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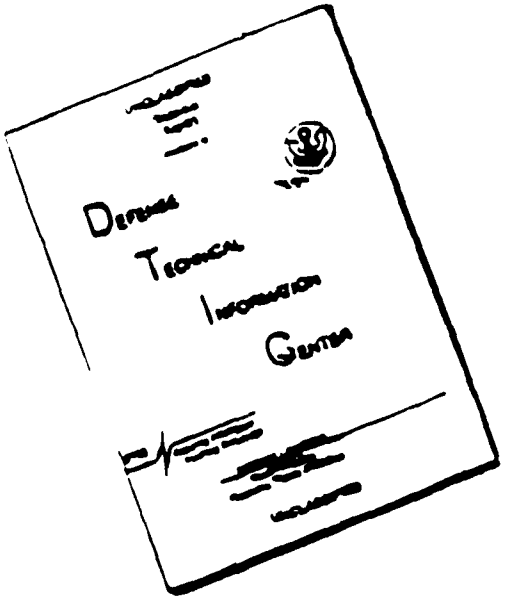

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STRUCTURAL INTERMETALLICS

PERSPECTIVES ON SCIENCE AND TECHNOLOGY

February 5 & 6, 1994

DEFENCE METALLURGICAL RESEARCH LABORATORY
HYDERABAD
INDIA

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Vol. I

Metals Group,
MATERIALS RESEARCH SOCIETY OF INDIA

ASIAN OFFICE OF AEROSPACE RESEARCH & DEVELOPMENT
US Air Force

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FOREWORD

A two day symposium on "Structural Intermetallics - Perspectives on Science and Technology" was held at the Defence Metallurgical Research Laboratory, Hyderabad, India on February 5 and 6, 1994, preceding the Annual General Meeting of the Materials Research Society of India. The Symposium was organised by the Metals Group of the Materials Research Society of India and co-sponsored by the Asian Office of Aerospace Research and Development, US Air Force. C.V.Sundaram, Chairman, Metals Group of the Materials Research Society of India noted in his introductory remarks that the progress towards the development of intermetallics to application has been 'exasperatingly' slow. Robert Cahn of the University of Cambridge, UK, in a keynote lecture provided a historical perspective on early research on 'weakly ordered' alloys and examples of more recent work on 'strongly ordered' compounds.

The symposium featured ten overview talks. Dan Miracle of Air Force Wright Laboratory addressed both science-based issues and engineering concerns related to the metallurgy of NiAl. He noted that NiAl could be significantly strengthened to the levels of several superalloys and, in any case, possessed a variety of attractive properties such as low density, high thermal conductivity and excellent environmental resistance. Nevertheless, a reasonable combination of toughness and high temperature strength continues to be an elusive goal, and the current approach emphasises design methodologies which can use low toughness materials with adequate factors of safety. The alloy system presents large opportunities for research in fabrication (casting technology), strengthening and deformation behaviour. Vinod Sikka presented the status of Fe_3Al and Ni_3Al from an applications engineering perspective with emphasis on work at the Oak Ridge National Laboratory, USA. He stressed specially the excellent corrosion and sulphidation resistance of the Fe_3Al base alloys and their cost benefits in relation to stainless steel. High temperature strength levels continue to be of concern and strong environmental effects on ductility at room temperature have been identified. It appears unlikely that Ni_3Al base alloys will find aeroengine applications, but their excellent carburisation resistance and high temperature strength lend them to applications in heat treatment furnaces, automotive vehicles and in manufacturing. Cost is a key concern in these applications. A summary of the work on Ti_3Al and Ti_2AlNb base alloys at the Defence Metallurgical Research Laboratory, with emphasis on the key issues that limit application, was provided by Ashok Gogia. He described microstructural and compositional effects on primary creep in some detail emphasising that this area has not received adequate attention

in the literature, although the major contribution to creep strain arises from transient behaviour. Other drawbacks relate to oxygen induced dynamic embrittlement over the range of application temperatures and poor burn resistance, a feature common to all titanium alloys with the exception of TiAl. Patrick Martin from Rockwell Science Centre, USA described the current status on TiAl. Successful engine ground tests at General Electric of cast Ti-47Al-2Cr-Nb offer a positive outlook for application of an intermetallic alloy in rotating applications. His talk emphasised issues related to thermomechanical processing of these alloys as they affect microstructure evolution and emphasised the need to refine the processing-microstructure-property envelope in full scale ingot conversion and the development of low cost processing approaches for potential automotive applications.

Work on molybdenum disilicide was covered in two presentations : Dallis Hardwick summarised the physical metallurgy of $MoSi_2$ and described in some detail Rockwell Science Centre work on this material, while Sadananda from the Naval Research Laboratory, USA concentrated on the effect of SiC particulates and whisker composites with $MoSi_2$ on creep resistance. While composite microstructure can be designed to provide creep resistance much superior to superalloys and approaching ceramic-ceramic systems at temperatures greater than 1000°C, it was clear that low temperature toughness must be enhanced, perhaps utilising ductile phase toughening or laminate design. Two approaches to the stability of intermetallics were described by Raju from Indira Gandhi Centre for Atomic Research, India, and Ashok Singh from the Defence Metallurgical Research Laboratory, India. Raju described the variety of semi-empirical approaches using alloy theory parameters and concluded with his own work in developing a new structure map parameter which offers advantages over the Pettifor scheme. Ashok Singh offered a description of a variety of thermodynamic approaches including CVM to developing ground state structures in ordered hexagonal systems. Tassaduq Khan of ONERA, France described the nature and substance of European Community Schemes such as BRITE-EURAM, COST and CEASI as related to intermetallic programmes and provided a summary of ONERA work on B2 alloys based on the Ti-Al-Nb system and approaches to TiAl alloy development.

A variety of contributed presentations from various research groups in India covered work on phase transformations in TiAl, Zr_3Al and B2-DO_3 systems, powder metallurgy and ingot approaches to processing Fe_3Al and Al_3Ti alloys, the mechanical behaviour of alloys of the Ti_3Al-Nb system and oxidation resistance of Ti_3Al alloys. A dominant metallurgical theme that emerged from the symposium was the dichotomy that exists between high temperature strength and low temperature ductility in the

intermetallics. Alloying and processing schemes that enhance the one, almost inevitably do so at the expense of the other.

A hard copy of the material presented in the overview talks is provided in two volumes. The first covers the aluminides : NiAl, TiAl, Ni_3Al, Fe_3Al and Ti_3Al. The second presents the material on European intermetallic activities, molybdenum disilicide and its composites, the ground state structures and stability of intermetallics.

March, 1994

D. Banerjee
Defence Metallurgical Research Laboratory
Hyderabad-500258, India

PROGRAMME

Saturday, Feb 5

9.00 - 9.45	Intermetallics - The Fashionable and Unfashionable *R.W.Cahn* University of Cambridge, U.K.
9.45 - 10.15	Coffee
10.15 - 11.00	Understanding and Applications of NiAl *D.B.Miracle* Air Force Wright Laboratory, USA
11.00 - 11.45	Technology and Applications of Ni_3Al-Based Materials *V. K. Sikka* Oakridge National Laboratory, USA
11.45 - 12.05	Development of Cold Rolling Texture in Ni_3Al (B) *R.K.Ray* Indian Institute of Technology, Kanpur, India
12.05 - 12.25	Recrystallisation of Ni_3Al *A.K.Jena* Indian Institute of Technology, Kanpur, India
12.25 - 1.15	Lunch
1.15 - 2.00	Promise versus Reality for High Temperature Applications of Gamma TiAl - A Perspective *P.L.Martin* Rockwell Science Centre, USA
2.00 - 2.20	Diffusional Composition Invariant and Coarsening Phase Transformations in TiAl Base Alloys *R.V.Ramanujam* Bhabha Atomic Research Centre, Bombay, India
2.20 - 2.40	Interface Modification in two phase ($\gamma+\alpha_2$) Titanium Aluminide by Ternary Additions and their Deformation Behaviour *S.R.Singh* National Metallurgical Laboratory, Jamshedpur, India
2.40 - 3.15	Tea
3.15 - 4.00	The Stability of Intermetallics *S.Raju* Indira Gandhi Centre for Atomic Research, Kalpakkam, India
4.00 - 4.45	Ground State Structures of Ordered Alloys *S. Lele & A.K.Singh* Banaras Hindu University, Varanasi, India

Sunday, Feb 6

9.00 - 9.45	European Intermetallic Activities - Contributions from France *T. Khan* ONERA, France
9.45 - 10.15	Coffee
10.15 - 11.00	Composites Based on Molybdenum Silicide : Progress and Prospects *D.A. Hardwick* Rockwell Science Centre, USA
11.00 - 11.45	Technology and Applications of Fe_3Al-based materials *V.K. Sikka* Oak Ridge National Laboratory, USA
11.45 - 12.05	Preparation and Processing of Fe_3Al Strips through Ingot and P/M processing *S.Bagchi, S.Suwas, S.Bhargava, S.Sangal and R.K.Dube* Indian Institute of Technology, Kanpur, India
12.05 - 12.25	Anti-phase boundaries in B2 and DO_3 Fe-Al-X (X=Cr, Mo) and $DO_{22}/L1_2$ Al-Ti-Ni Intermetallics *Ujjwal Prakash* Defence Metallurgical Research Laboratory, Hyderabad, India
12.25 - 12.45	Improvement in Mechanical Properties of Iron Aluminides *Aruna Bahadur* National Metallurgical Laboratory, Jamshedpur, India
12.45 - 2.00	Lunch
2.00 - 2.45	The Metallurgy of Ti_3Al Base alloys *A.K.Gogia* Defence Metallurgical Research Laboratory, Hyderabad, India
2.45 - 3.05	Low Cycle Fatigue Behaviour of Ti-27Al-15Nb *P.N.Singh, B.K.Singh, C.Ramachandra and V.Singh* Banaras Hindu University, Varanasi, India
3.05 - 3.25	High Temperature Oxidation of Ti_3Al *T.K.Roy, R.Balasubramaniam and A.Ghosh* Indian Institute of Technology, Kanpur, India
3.25 - 4.00	Tea
4.00 - 4.20	Morphological Features of Ti_3Al Based Intermetallic Alloys Prepared by Reaction Synthesis *M.Sujata, S.Bhargava and S.Sangal* Indian Institute of Technology, Kanpur, India
4.20 - 4.40	Phase Transformations in Zr_3Al Base Alloys *R.Tewari, G.K.Dey and P.Muthopadhyay* Bhabha Atomic Research Centre, Bombay, India

