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PRIMARY FABRICATION PROCESSES FOR NICKEL AND IRON ALUMINIDES

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ABSTRACT

Alloys based on the intermetallic compounds Ni_3Al and Fe_3Al have been developed. Intermetallic compounds are characteristically brittle at room temperature, and some are also brittle at elevated temperatures. Nickel-aluminide alloys have been made ductile by alloying with a small amount of boron (200 ppm by weight) and adjusting the aluminum content to 24 at. % or less. Iron-aluminide alloys are ductile when chromium is added (>wt 2%) and the aluminum is adjusted to 28 at. %. These alloys begin ordering upon solidification; therefore, a greater shrinkage must be accommodated during casting. The hot-working temperature "window" for the nickel-aluminide alloy is very narrow; however, the alloy can be cold-worked large amounts. Iron-aluminide alloys have a very broad hot-working temperature range but have limited ductility (<20%) at room temperature. The strength and oxidation resistance of these alloys are such that many potential applications exist. Commercialization is in progress.

INTRODUCTION

Intermetallic compounds have an ordered crystal structure; many of them are quite strong and have high melting temperatures. Until recently, none of them have been used as structural materials because of their brittleness. Recently, iron- and nickel-aluminide alloys, based on the compounds Ni_3Al and Fe_3Al, have been made ductile by micro- and macro-alloying. Alloying with 2 to 6 wt % Cr and adjusting the aluminum concentration to 28 at. % produce reasonable ductility (15 to 20% tensile elongation) in the iron aluminide. Adding 200-wt-ppm boron and adjusting the aluminum concentration to 24 at. % or less make the nickel aluminide quite ductile at room temperature (30 to 50% tensile elongation).

Additional alloying has enhanced certain properties such as aqueous corrosion, strength, oxidation resistance, castability, and workability. The result is that three nickel aluminides and three iron-aluminide alloys have been developed. The compositions of the alloys are shown in Tables 1 and 2.

Table 1. Compositions of ductile, Ni_3Al-based alloys

Element	Alloy designation (wt %)		
	IC-50[a]	IC-218LZr[b]	IC-221M[c]
Al	11.3	8.69	7.98
Cr	--	8.08	7.74
B	0.02	0.02	0.008
Zr	0.6	0.20	1.70
Mo	--	--	1.43
Ni	88.08	83.01	81.15

[a]Direct-castable or near-net-shapable alloy.
[b]Hot workable, potentially processable by conventional processing techniques.
[c]Castable alloy.

Table 2. Compositions of ductile, Fe_3Al-based 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	--
Nb	--	--	1.0
C	--	--	0.05
Fe	Balance	Balance	Balance

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

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FABRICATION PROCESSES FOR Ni_3Al-BASED ALLOYS

There are at least three primary fabrication processes for nickel-aluminide alloys. These include: powder metallurgy, near-net shaping, and conventional techniques. Each of these processes is briefly described below.

POWDER METALLURGY - The nickel-aluminide powder can be produced by argon or nitrogen-gas atomization. Ametek Specialty Metal Products Division (Eighty Four, Pennsylvania) is licensed to produce and supply nitrogen-gas-atomized powder. The nickel-aluminide powder can be readily consolidated (1,2)* to 100% density by extruding the powder in a mild steel can at 1100°C to a reduction ratio of ≥9:1. The powder can also be consolidated by hot-isostatic pressing (3,4). The extrusion-process-consolidated powder has a grain structure that can be superplastic (5) under proper conditions of temperature and strain rate. The isothermal-compression tests demonstrating the superplastic behavior are shown in Fig. 1. The fabrication of a prototype turbine disk (Fig. 2) provides further demonstration of the superplastic behavior of a Ni_3Al-based alloy (IC-218) containing chromium.

NEAR-NET SHAPING - The near-net-shape or net-shape casting of parts directly from liquid metal is a highly desirable method for the fabrication of nickel-aluminide alloys. Among the near-net-shape methods is the method of sheet fabrication (6) by bringing liquid metal in direct contact with a rotating drum. Coils of sheet fabricated by this method are shown in Fig. 3. The as-cast sheet thicknesses ranged from 1 to 1.8 mm and the width was 305 mm. The sheet thicknesses are controlled by the speed of the drum. The as-cast sheets are highly ductile, and their strength can be enhanced significantly by cold rolling. Results of cold working on the room-temperature tensile curves of alloy IC-50 are shown in Fig. 4.

Continuous lengths of 6- and 12-mm-diam bars of nickel-aluminide alloys can be directly cast (7) by controlled solidification in a mold attached directly to the melt furnace. A 6-mm-diam bar produced by this method is shown in Fig. 5. The bar has excellent surface appearance but contains witness marks resulting from the exit at the breaking (Fig. 6). The control of the witness mark depth is critical to the success of subsequent processing. The 6-mm-diam bar (Fig. 5) was hot and cold swaged into different sizes of welding wire.

The IC-221M alloy can be precision cast into shapes as complex as turbocharger rotors (Fig. 7). The mold temperature and the liquid-metal superheat are critical in order for the best quality casting possible, and both have been optimized for the turbocharger rotors. Properties of cast IC-221M alloy are compared with the IN-713C alloy (Fig. 8), which shows the significant advantage in strength and ductility of cast nickel aluminide over cast IN-713C. The strength advantage of nickel aluminide is particularly significant at ≥800°C. The fatigue properties at 650°C of cast test bars (Fig. 9) show an order-of-magnitude better fatigue life than IN-713C cast under the same conditions. The combination of oxidation resistance, high-temperature tensile strength, and fatigue strength makes the castable alloys suitable for many high-temperature mold and die applications.

