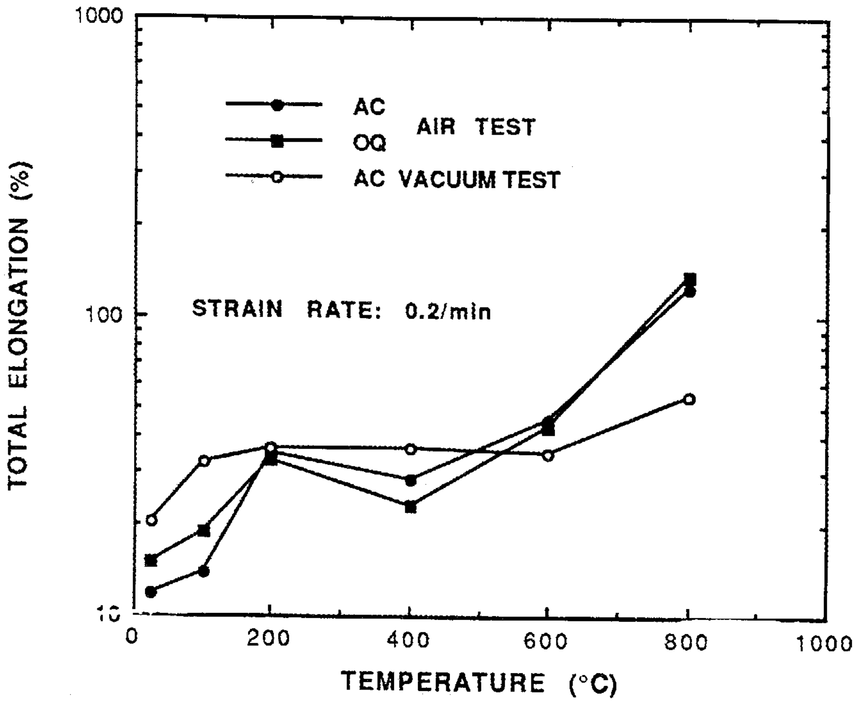


Fig. 20. Effect of cooling medium on total elongation as a function of test temperature for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Total elongation values are higher for oil-quenched (OQ) specimens than for air-cooled (AC) specimens for test temperatures <200°C.

ORNL-DWG 90-17154

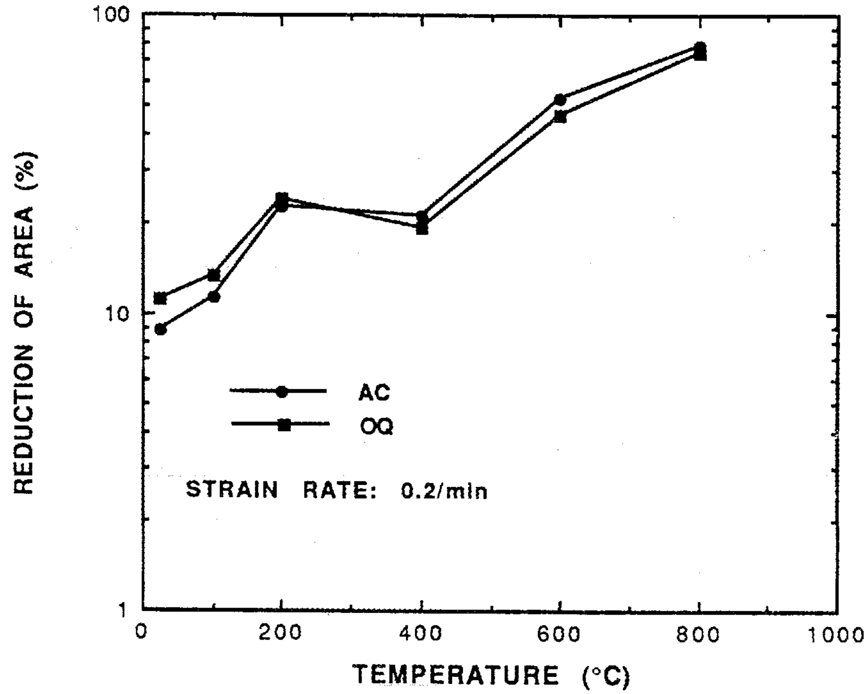


Fig. 21. Effect of cooling medium on reduction of area as a function of test temperatue for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Reduction of area values are higher for oil-quenched (OQ) specimens than for air-cooled (AC) specimens for test temperatures <200°C.