3. Structural Applications of NiAl

DB Miracle
AF Wright Laboratory, USA

STRUCTURAL APPLICATIONS of NiAl

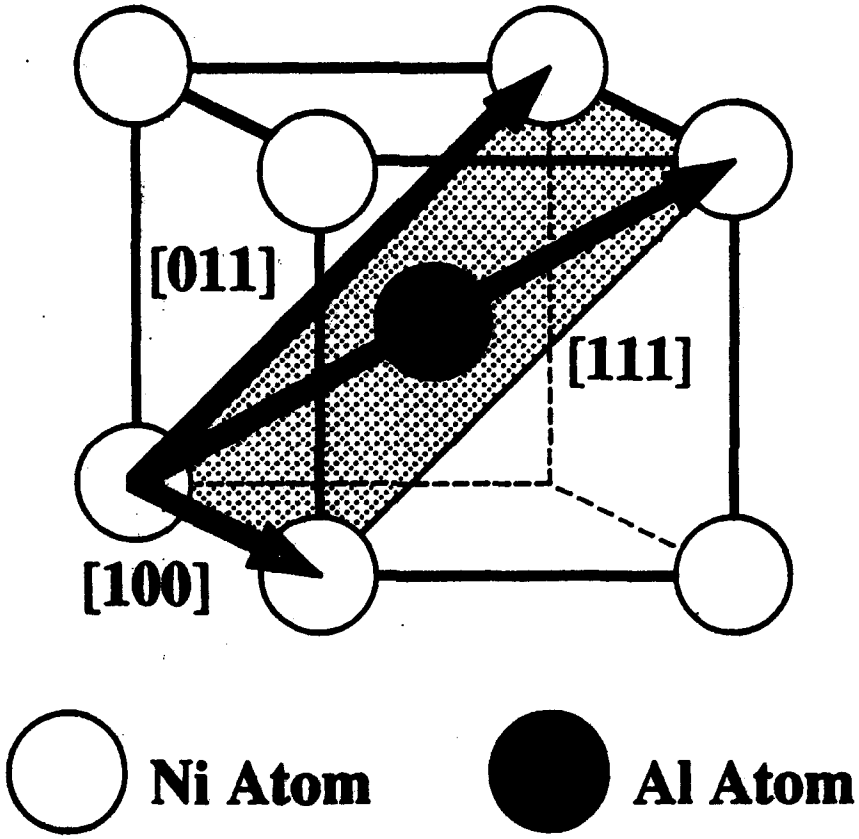
Dr. Daniel B. Miracle
AF Wright Laboratory
Wright-Patterson AFB, OH
5 February 1994

INTRODUCTION

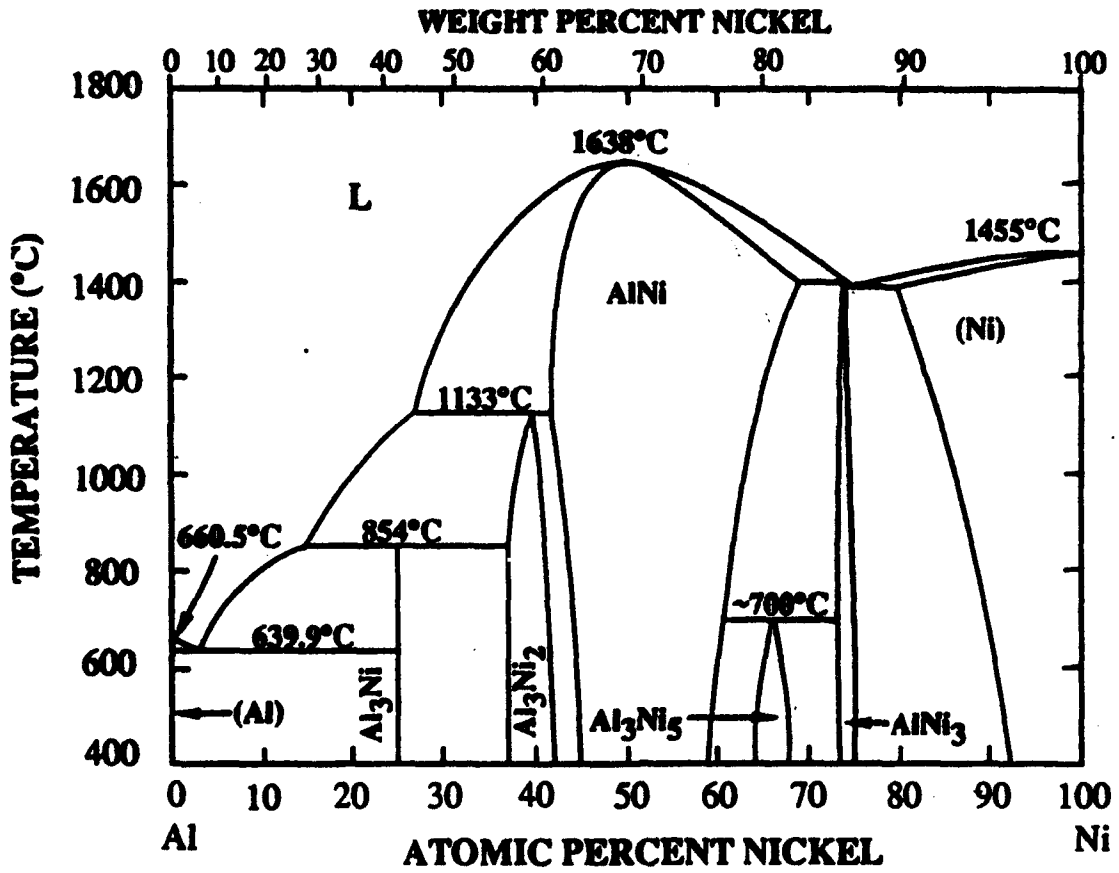
- Exceedingly extensive database is available for NiAl
- Significant activity to develop NiAl as a structural material for aerospace applications over the past 10 years
- Physical and mechanical properties, including deformation mechanisms, as well as application-related issues, will be reviewed
- Suggestions for studies will be provided

- PHYSICAL PROPERTIES
- CRYSTAL DEFECTS
- MECHANICAL PROPERTIES
- STRUCTURAL APPLICATIONS
- ISSUES

"NiAl Crystal Structure"



"NiAl Phase Diagram"



PHYSICAL PROPERTIES

"*Crystal Structure/Phase Stability*"

A. NiAl possesses a wide solubility range and high melting temperature

B. NiAl exhibits the cP2 (CsCl) ordered crystal structure; strong order is maintained to the melting point

   1. long-range order and thermodynamic properties are consistent with strong Ni-Al bonding

C. A fully-reversible shape-memory effect results from the martensitic NiAl at Ni-rich compositions

D. The density of stoichiometric NiAl is 5.85 gm/cm3

E. Many characteristics depend sensitively on composition; both bulk composition, as well as type and amount of impurities should be carefully specified

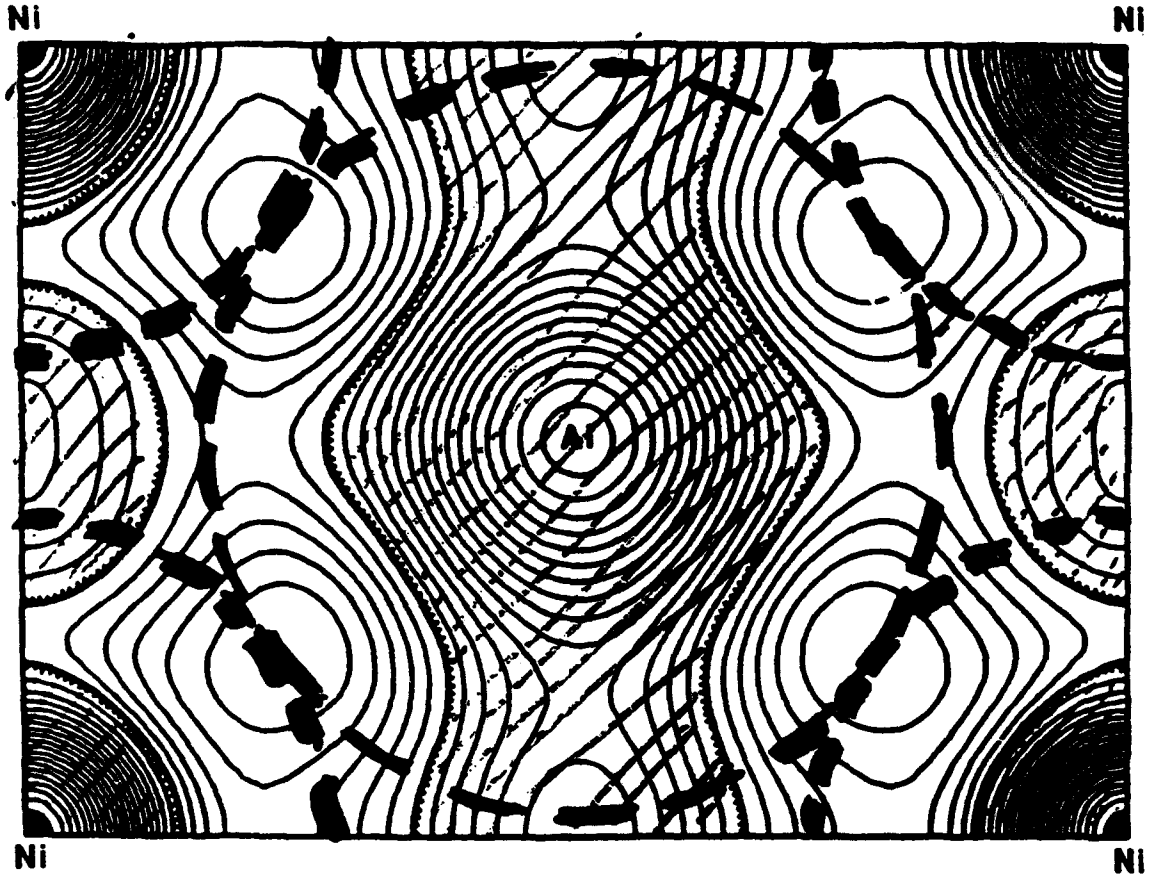


Figure 1 The bonding charge density on a {110} plane in NiAl from Fig. 4 of Fox and Tabbernor.[24] The dashed circles represent muffin tin spheres of Al and Ni atoms, and schematically illustrate the volumes averaged for determining electron transfer. The interstitial regions between the spheres are also apparent. The contours are in intervals of 20 electrons per nm^3, and the zero contours are ticked toward regions of electron depletion.