*Numbers in parentheses designate references at end of paper

CONVENTIONAL TECHNIQUES - The Ni_3Al-based alloys can be scaled up to large-diameter ingots by electroslag remelting (ESR). ESR ingots of 102- and 203-mm diam were cast (8,9) in the development phase of this program. The latest ingot (Fig. 10) cast by this process is 406-mm diam from IC-218LZr. This ingot had a length of 2.7 meters and was cast at Precision Rolled Products (Florham Park, New Jersey). The ingot can either be used in the as-cast condition or has the potential of being processed down to wrought product through rotary forging and subsequent bar rolling. The details of forging and rolling temperatures and the total area reduction are currently being optimized.

IRON-ALUMINIDE FABRICATION

The ductile, Fe_3Al-based iron aluminides can be fabricated by either powder metallurgy or conventional processing. Each of these methods is briefly described here.

POWDER METALLURGY - Iron-aluminide powders can be produced by argon-gas or nitrogen-gas atomization. Powders from either process can be consolidated[10] to full density by hot extrusion at 1000°C to a reduction ratio of ≥9:1. The nitrogen-gas-atomized powder yielded (10,11) better strength and ductility properties than argon-gas-atomized powder. The powders can also be used to produce (12) corrosion-resistant coatings on other materials.

CONVENTIONAL PROCESSING - The iron aluminides can be melted (13,14) by vacuum-induction melting (VIM) in a magnesia crucible. The VIM ingots can be further refined (14) in chemical composition by vacuum-arc remelting (VAR) or ESR. The ingot sizes produced by VIM, VAR, and ESR processes have ranged from 102- to 203-mm diam. A 203-mm-diam ingot produced by ESR is shown in Fig. 11. The ingots, melted by any of the processes, can be hot worked by forging or bar rolling into plate or bar stock. Hot-rolled bars, 25-mm diam, produced from 102- and 152-mm-diam ingots are shown in Fig. 12.

The best results in room-temperature ductility are obtained by hot working at 1000°C, followed by at least 50% work each at 800 and 650°C. The finished product needs a two-step final heat treatment (15) for maximum room-temperature ductility. Various products fabricated from iron aluminides are shown in Fig. 13. Products such as knives made from this material can be fabricated by a single, close-die operation. The knife edge, made from Fe_3Al-based aluminide, requires no additional heat treatment as is the case of knives made from steel.

The next scaleup of ingot metallurgy is currently under way. This will involve preparing a 330-mm-diam electrode by the VIM process. The electrode will be subsequently processed by ESR to a 406-mm-diam ingot. The ingot will then be processed into plate and bar product in a commercial mill.

The tensile properties of Fe_3Al alloy (FA-129) in wrought and cast conditions are compared in Fig. 14. This figure shows that the cast material has higher strength and lower ductility than wrought material. These properties need to be taken into account for the processing and fabrication of Fe_3Al-based iron aluminides.

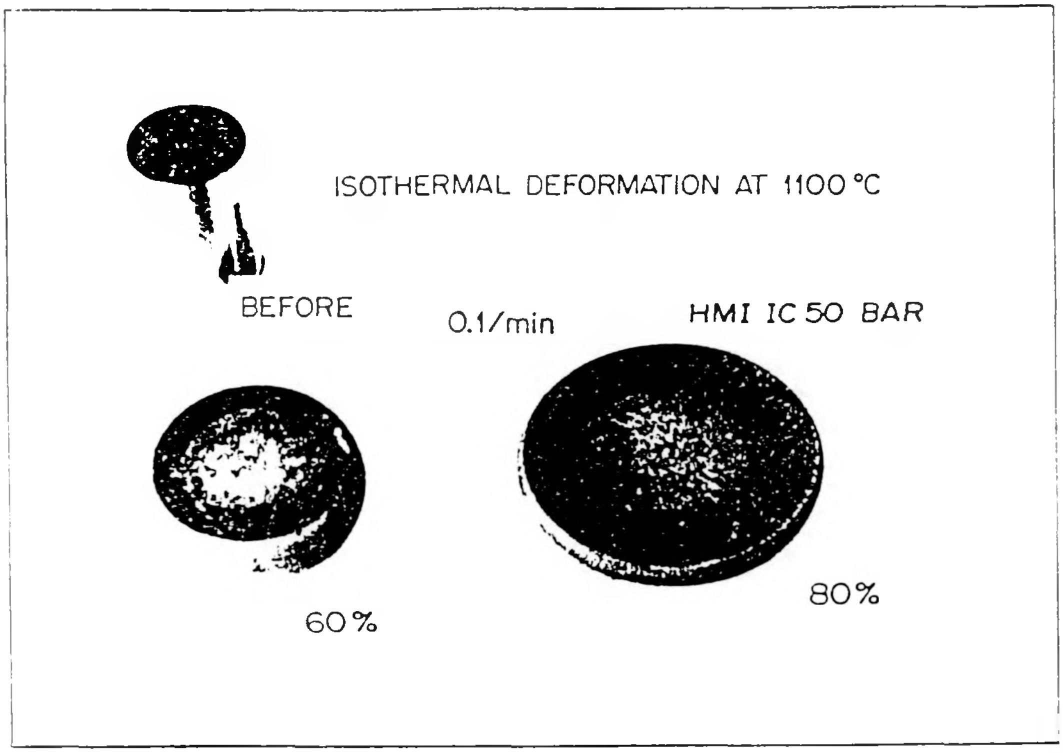

Fig. 1. Isothermal compaction of powder-extruded bar of Ni_3Al-based alloy (IC-50) at 1100°C and a strain rate of $1.67 \times 10^{-3}/s^{-1}$.