ORNL-DWG 90-17155

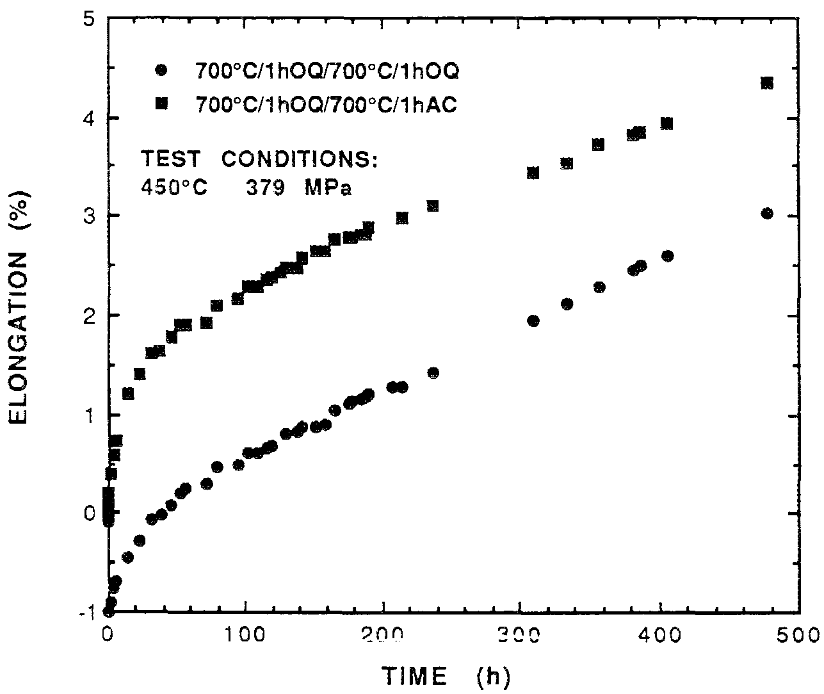


Fig. 22. Effect of cooling medium on creep behavior for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacuum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Oil quenching (OQ) is compared with air cooling (AC). Creep tests were conducted at 450°C and 379 MPa.

ORNL-DWG 90-17156

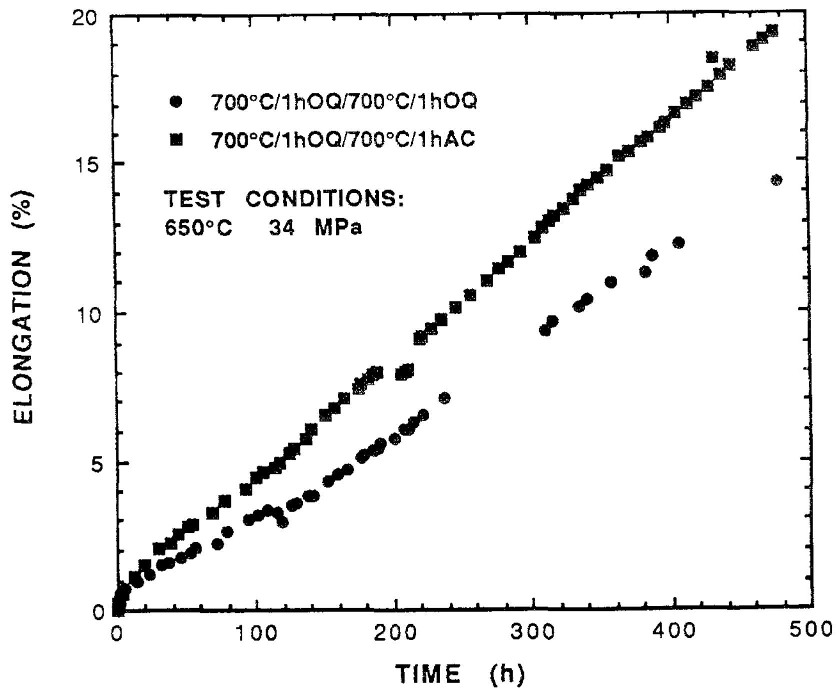


Fig. 23. Effect of cooling medium on creep behavior for specimens from 0.76-mm-thick (0.030-in.) sheet fabricated from 102-mm-diam (4-in.) vacum-induction-melted ingot melted in a MgO crucible at Special Metals Corporation. Oil quenching (OQ) is compared with air cooling (AC). Creep tests were conducted at 650°C and 34.5 MPa.