PHYSICAL PROPERTIES
"Atomic Bonding"

A. Electron charge density plots show depletion of electrons at Ni and Al atom sites, and between like atoms along <100> directions

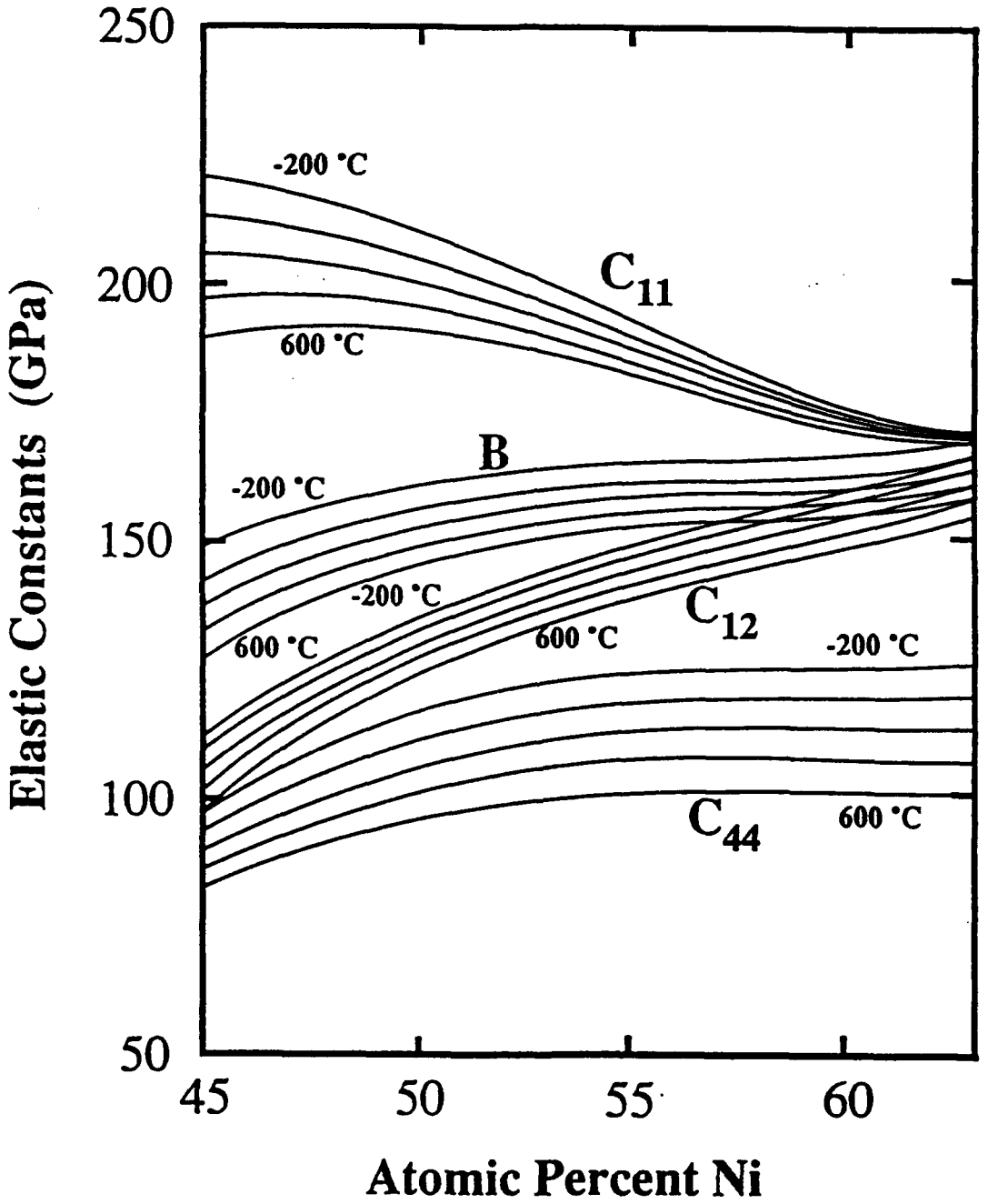
B. A concentration of electrons is observed along <111> between Al and Ni sites

   1. this is consistent with measurements of Al-p/Ni-d bond hybridization along <111>

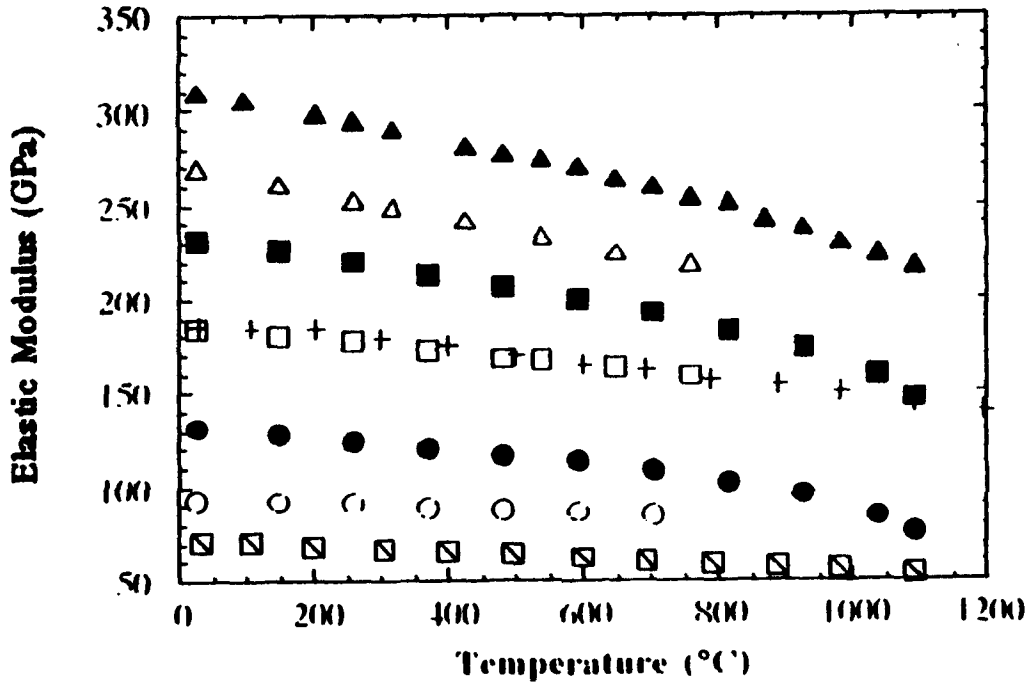
C. A strong covalent bond between Ni and Al atoms results, as well as a weak ionic repulsion between like atoms

   1. this may produce the observed elastic anisotropy

D. These bonds are superimposed over a metallic bond in NiAl


250
200
150
100
50
45
50
55
60
Elastic Constants (GPa)
Atomic Percent Ni
-200 °C
600 °C
C_{11}
B
-200 °C
-200 °C
600 °C
600 °C
C_{12}
-200 °C
C_{44}
600 °C

"Young's Modulus"



Young's modulus as a function of temperature for single crystal NiAl along the (○) <100>, (□) <110>, and (Δ) <111> directions (Wasilewski, 1966). and for a single crystal Ni-base superalloy along the (●) <100>, (■) <110>, and (▲) <111> directions (Lahrman and Darolia, 1992). The (+) Young's modulus and (▨) shear modulus of polycrystalline NiAl is also provided (Moose, 1991).

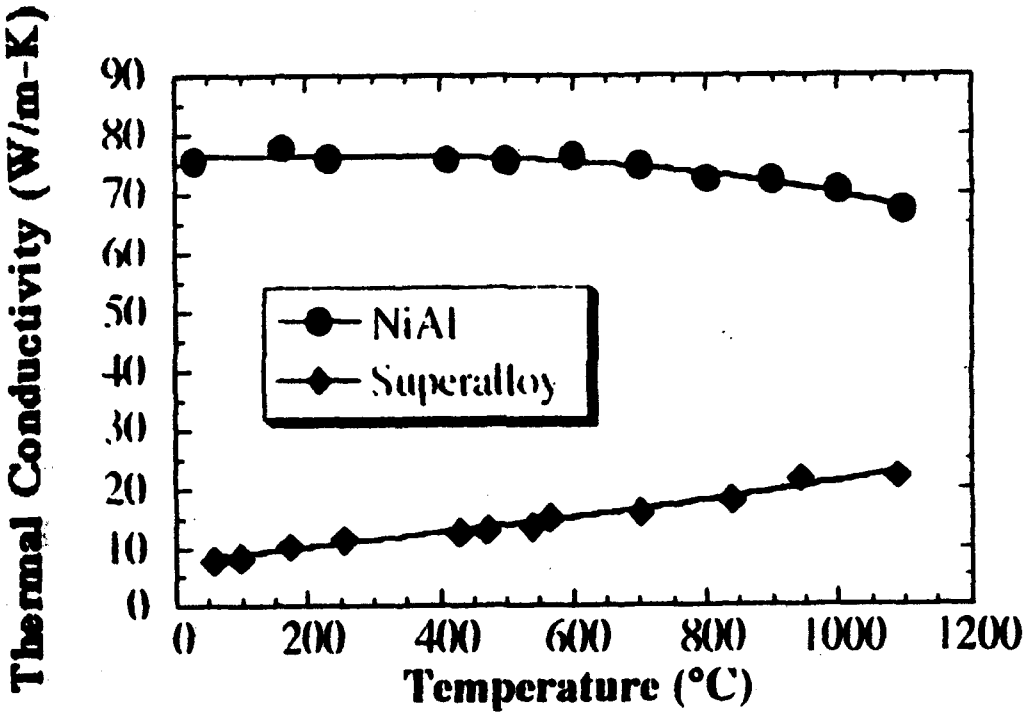
PHYSICAL PROPERTIES
"Elastic Properties"

A. NiAl is elastically anisotropic (A=3.28)

   1. A has a weak temperature dependence, and a strong composition dependence

B. Elastic modulus is about 10% lower than Ni-base superalloys

"Thermal Conductivity"



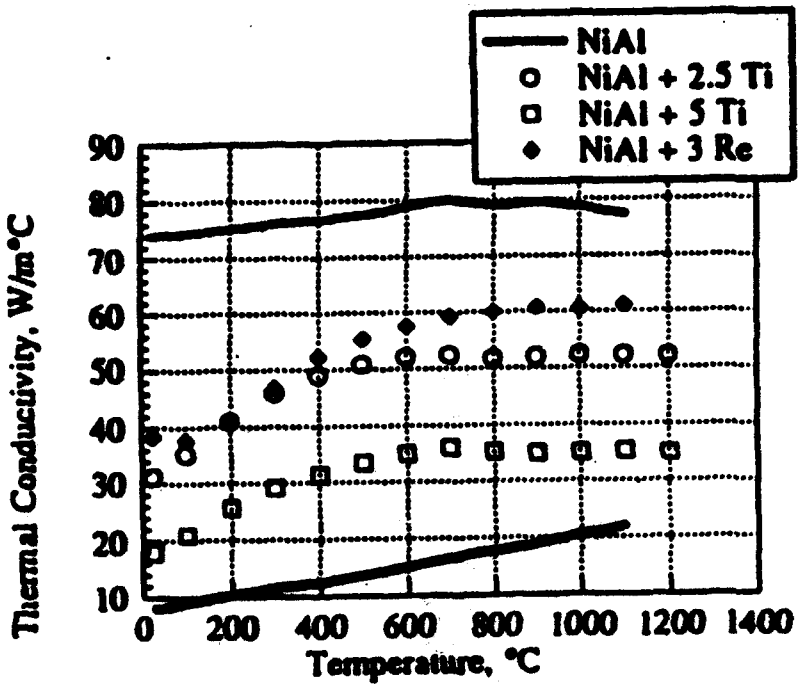


Figure 7. Thermal conductivity of NiAl and NiAl alloys with Re and Ti.