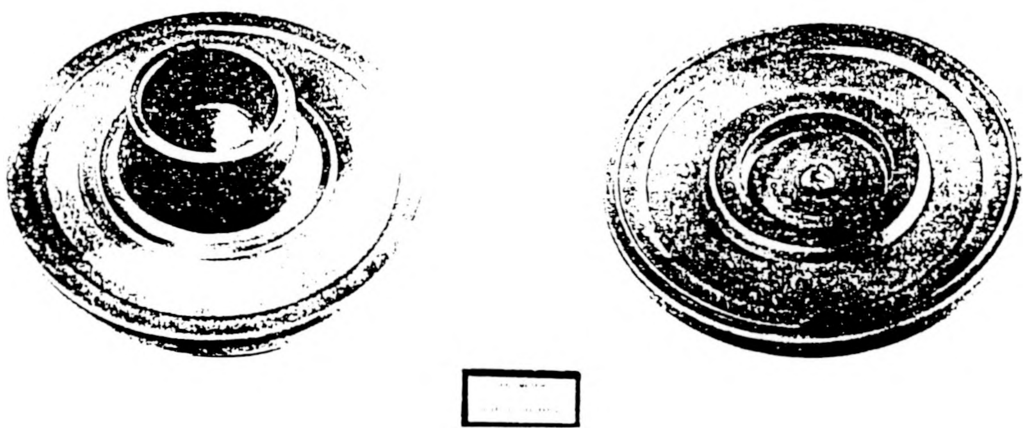

Fig. 2. Turbine disks produced by isothermal deformation of a powder-extruded bar of IC-218 alloy at 1100°C and a strain rate of $8.3 \times 10^{-3}/s$. Forging was carried out at Ladish Company (Cudahy, Wisconsin).

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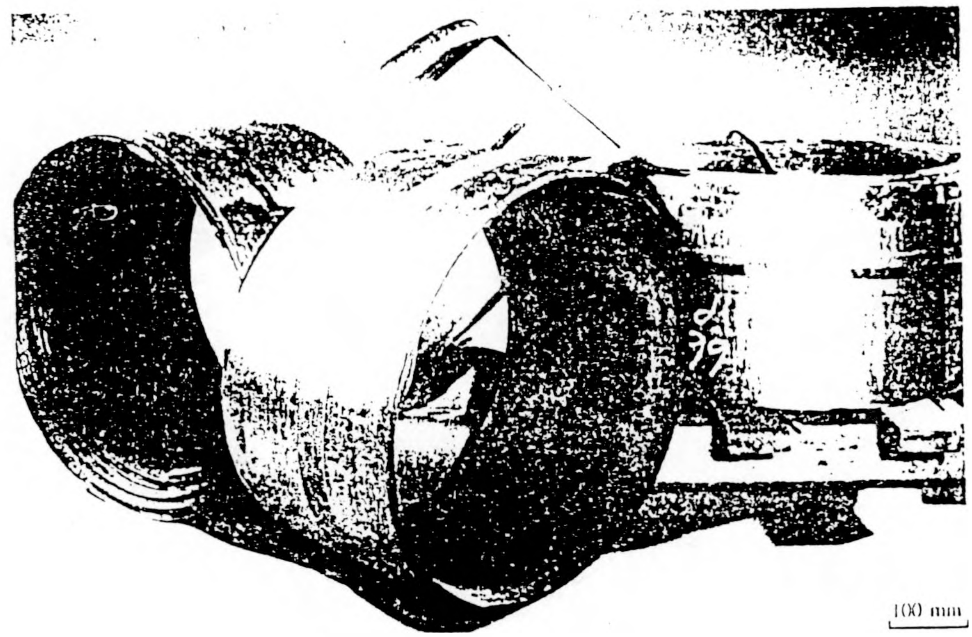

Fig. 3. Direct-cast sheet coils of nickel-aluminide alloy (IC-50). The sheet was cast at Allegheny Ludlum Steel Corporation (Brackenridge, Pennsylvania).