ORNL-DWG 90-17157

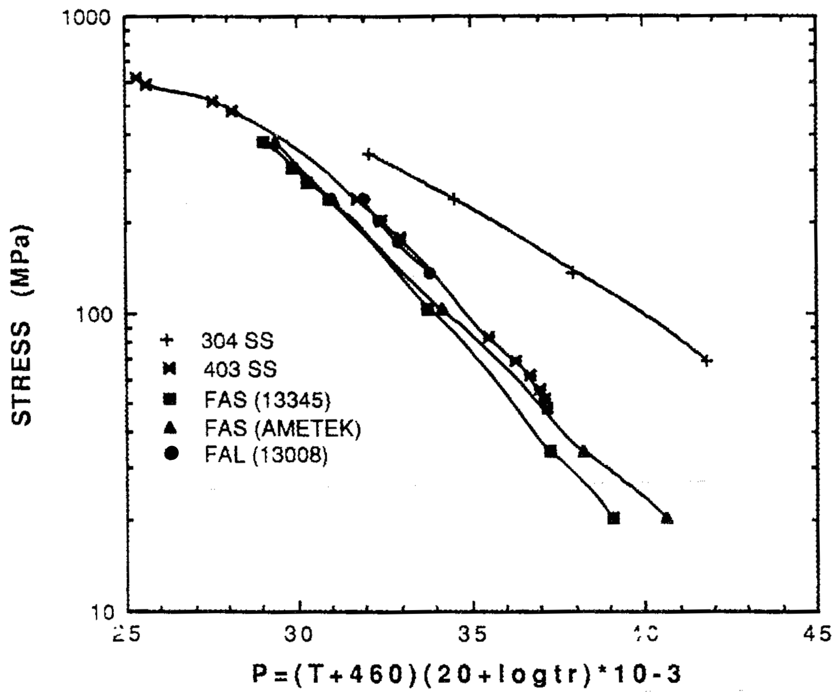


Fig. 24. Larson-Miller plot showing the status of creep testing of FAS and FAL alloys. Data on 403 and 304 stainless steels are included for comparison. Creep tests are for temperatures of 450 to 704°C. All tests are on cast and processed material except the Ametek material, which was produced from powder.

ORNL-DWG 90-17158

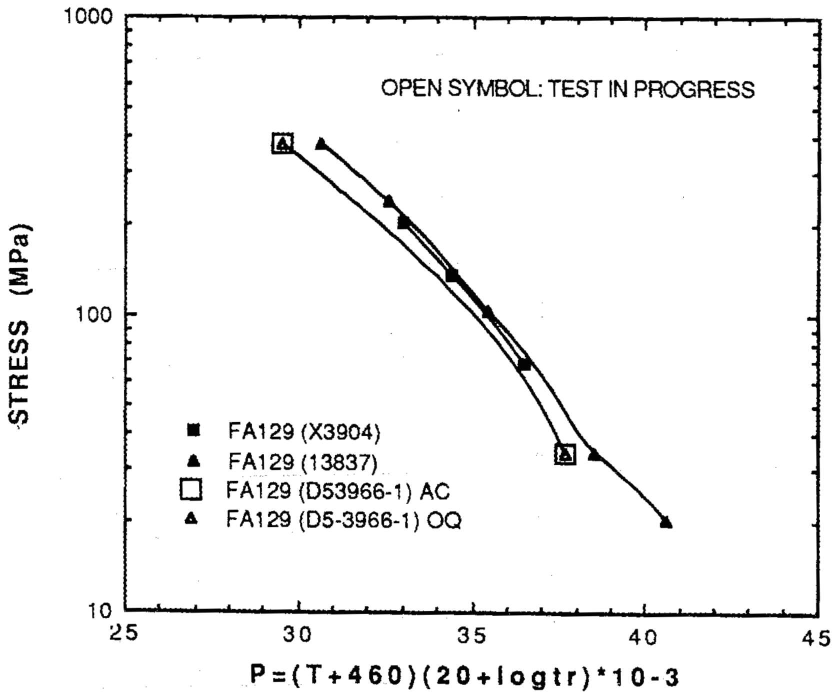


Fig 25. Larson-Miller plot showing the status of creep testing of FA-129 alloy. Creep tests are on one experimental heat and two commercial heats. Test temperatures ranged from 450 to 704°C.