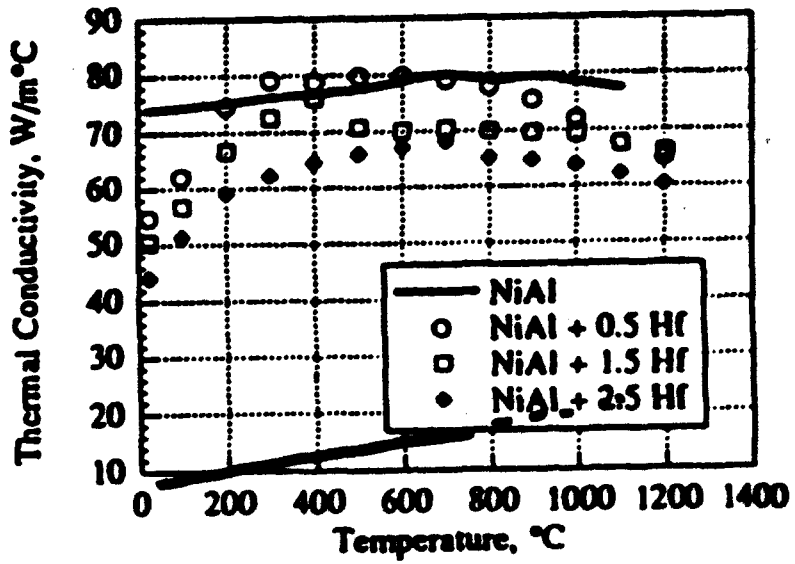


Figure 8. Thermal conductivity of NiAl and NiAl alloys with Hf.

PHYSICAL PROPERTIES
"Thermal Properties"

A. NiAl has a thermal conductivity 3-8X higher than Ni-base superalloys.

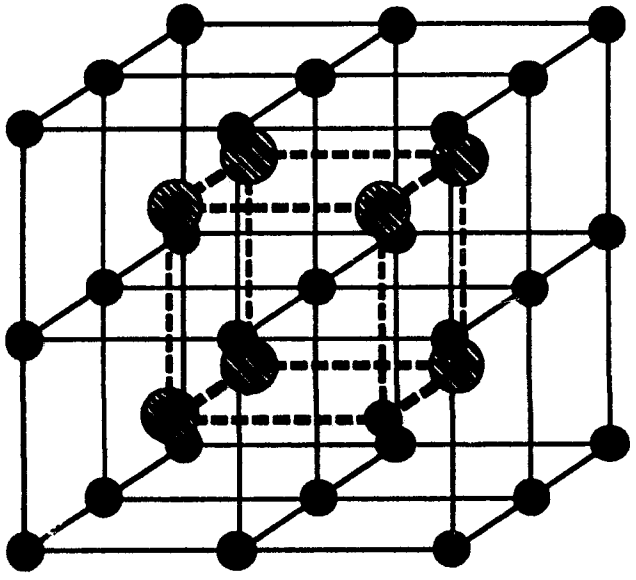
   1. this provides benefits of either reduced cooling flow, or reduced operating temperature

B. Thermal conductivity decreases with increasing alloying additions

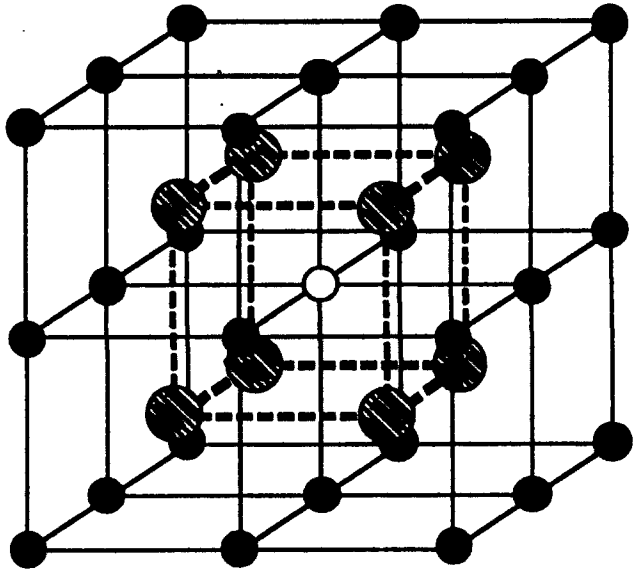
- PHYSICAL PROPERTIES
- CRYSTAL DEFECTS
- MECHANICAL PROPERTIES
- STRUCTURAL APPLICATIONS
- ISSUES

"Constitutional Point Defect Structure"

Ni-Rich



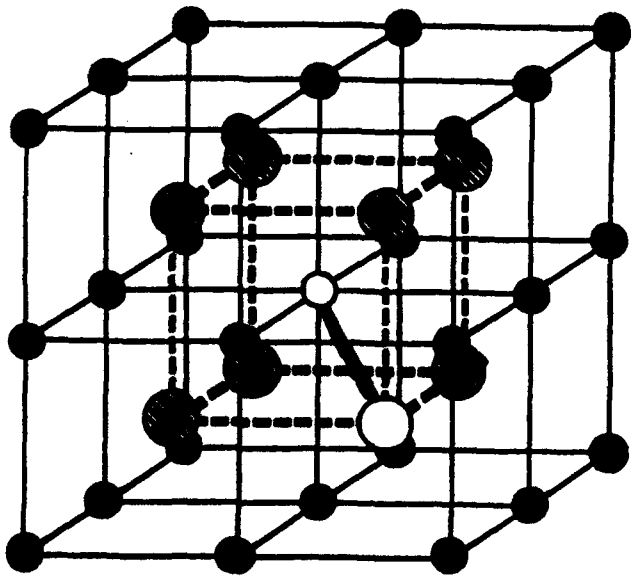
Al-Rich



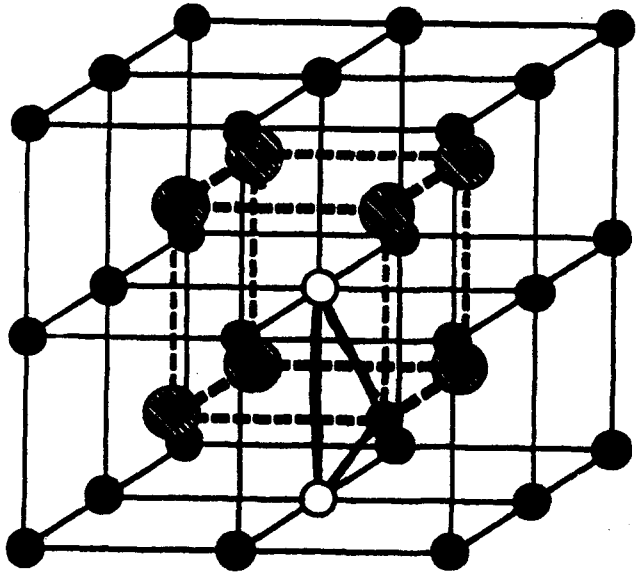
● Ni ● Al ○ Ni Vacancy ● Ni Anti-site

THERMAL DEFECTS

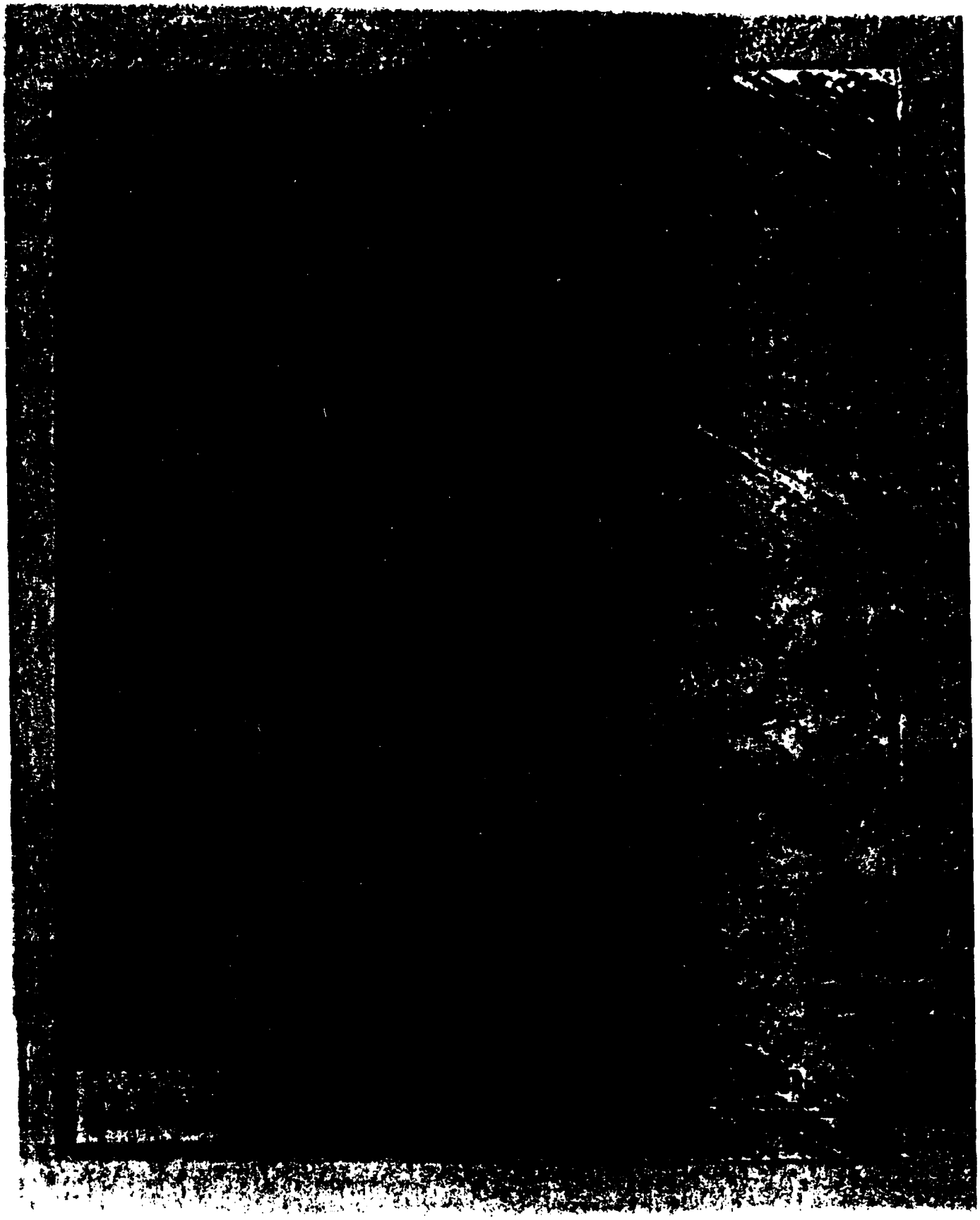
"Divacancy"