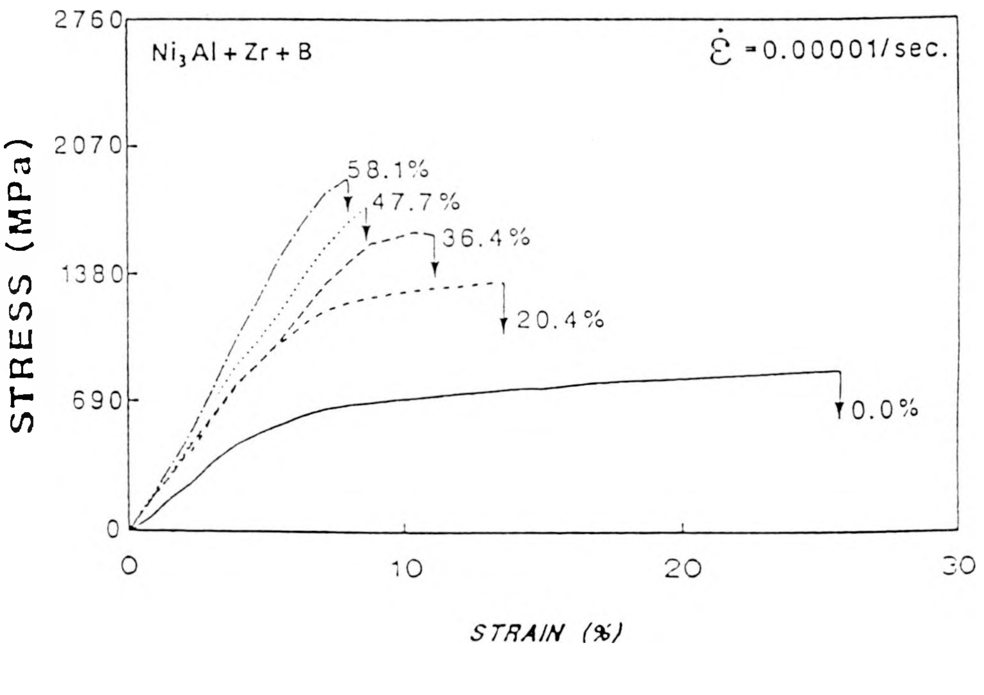

Fig. 4. Comparison of the engineering stress-strain curves at room temperature for the cold-deformed, Ni_3Al-based, intermetallic compound (IC-50) at a strain rate of 10^{-5}/s.

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Fig. 5. A 6-mm-diam, direct-cast bar of nickel-aluminide alloy (IC-221M). The bar was cast at Harrison Alloys (Harrison, New Jersey).

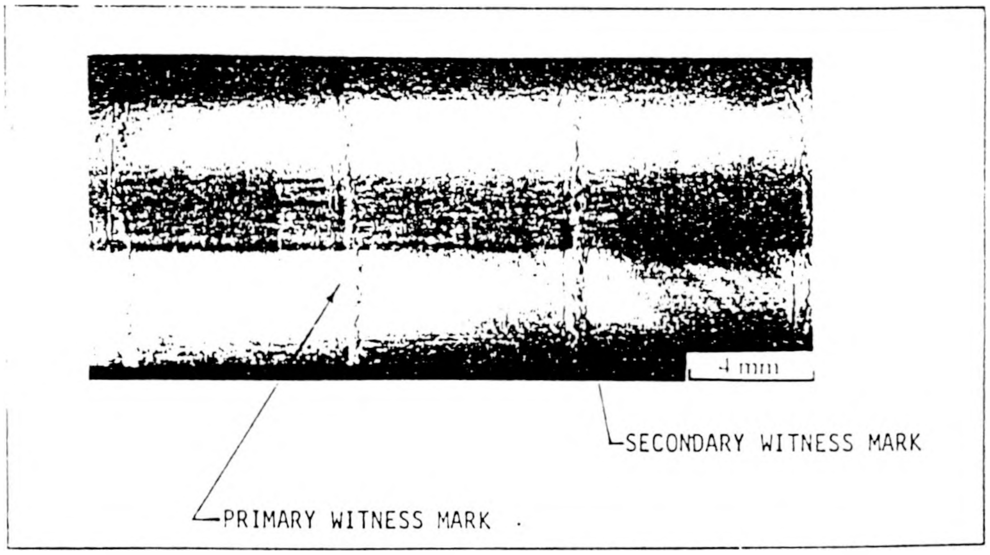

Fig. 6. Primary and secondary witness marks on a 12-mm-diam, direct-cast bar of Ni_3Al alloy (IC-50).

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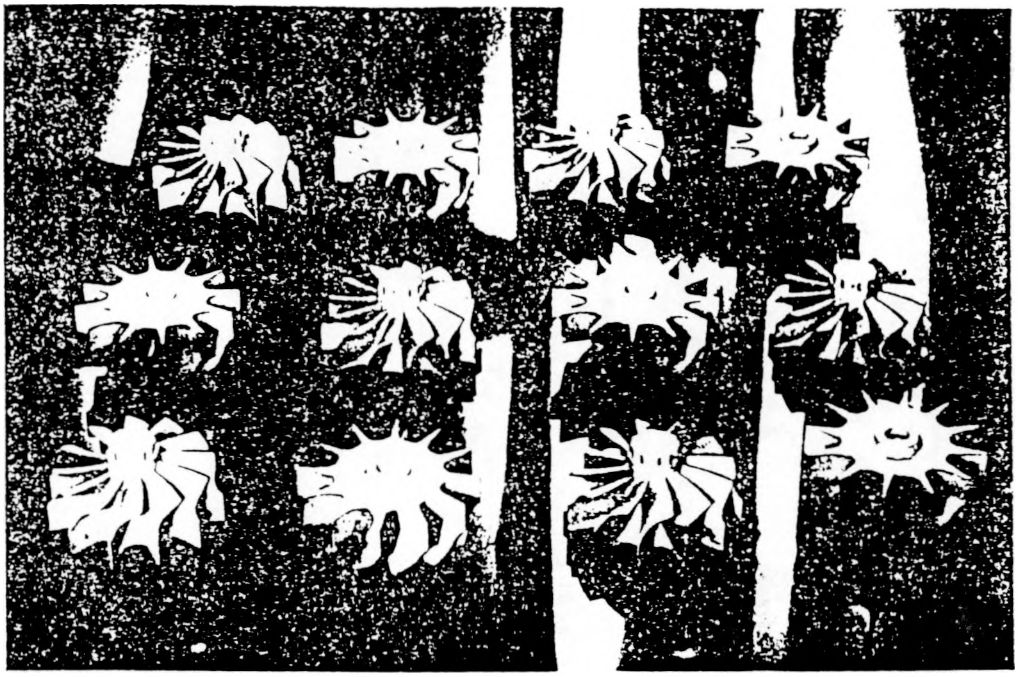