scaleup process meet the strength of 403 stainless steel (Fig. 24). There is a small difference in the creep behavior of experimental scaled-up heats of FA-129 (Fig. 25). The work in progress in strengthening the iron aluminides is aimed at increasing the in creep strength to that of 304 stainless steel.

INTERACTION WITH INDUSTRY

There is a great deal of interest in properties of iron aluminides, and it is reflected in strong interaction with industry. Each industry is listed below with a brief description of the interaction.

1. Ametek Specialty Metal Products Division has signed an exclusive licensing agreement with ORNL for powder production. Ametek is now a commercial source of iron aluminide powder and is developing techniques for powder consolidation and spraying.
2. PALL Corporation, a porous, metal filter producer, has been working on the development and production of iron-aluminide gas-metal cleanup filters.
3. Haynes International, Inc., has produced several VIM and ESR ingots of iron aluminide. However, Haynes has not yet decided to commercially scale up these alloys.
4. Carpenter Technology Corporation has melted by the VIM and ESR processes an 203-mm-diam (8-in.) ingot of iron aluminide. Carpenter has processed the ingot into round, machined round, and slab configurations. However, Carpenter Technology has not yet decided to commercialize these materials.
5. Special Metals Corporation has produced several heats of iron-aluminide alloys using VIM, VAR, and ESR processes, and has processed 102- and 152-mm-diam (4- and 6-in.) ingots into bar stock on its commercial bar mill. Special Metals Corporation has not yet decided to commercialize these alloys.
6. Wisconsin Centrifugal is interested in centrifugal casting of tubes and pipes of these alloys and has recently melted a 40-kg (80-lb) heat of FA-129, which has been centrifugally cast into a 254-mm-OD × 152-mm-ID (10- × 6-in.) tube. Pieces from this heat have been received at ORNL for chemical analysis. At present, Wisconsin Centrifugal plans to centrifugally cast pipes of these alloys; a joint test program between Wisconsin Centrifugal and ORNL is under way.

7. The Timken Company/Latrobe Steel Company has an interest in producing seamless pierced pipe and bar product of iron aluminide. This company has melted several 50 kg (100 lb) heats and has performed nondestructive examination and hot-workability tests on these alloys. At present, however, it is not sure of future commercialization efforts.
8. Precision Rolled Products, Inc., is very interested in bar and slab rolling of these alloys and has already taken one 102-mm-diam (4-in.) billet of one of the Fe_3Al-based alloys and bar-rolled it in their commercial mill into 102-mm-diam (4-in.) bar.
9. Dresser-Rand is evaluating the use of Fe_3Al for steam turbine applications. It has conducted initial tests and is satisfied with the corrosion concerns.
10. Ford Motor Company is evaluating the material for exhaust system applications. Initial results look encouraging.

SUMMARY AND CONCLUSIONS

Scaleup was carried out for three alloys based on Fe_3Al. The FAS alloy was scaled up by both powder metallurgy and casting. The FAL alloy was scaled up by the VIM and ESR processes; the largest ingot size was 203-mm-diam (8-in). The FA-129 alloy was scaled up by the VIM, VAR, and ESR processes to 102- and 152-mm-diam (4- and 6-in.) ingots. The effect of melting in MgO and Al_2O_3 crucibles on the final composition was studied for FA-129. The 203-mm-diam (8-in.) ingot of FAL and the 102- and 152-mm (4- and 6-in.) ingots of FA-129 were commercially processed into bar stock. The FA-129 alloy processed satisfactorily under commercial processing conditions. The FA-129 ingot melted in a MgO crucible was processed at ORNL into sheet and plate stock. Limited of tensile and creep tests were completed on the MgO-melted VIM ingot of FA-129 at Special Metals Corporation. Some material was also supplied for welding, toughness, fatigue, and environmental-effect studies. The following eight conclusions are possible from these studies.