"Triple Defect"



● Ni ● Al ○ Vacancy ● Ni Anti-site



CRYSTAL DEFECTS

"*Point Defects*"

A. Ni-rich NiAl exhibits Ni anti-site defects, and Al-rich NiAl possesses Al vacancies

1. Al vacancies are more potent strengtheners

B. Long-range order of constitutional point defects has been proposed, but is inconsistent with x-ray diffraction and scattering studies

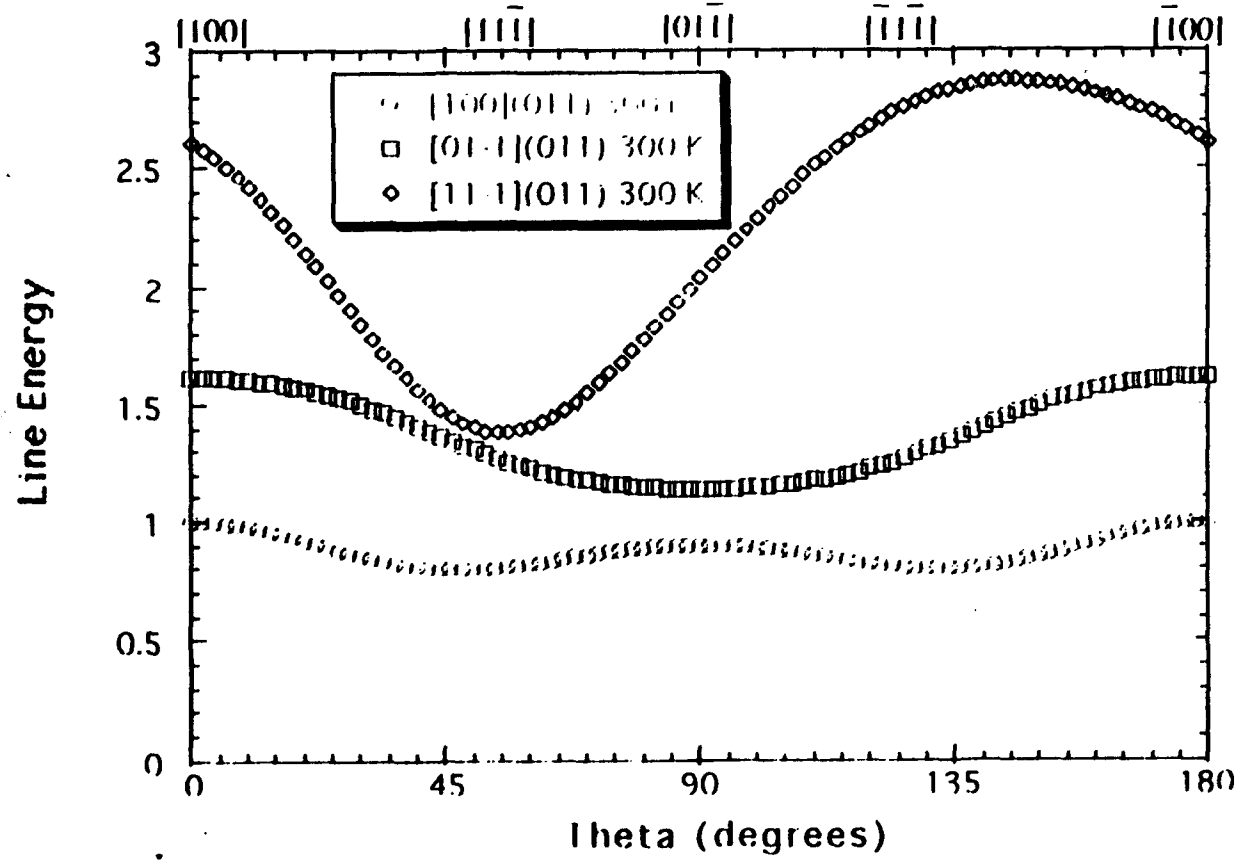
C. Clustering of constitutional defects has also been proposed

D. The formation energy of a divacancy is low (1.6eV), and so a large fraction of thermal vacancies (up to 2%) may exist near the melting temperature

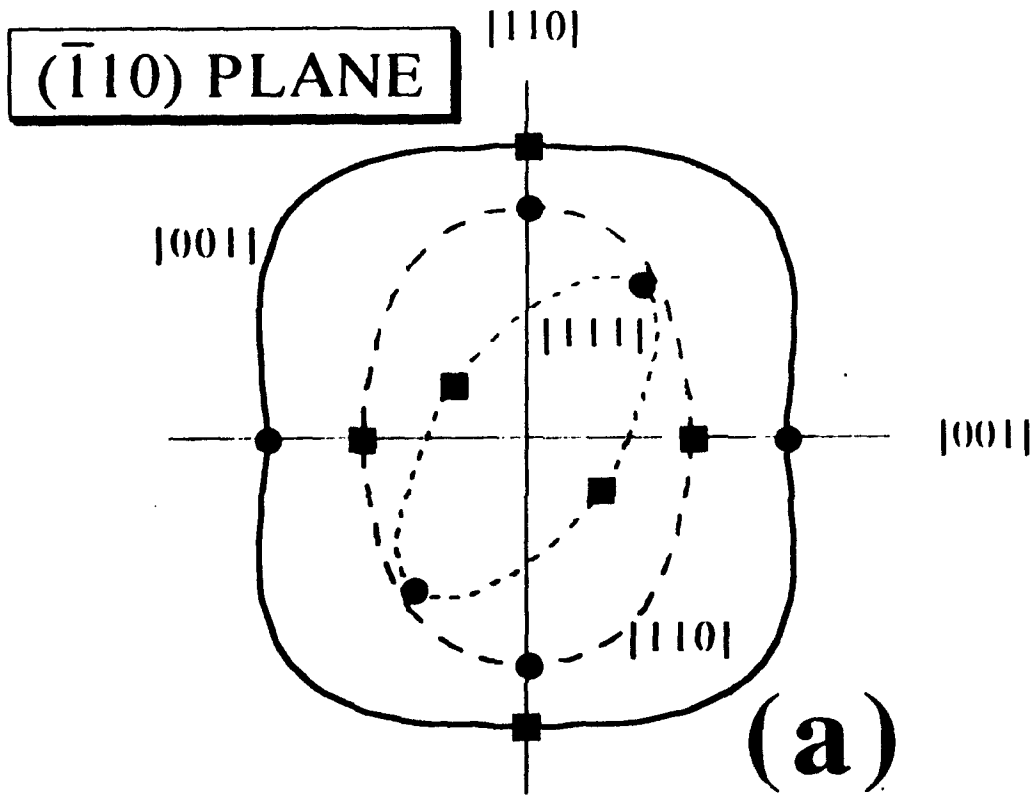
E. Thermal vacancies can produce prismatic loops, which may act as sources of mobile dislocations upon subsequent loading

F. "Triple defects" have been proposed, but not observed

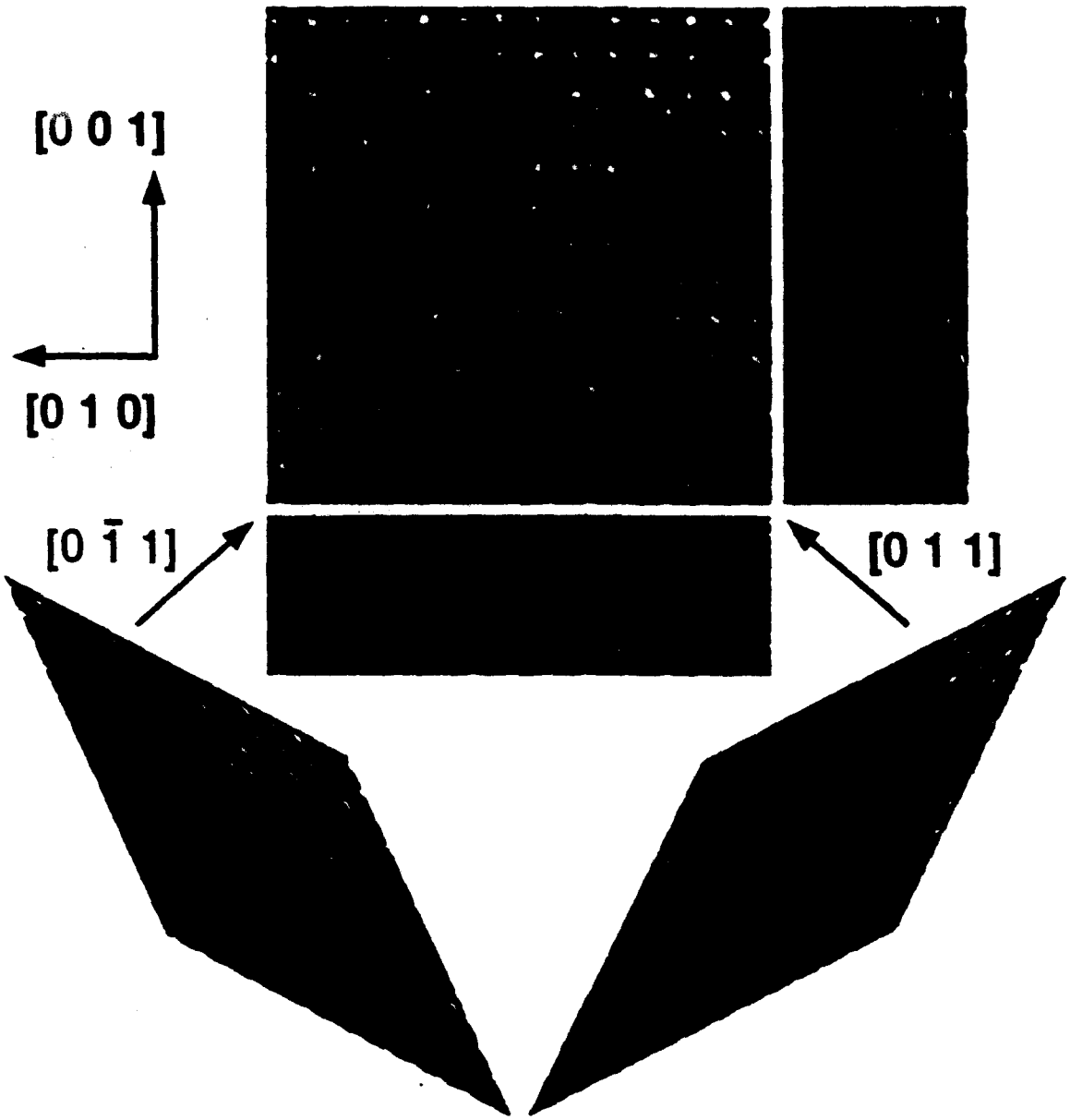
"Dislocation Line Energy"



"Wulff Plot"



a[010] Edge Dislocation in NiAl



Core is compact with no apparent dissociation.