Fig. 7. Precision-cast turbocharger rotors of nickel-aluminide alloy (IC-221M). Casting was carried out at Precision Castparts Corporation (Portland, Oregon).

SUMMARY AND CONCLUSIONS

The chemical compositions of the ductile, iron- and nickel-aluminide alloys for near term commercialization are presented. Methods suitable for commercial processing of both types of intermetallic alloys are described. The following conclusions are possible from this study:

1. Nickel aluminides can be fabricated by powder metallurgy, near-net-shape processes, and conventional processing. Among the three methods, near-net shaping is the most advanced, the most useful, and the most economical. The near-net-shaping methods include: precision casting, sand casting, direct sheet and bar casting, and centrifugal casting. Additional work is required in processing large ingots by conventional techniques.
2.. Iron aluminides are fabricated by powder metallurgy and conventional processing. The conventional processing of ingots can be done by hot working in the temperature range of 650 to 1000°C. Cold working requires smaller reduction passes and frequent anneals.
3. Nickel aluminides are currently being produced for commercial application. Iron aluminides are close to commercial production.

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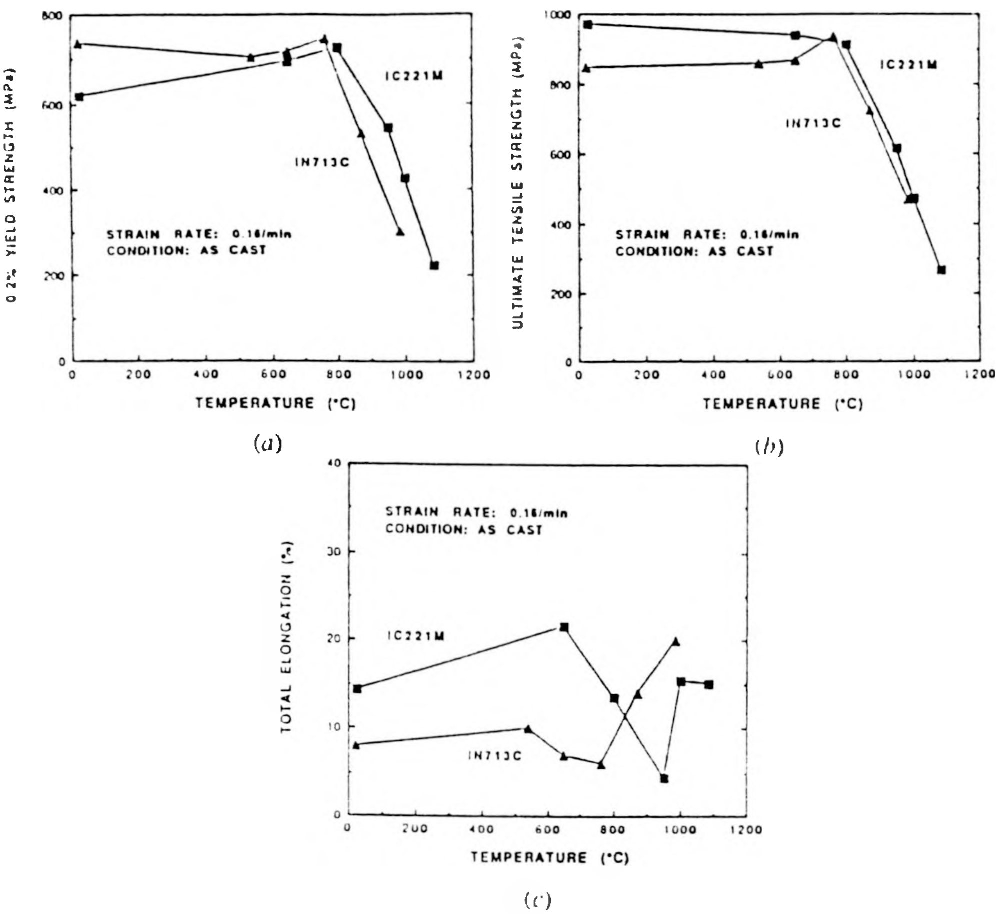

Fig. 8. Tensile properties of IN-713C and IC-221M in the as-cast condition: (*a*) 0.2% yield strength, (*b*) ultimate tensile strength, and (*c*) total elongation.