1. No unusual problems have been encountered in scaling up the FAS alloy through nitrogen-gas powder production of AIM material. Ametek Special Metal Products Division has obtained an exclusive license from ORNL, and powder production is underway.
2. The tensile and creep properties of material from nitrogen-atomized Fe_3Al powder were found to be similar to that of cast and processed material.

3. The MgO in the slag used in the ESR process at Carpenter Technology Corporation introduced magnesium into the ingot. The ingot could be commercially forged at Carpenter Technology Corporation, but it was generally crack-sensitive on the surface and in the forged slab center.
4. The FA-129 alloy was scaled up by the VIM, VAR, and ESR processes. The VIM ingot melted in the MgO crucible contained twice as much magnesium as the ingot melted in the Al_2O_3 crucible. However, the 20 ppm of magnesium in the MgO-melted crucible is not detrimental to processing.
5. The MgO-melted VIM ingot was successfully processed into plate and sheet at ORNL. The VIM, VAR, and ESR ingots were successfully bar rolled at both Special Metals Corporation and Precision Rolled Products.
6. Tensile properties of the MgO-melted ingots were similar to properties of experimental heats observed previously. The oil-quenched specimens showed higher ductility than air-cooled specimens at room temperature. At >100°C, the tensile properties were similar for oil-quenched and air-cooled specimens.
7. Creep properties of the oil-quenched and air-cooled specimens at 450 and 650°C were identical for the MgO-melted VIM ingot of FA-129.
8. Test data are not yet complete to make any definite conclusions regarding the melting method among the VIM, VAR, and ESR processes to produce the best combination of strength, ductility, and toughness.

FUTURE WORK

A significant amount of additional work is required on scaled-up heats to fully characterize them. This work includes understanding the reasons for higher crack sensitivity of the FAL ingot prepared at Carpenter Technology Corporation; additional processing at ORNL of the VAR and ESR ingots into sheets and slabs; tensile and creep property data on sheets, slabs, and bars produced at Special Metals Corporation; determination of cast properties of ingots prepared by the VIM, VAR, and ESR processes; and detailed metallography to characterize the cast and wrought structure of various ingots and product forms.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Kenneth S. Blakely and Edward C. Hatfield for processing at ORNL; Richard L. Cook, Kristen Anderson, and James T. Mavity at

Precision Rolled Products, Inc., for bar rolling; Eva Samuelsson at Special Metals Corporation for producing VIM, VAR, and ESR ingots and for bar rolling; N. C. Cole and R. W. Swindeman for reviewing the paper; and M. Atchley and M. R. Upton for final preparation of the report.

REFERENCES

1. V. K. Sikka, C. G. McKamey, C. R. Howell, and R. H. Baldwin, *Fabrication and Mechanical Properties of Fe_3Al-Based Aluminides*, ORNL/TM-11465, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, March 1990.

2. V. K. Sikka, R. H. Baldwin, C. R. Howell, and J. H. Reinshagen, "Powder Production, Processing, and Properties of Fe_3Al," pp. 207-18 in *Advances in Powder Metallurgy 1990*, Vol. 2, eds. E. R. Andreotti and P. J. McGeehan, Metal Powder Industries Federation, Princeton, N.J., 1990.

INTERNAL DISTRIBUTION

1-2. Central Research Library
3. Document Reference Section
4-5. Laboratory Records Department
6. Laboratory Records, ORNL RC
7. ORNL Patent Section
8-10. M&C Records Office
11. D. J. Alexander
12-16. R. A. Baldwin
17. P. F. Becher
18. R. A. Bradley
19. C. R. Brinkman
20. V. R. Bullington
21. P T. Carlson
22. D. A. Childress
23. D. F. Craig
24. F. M. Haggag
25. J. A. Horton
26-30. C. R. Howell
31. C. R. Hubbard
32. R. R. Judkins
33. R. T. King
34. K. C. Liu
35. J. R. Mayotte
36. P. J. Maziasz
37-41. C. G. McKamey
42. W. D. Porter
43-47. V. K. Sikka
48. G. M. Slaughter
49. J. O. Stiegler
50. R. W. Swindeman
51. P. F. Tortorelli
52. J. R. Weir
53. D. F. Wilson
54. A. D. Brailsford (Consultant)
55. Y. A. Chang (Consultant)
56. H. W. Foglesong (Consultant)
57. J. J. Hren (Consultant)
58. M. L. Savitz (Consultant)
59. J. B. Wachtman (Consultant)