IMPLICATIONS FOR MACROSCOPIC BEHAVIOR

***a*<100> cores are compact, which would:**

A. favor both cross-slip (screw) and climb (edge)

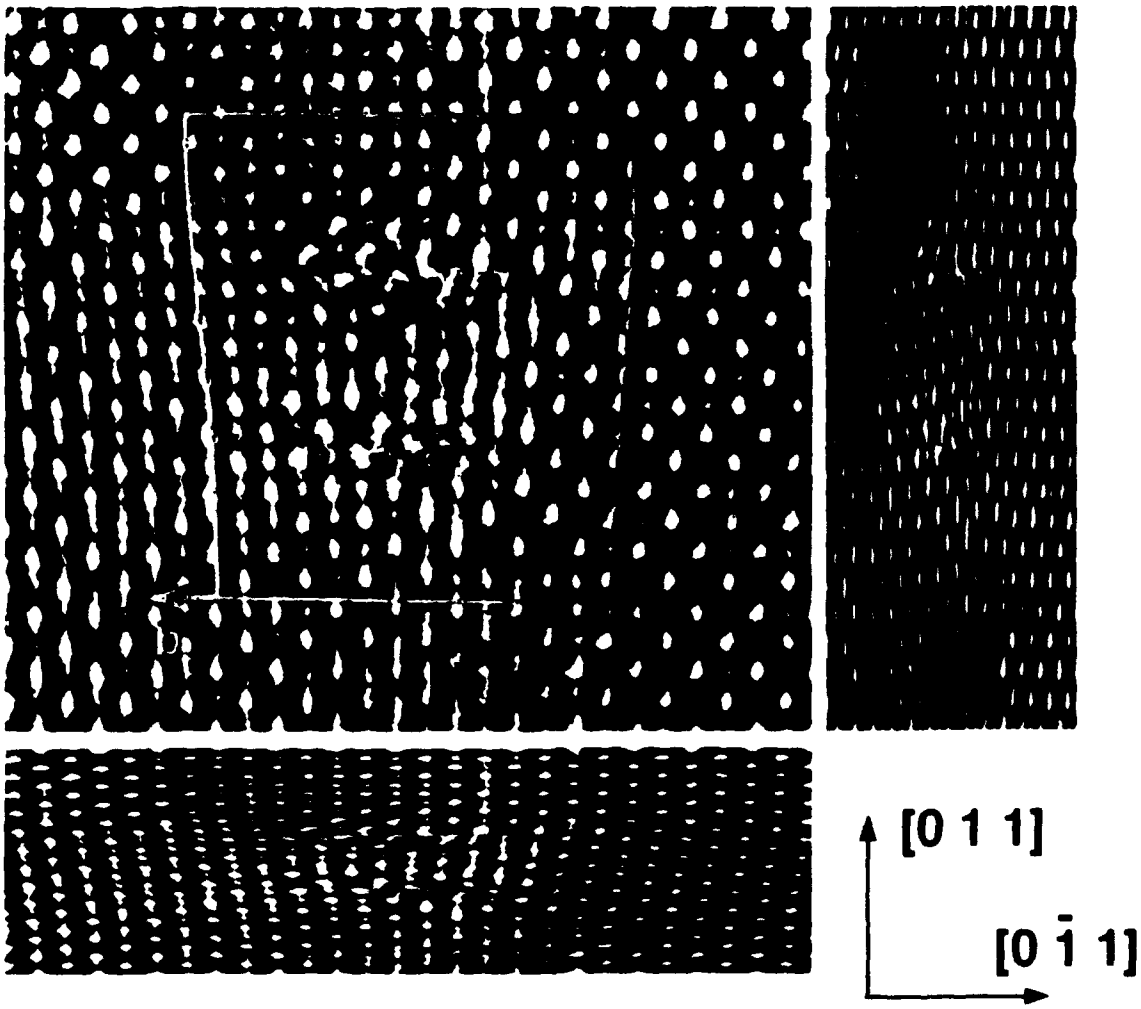
B. produce a large Peierl's barrier to glide

C. (thermally-activated) movement by kink-pair mechanism

D. strain-rate dependence

E. produce strong interactions with defects

a[0 1 $\bar{1}$] Dislocation in NiAl



Decomposed Core:

$$a[0\ \bar{1}\ \bar{1}] \longrightarrow a[0\ 1\ 0] + a[0\ 0\ \bar{1}]$$

- **The a<010> dislocations are *not* coplanar**
  ⟶ simple glide impossible.

IMPLICATIONS FOR MACROSCOPIC BEHAVIOR

***a*<110> cores are extended, and each would requir significant thermal activation**

A. consistent with log(τ) *vs.* 1/T, and with T-dependence of DBTT

B. deformation is predicted to be sensitive to the sense of stress and stress state

C. strong interactions with defects are expected to occur

D. strain-rate dependence is anticipated

CRYSTAL DEFECTS
"Shear-Induced Planar Defects"

A. Shear-induced planar faults have not been observed in NiAl

B. Lower limits on APB, based on experimental observations and calculations, suggests Eapb ≥ 500 and 750 mJ/m2 on (110) and (112) planes, respectively

CRYSTAL DEFECTS
"*Line Defects*"

A. Three basic translation vectors which do not disrupt atomic order are $\mathscr{a}$<100>, $\mathscr{a}$<110>, and $\mathscr{a}$<111>

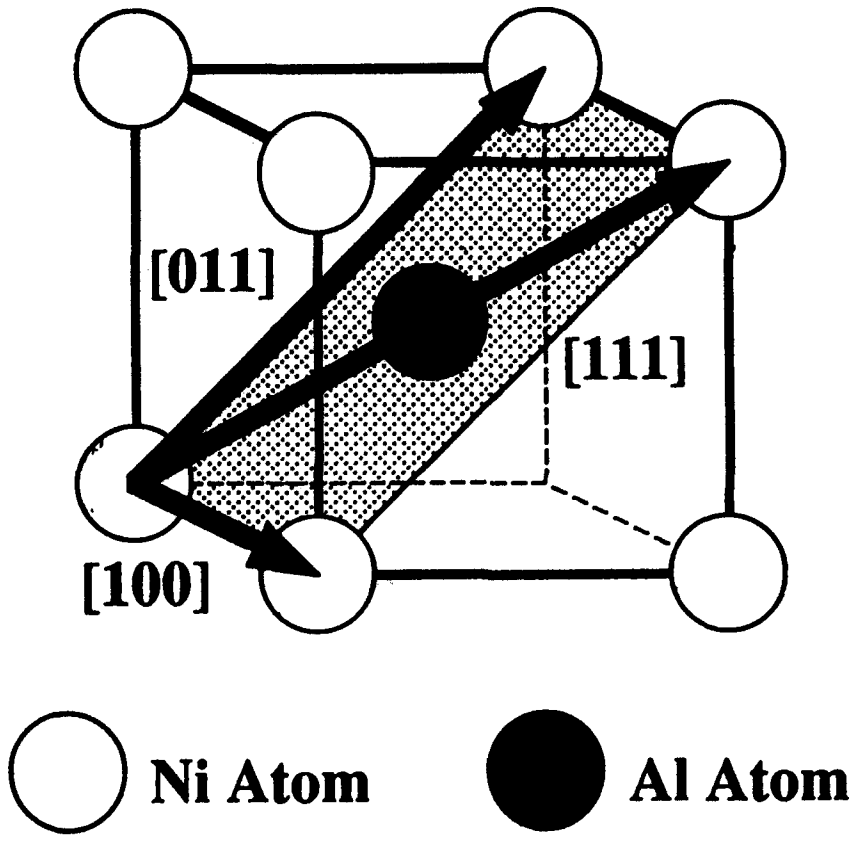
1. Burgers vector is large
2. a/2 does not occur
3. a<100> core is compact, and on a single plane
4. a<110> decomposes by climb to form two a<100>

B. Line Energy is anisotropic

1. <110>, <111> may decompose, but an APB is formed

C. <100> screw dislocations are elastically unstable

"NiAl Crystal Structure"



- PHYSICAL PROPERTIES
- CRYSTAL DEFECTS
- MECHANICAL PROPERTIES
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- ISSUES

MECHANICAL PROPERTIES
"Mechanisms of Deformation"

A. Slip system is <100>{100} and <100>{110} in 'soft' single crystals and polycrystals

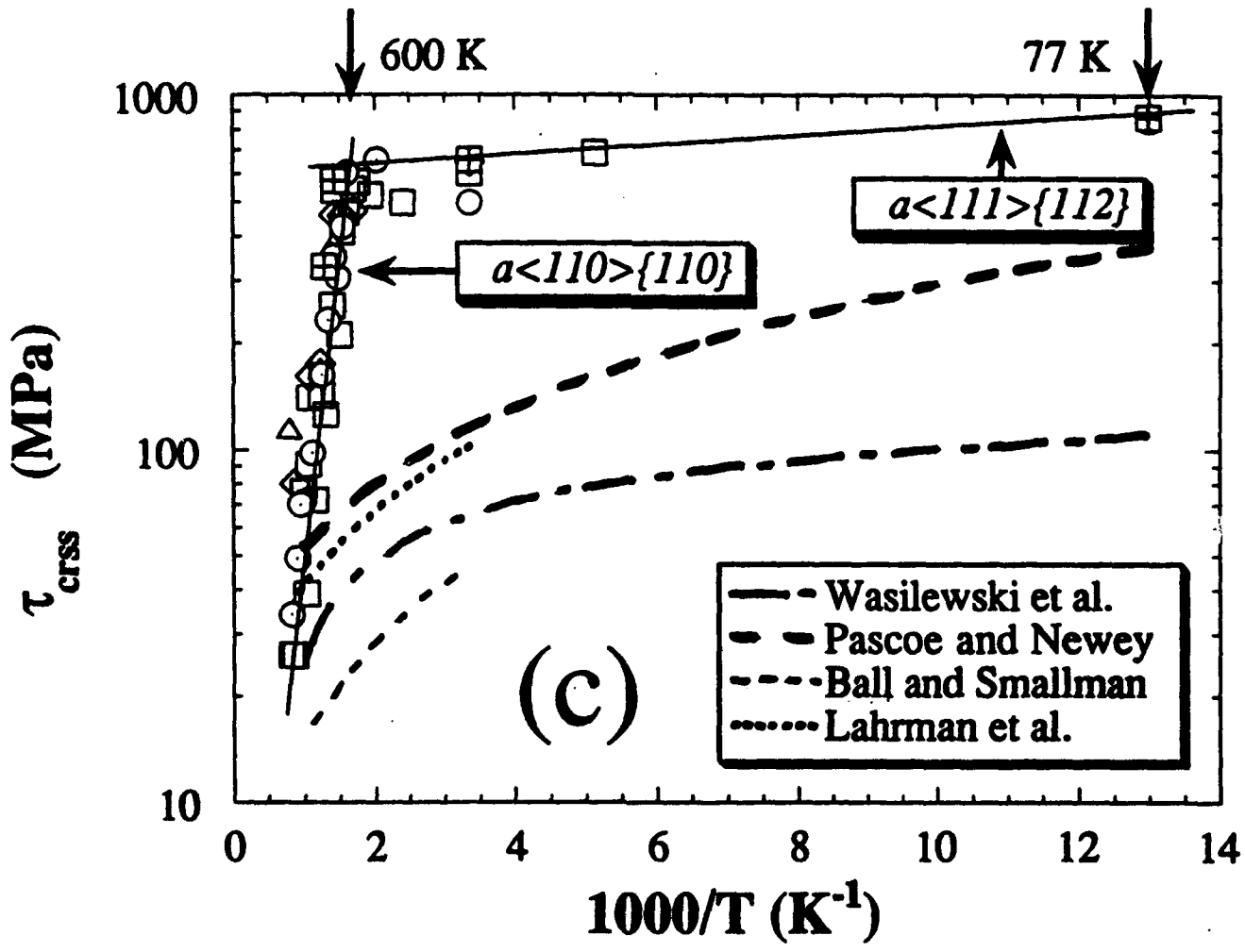
   1. only three independent strains may be produced by glide