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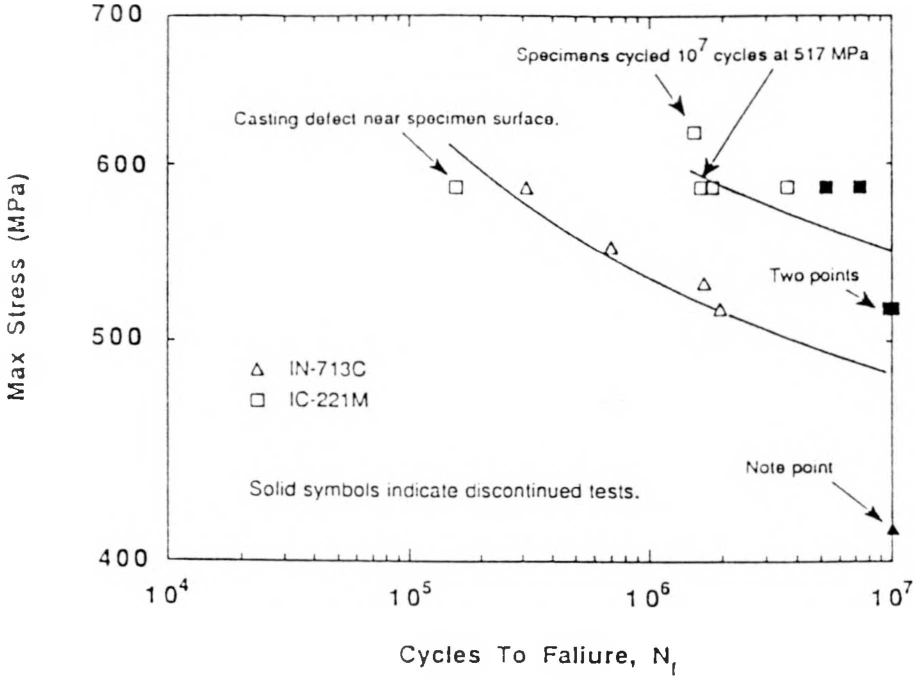

Fig. 9. Fatigue data in air at 650°C for precision-cast test bars of IN-713C and IC-221M.

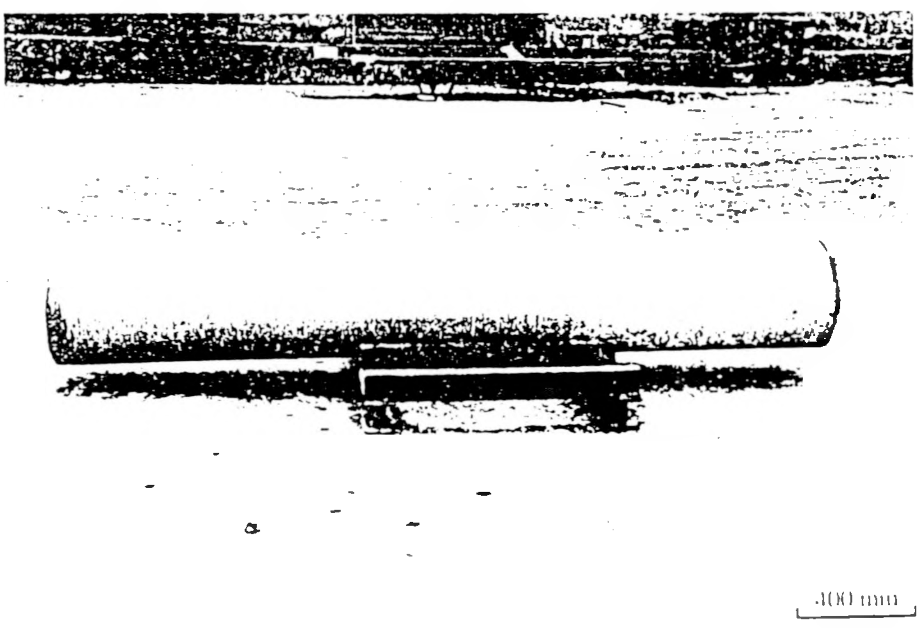

Fig. 10. A 406-mm-diam × 2.7-m-long ingot of IC-218LZr prepared by electroslag remelting at Precision Rolled Products (Florham Park, New Jersey).