EXTERNAL DISTRIBUTION

60-61. AIR FORCE WRIGHT AERONAUTICAL LABORATORIES, Metals and Ceramics Division, Wright-Patterson Air Force Base, OH 45433

D. M. Dimiduk
W. R. Kerr

62. ALUMINUM COMPANY OF AMERICA LABORATORIES, Alcoa Technical Center, Route 780, Seventh Street Road, Alcoa Center, PA 15269

G. MacZura

63. AMERICAN WELDING SOCIETY, 550 LeJeune Road, Miami, FL 33126

H. G. Ziegenfuss

64. AMETEK SPECIALTY METAL PRODUCTS DIVISION, Route 519, P.O. Box 427, Eighty Four, PA 15330

J. H. Reinshagen

65. ARGONNE NATIONAL LABORATORY, Materials and Components Technology Division, 9700 S. Cass Ave., Argonne, IL 60439

K. Natesan

66-67. BABCOCK & WILCOX COMPANY, 20 S. Van Buren Ave., Barberton, OH 44203

M. Gold
J. E. Mack

68. CARNEGIE-MELLON UNIVERSITY, Department of Metallurgical Engineering and Materials Science, Pittsburgh, PA 15213

T. B. Massalski

69. CASE WESTERN RESERVE UNIVERSITY, Department of Metallurgical and Materials Science, 10900 Euclid Avenue, Cleveland, OH 44106

K. Vedula

70. COMBUSTION ENGINEERING, INC., 911 W. Main Street, Chattanooga, TN 37401

D. A. Canonico

71-72. CORNELL UNIVERSITY, Ithaca, NY 14850

Che-Yu Li
S. L. Sass

73. CYTEMP POWDER PRODUCTS, 600 Mayer Street, Bridgeville, PA 15017

L. W. Lherbier

74-75. EG&G IDAHO, INC., Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83415

J. E. Flinn
R. N. Wright

76-79. ELECTRIC POWER RESEARCH INSTITUTE, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303

W. T. Bakker
D. J. Frey
R. I. Jaffee
J. Stringer

80. EXXON RESEARCH AND ENGINEERING COMPANY, Clinton Township,Route 2, East, Annandale, NJ 08801

M. L. Gorbaty

81. FOSTER WHEELER DEVELOPMENT CORPORATION, 12 Peach Tree Hill Road, Livingston, NJ 07939

J. L. Bough

83-83. GARRETT TURBINE ENGINE COMPANY, Advanced Materials, Materials Engineering, 111 South 34 Street, P.O. Box 5217, Phoenix, AZ 85010

G. S. Hoppin
B. Keiser

84. GENERAL ATOMICS, P.O. Box 81608, San Diego, CA 92318

D. I. Roberts

85-87. GENERAL ELECTRIC COMPANY, Bldg. 81, Room E102, Schenectady, NY 12345

K. M. Chang
S. C. Huang
A. I. Taub

88. GENERAL ELECTRIC COMPANY, Corporate Research and Development, P.O. Box 8, Schenectady, NY 12301

R. L. Fleischer

89. GENERAL ELECTRIC COMPANY, Quartz and Chemicals Department, 24400 Highland Road, Richmond Heights, OH 44413

G. W. Weber

90. GENERAL MOTORS RESEARCH, Metallurgical Department, Warren, MI 48090-9055

S. Schuon

91. GEORGIA INSTITUTE OF TECHNOLOGY, School of Materials Engineering, Bunger-Henry Bldg., Atlanta, GA 30332

S. Antolovich

92. HAYNES INTERNATIONAL, Technology Dept., 1020 W. Park Avenue, Kokomo, IN 46901

A. Asphahani

93. INSTITUTE OF DEFENSE ANALYSES, 1801 Beauregard Street, Alexandria,VA 22311

T. F Kearns

94. LEHIGH UNIVERSITY, Materials Research Center, Bethlehem, PA 18015

Y. T. Chou

95-96. LOCKHEED CORPORATION, Palo Alto Laboratories, 3251 Hanover Street, Palo Alto, CA 94303