B. <111> slip observed below 300°C in cube-oriented ('hard') single crystals

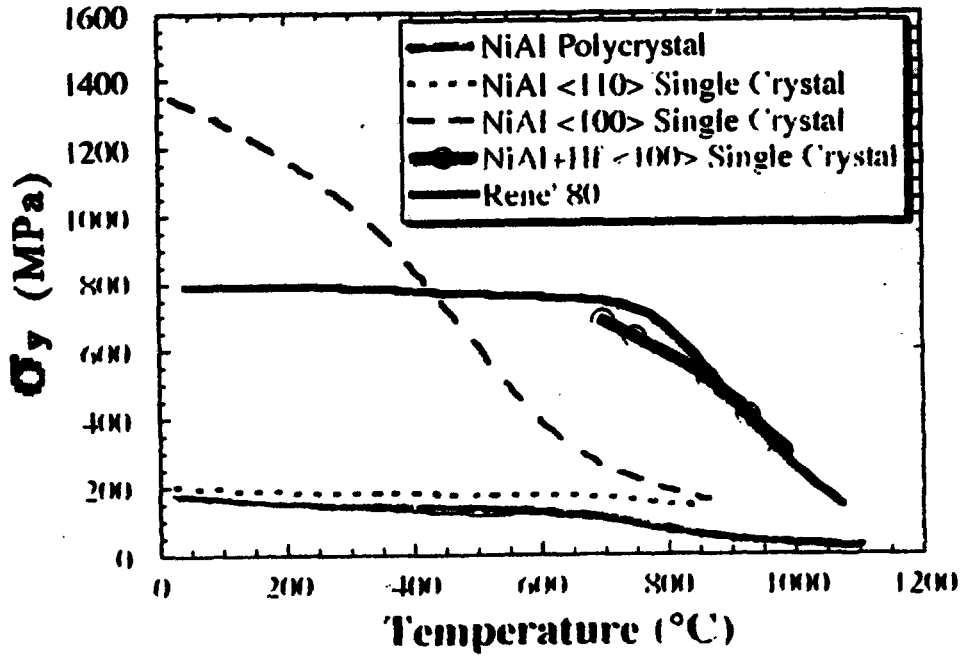
   1. CRSS is 7-10x higher than for <100>

C. <110> slip becomes operative in 'hard' single crystals above 300°C

"CRSS vs. 1/T"

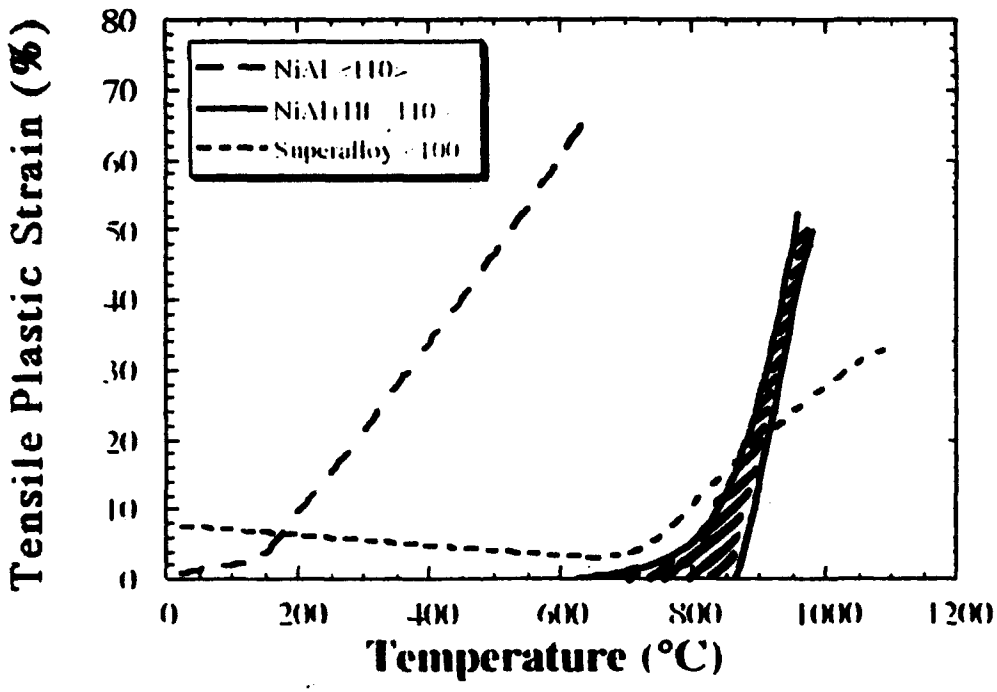

600 K
77 K
1000
100
10
τ_{crss} (MPa)
a<111>{112}
a<110>{110}
(c)
Wasilewski et al.
Pascoe and Newey
Ball and Smallman
Lahrman et al.
0
2
4
6
8
10
12
14
1000/T (K^{-1})

"Yield Stress vs. Temperature"



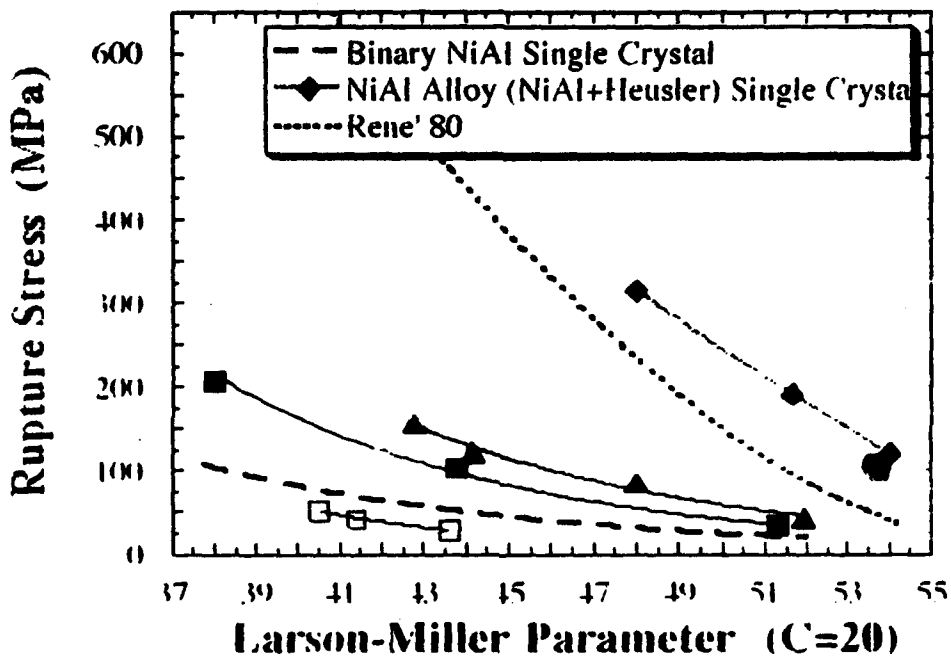
The temperature dependence of the tensile yield strength of binary, polycrystalline NiAl (Rozner and Wasilewski, 1966) and binary NiAl single crystals tested along <110> (Darolia et al., 1992) and <100> (Field et al., 1991b). Data for polycrystalline Rene' 80 (Darolia, 1991) are included for comparison. The strength improvement for NiAl alloyed with Hf tested along a <100> axis is also shown (Darolia et al., 1992).

"Single Crystal Ductility"



Tensile ductility as a function of temperature typical of strengthened NiAl single crystal alloys in the cross-hatched area (Darolia et al., 1992a). The ductility of binary NiAl and a typical Ni-base superalloy are shown for comparison.

"Stress-Rupture of NiAl"



The Larson-Miller parameter is P = (T/1000)(logt + 20), where T is the absolute temperature in Rankine, and t is the time in hours. The data is for (□) binary, polycrystalline NiAl (Grala, 1960); and alloys of (●) NiAl+9% Mo aligned eutectic (Stover, 1966), (■) NiAl+6vol% ThO2 (Seybolt, 1966), and (▲) NiAl+20vol% TiB2 (Kumar, 1991). The dashed lines are from Fig. 12 of Darolia (1991). The line for the NiAl single crystal alloy with Heusler precipitates represents the upper bound of a range of data (Darolia et al., 1992a; Darolia et al., 1992b), and this alloy is equivalent to single crystal Ni-base superalloy Rene N4.