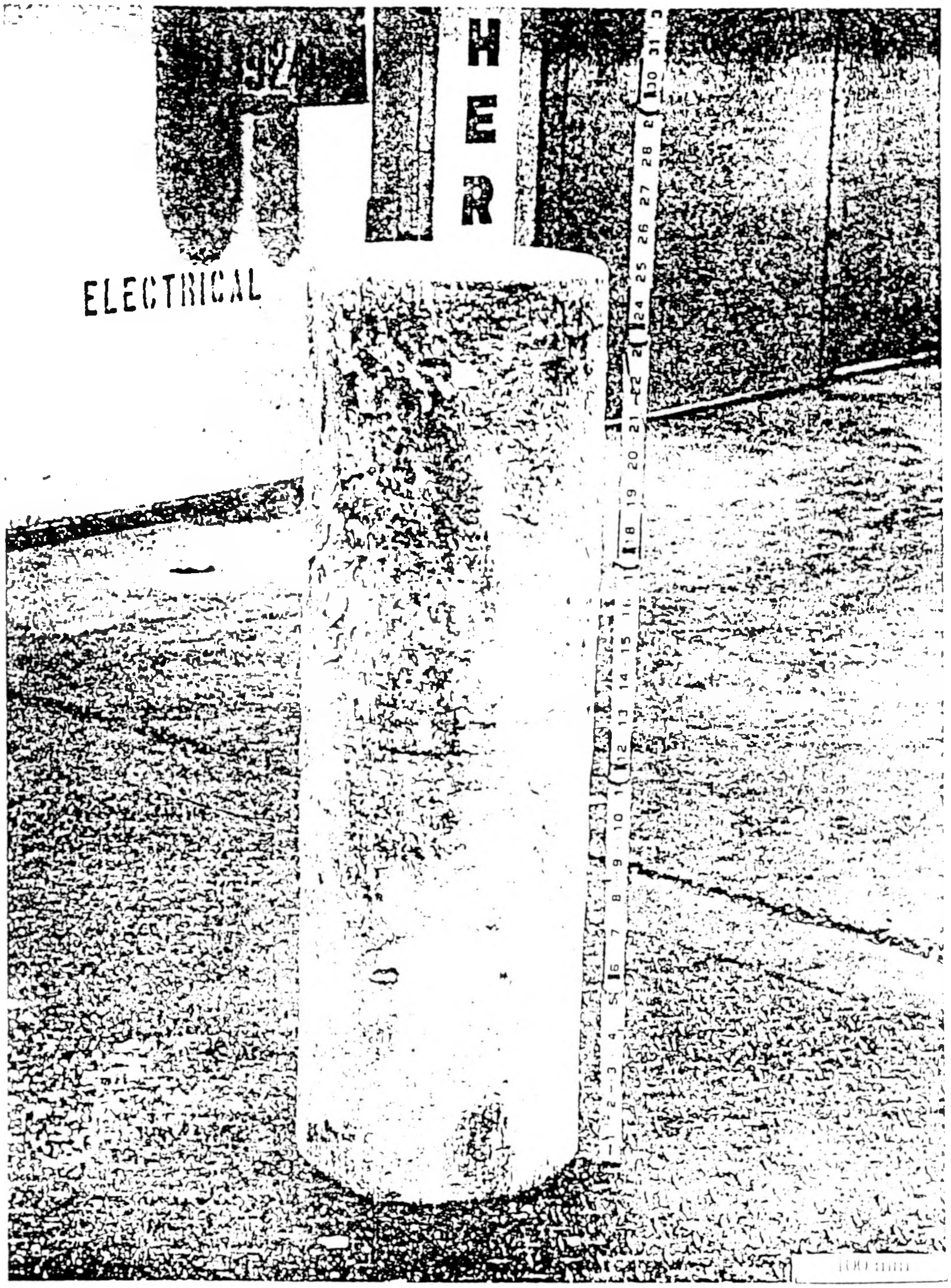

Fig. 11. A 203-mm-diam × 635-mm-long ingot of iron-aluminide alloy (FAL) prepared by electroslag remelting at Carpenter Technology (Reading, Pennsylvania).

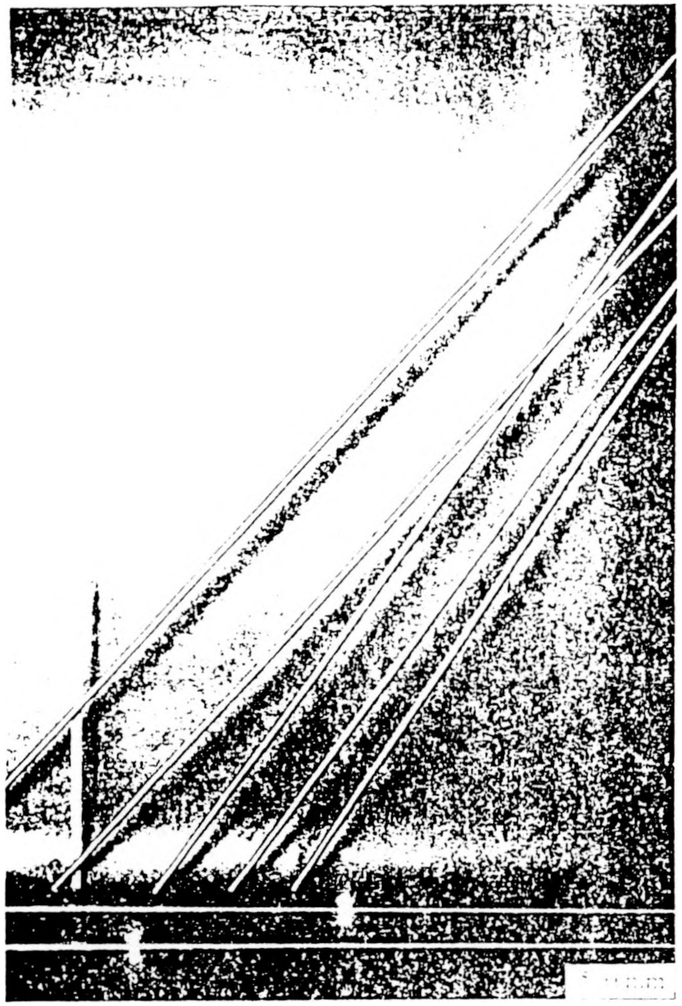

Fig. 12. Hot-rolled bars, 25-mm diam, produced from 102- and 152-mm-diam ingots at Special Metals Corporation (New Hartford, New York).