E. C. Burke
R. A. Perkins

97-99. LOS ALAMOS NATIONAL LABORATORY, Los Alamos, NM 87545

S. P. Chen
P. J. Hay
R. S. Skaggs

100. THE MATERIALS PROPERTIES COUNCIL, INC., 345 E. Forty-Seventh Street, New York, NY 10017

M. Prager

101-102. MICHIGAN TECHNOLOGICAL UNIVERSITY, Department of Metallurgical Engineering, Houghton, MI 49931

D. Mikkola
C. L. White

103. MONSANTO COMPANY, P.O. Box 1311, Texas City, TX 77590

P. S. Gupton

104. NAVAL SURFACE WEAPONS CENTER, Code R32, White Oak, Silver Spring, MD 20910

H. M. DeJarnette

105. NAVAL SURFACE WEAPONS CENTER, Surface Weapons Materials Technology Program, Dahlgren, VA 22448

W. T. Messick

106. NORTH CAROLINA STATE UNIVERSITY, Materials Engineering Dept., Raleigh, NC 27650

C. C. Koch

107. OAK RIDGE ASSOCIATED UNIVERSITIES LIBRARY, Oak Ridge, TN 37831

MERT Division

108. RENSSELAER POLYTECHNIC INSTITUTE, Materials Engineering Department, Troy, NY 12181

N. S. Stoloff

109. SORELL CONSULTING SERVICES, 49 Brookside Terrace, North Caldwell, NJ 07006

G. Sorell

110. THE TIMKEN COMPANY, 1835 Dueber Avenue, SW, Canton, OH 44706

P. W. Lee

111. UNITED TECHNOLOGIES, Pratt and Whitney, Engineering Division, North, 400 Main St., East Hartford, CI 06108

D. N. Duhl

112. UNIVERSAL CYCLOPS SPECIALTY STEEL DIVISION, 650 Washington Road, Pittsburgh, PA 15228

H. L. Black

113. UNIVERSAL ENERGY SYSTEMS, INC., 4401 Dayton-Xenia Road, Dayton, OH 45432

M. G. Mendiratta

114. UNIVERSITY OF MASSACHUSETTS, Department of Polymer Science, Room 701, GRC, Amherst, MA 01003

R. S. Porter

115. UNIVERSITY OF TENNESSEE, Materials Science and Engineering Department, Knoxville, TN 37996

C. R. Brooks

116. VANDERBILT UNIVERSITY, Station B, P.O. Box 1621, Nashville, TN 37235

J. J. Wert

117. VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY, Blacksburg, VA 24016

D. A. Farkas

118-120. DOE, OFFICE OF ASSISTANT SECRETARY FOR CONSERVATION AND RENEWABLE ENERGY, Office of Transportation Technologies, Forrestal Building, 1000 Independence Avenue, Washington, DC 20585

T. J. Gross
M. E. Gunn, Jr.
P. H. Salmon-Cox

121-126. DOE, MORGANTOWN ENERGY TECHNOLOGY CENTER. P.O. Box 880, Morgantown, WV 26505

R. A. Bajura
R. C. Bedick
J. W. Byam, Jr.
R. J. Dellefield
J. M. Hobday
J. S. Wilson

127-128. DOE, OAK RIDGE OPERATIONS OFFICE, P.O. Box 2001, Oak Ridge, TN 37831-6269

Assistant Manager for Energy Research and Development
E. E. Hoffman

129-130. DOE, OFFICE OF FOSSIL ENERGY, Washington, DC 20545

D. J. Beecy, FE-14
J. P. Carr, FE-14

131. DOE, OFFICE OF VEHICLE AND ENGINE R&D, Route Symbol CE-131, Forrestal Building, Washington, DC 20585

R. B. Schulz

132-141. DOE, OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION, Office of Information Services, P.O. Box 62, Oak Ridge, TN 37831

For distribution by microfiche as shown in DOE/OSTI-4500, Distribution Categories UC-103 (Fluidized Bed Combustion), UC-109 [Coal Gasification (Surface and Underground)], and UC-114 (Coal-Based Materials and Components)