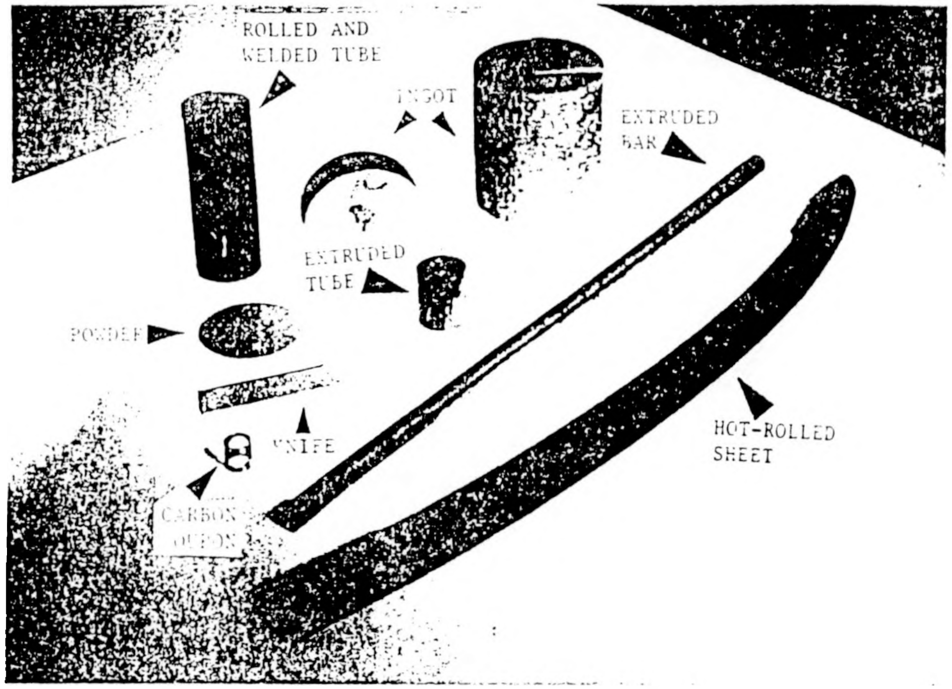

Fig. 13. Several different shapes fabricated from ductile, Fe_3Al-based, iron aluminides.

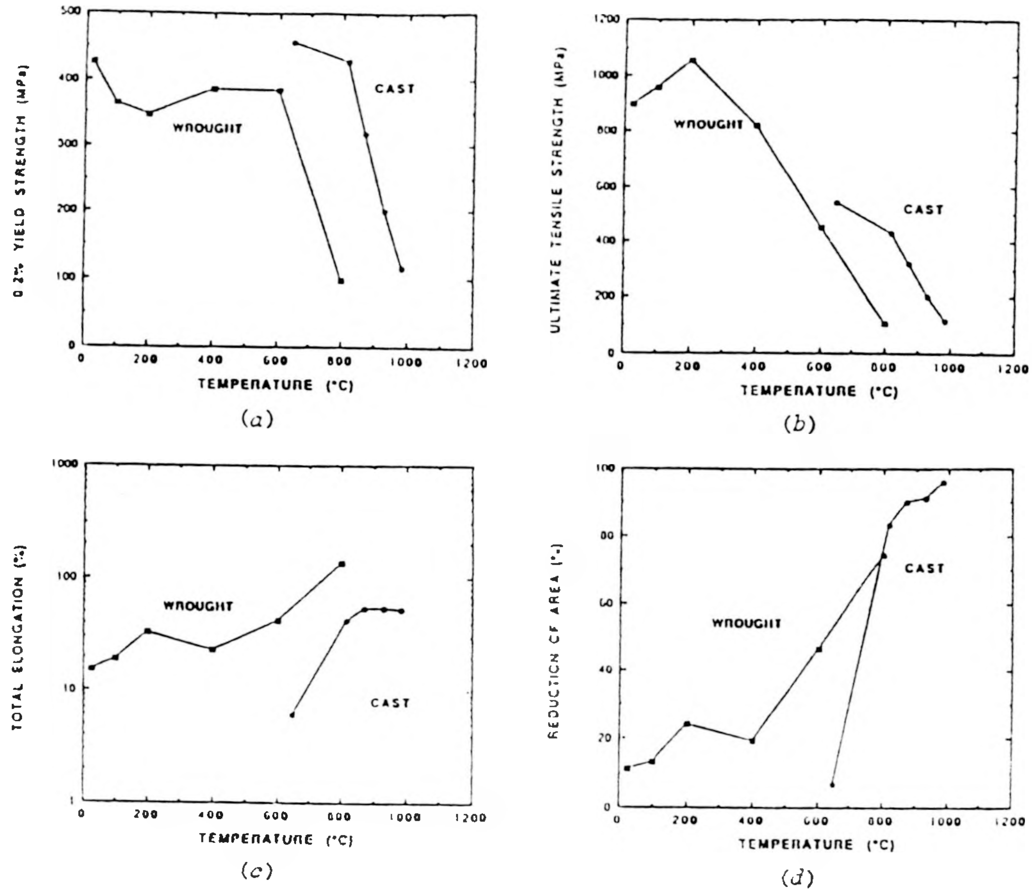

Fig. 14. The tensile properties of Fe_3Al alloy (FA-129) in wrought and cast conditions: (*a*) 0.2% yield strength, (*b*) ultimate tensile strength, (*c*) total elongation, and (*d*) reduction of area.

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