- PHYSICAL PROPERTIES
- CRYSTAL DEFECTS
- MECHANICAL PROPERTIES
- ✈ STRUCTURAL APPLICATIONS
- ISSUES

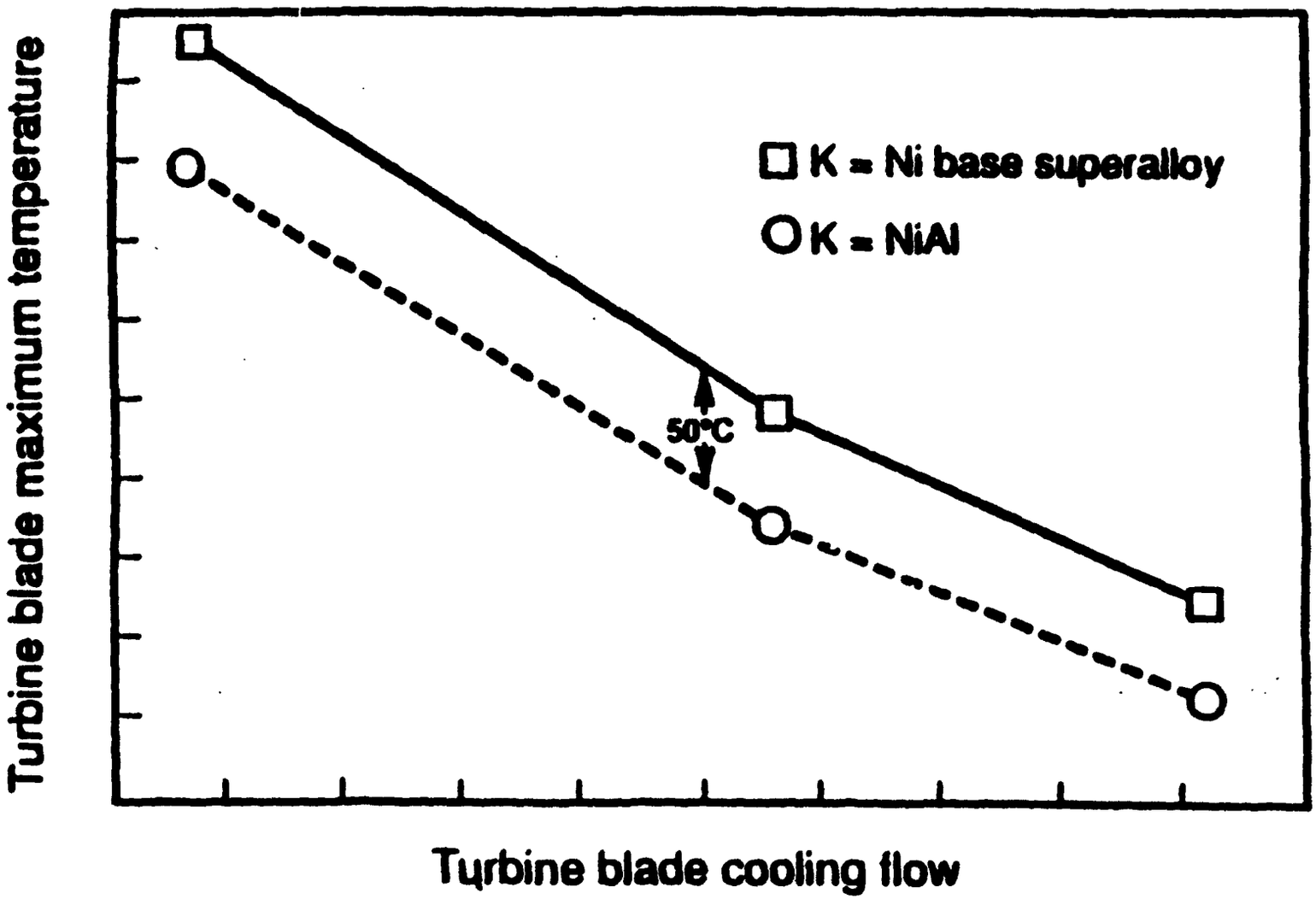
STRUCTURAL APPLICATIONS

A. Principle application is as a turbine airfoil

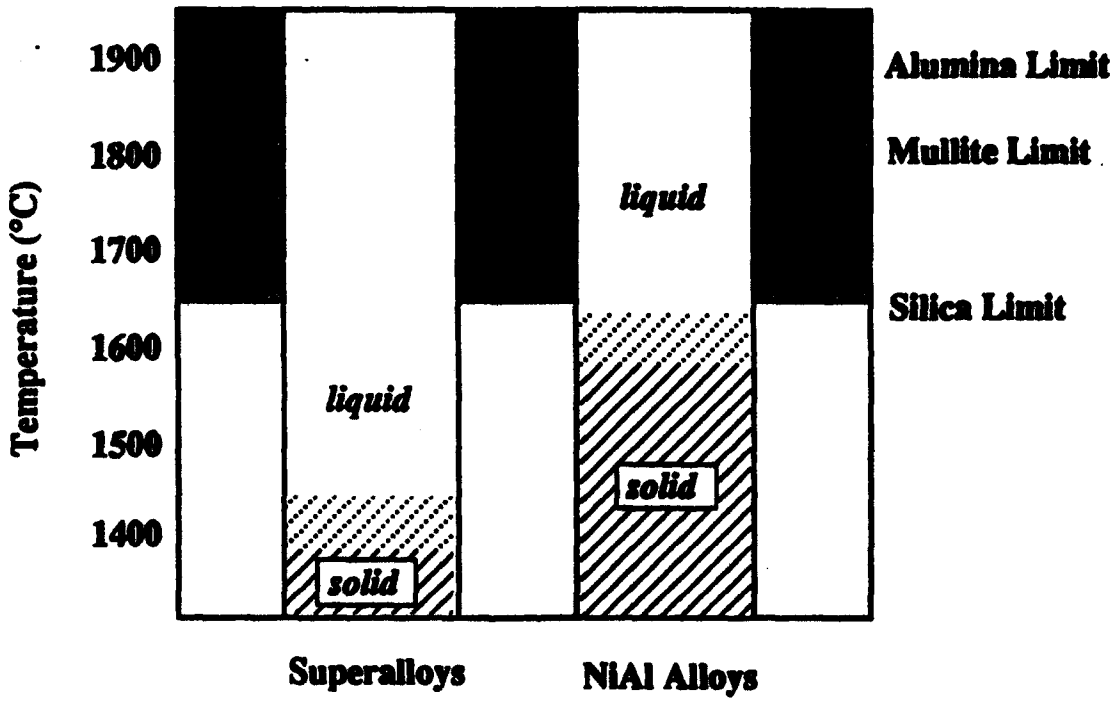
B. Attractive attributes include low density, high Tm, high thermal conductivity

C. Disadvantages are inadequate toughness/damage tolerance (or lack of design experience with brittle material), and inadequate processing, fabrication, and joining experience.

"Effect of Density"

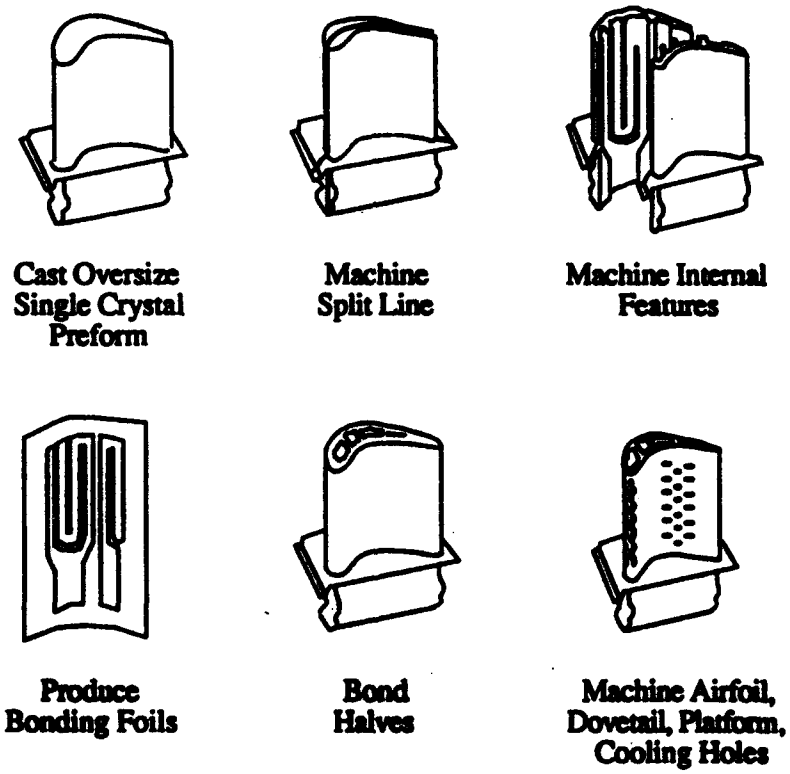

Turbine blade maximum temperature
K = Ni base superalloy
K = NiAl
50°C
Turbine blade cooling flow

"Temperature Limits of Mold Materials"



Temperature limits for investment casting mold and core materials with respect to the melting ranges for Ni-base superalloys and NiAl alloys (Darolia et al., 1992).

"Fabricated Blade Approach"

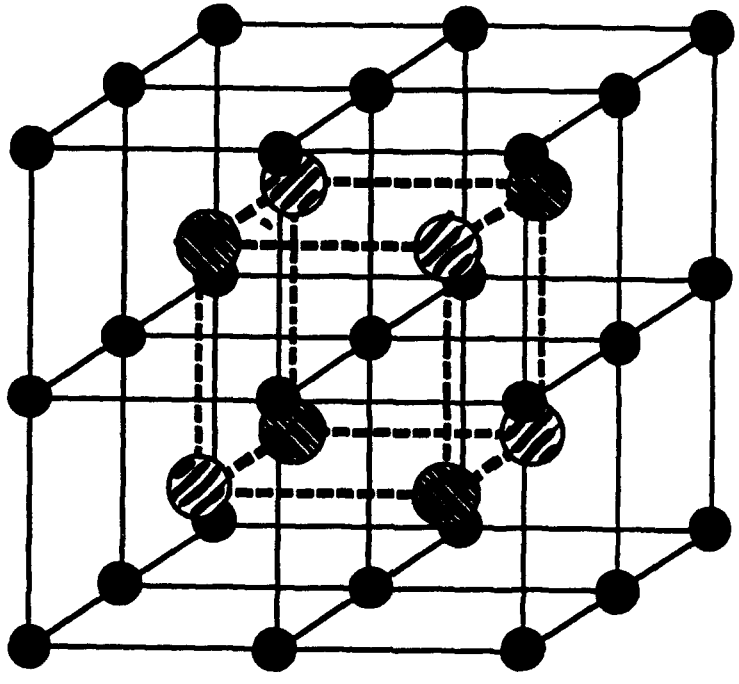


Fabricated blade processing sequence (Darolia et al., 1992).

- PHYSICAL PROPERTIES
- CRYSTAL DEFECTS
- MECHANICAL PROPERTIES
- STRUCTURAL APPLICATIONS

✈ ISSUES

"Related Crystal Structures"



STRUCTURE	COMPOUND	●	●	◍
B2	NiAl	Ni	Al	Al
$L2_1$	Ni_2AlTi	Ni	Ti	Al
DO_3	Fe_3Al	Fe	Fe	Al

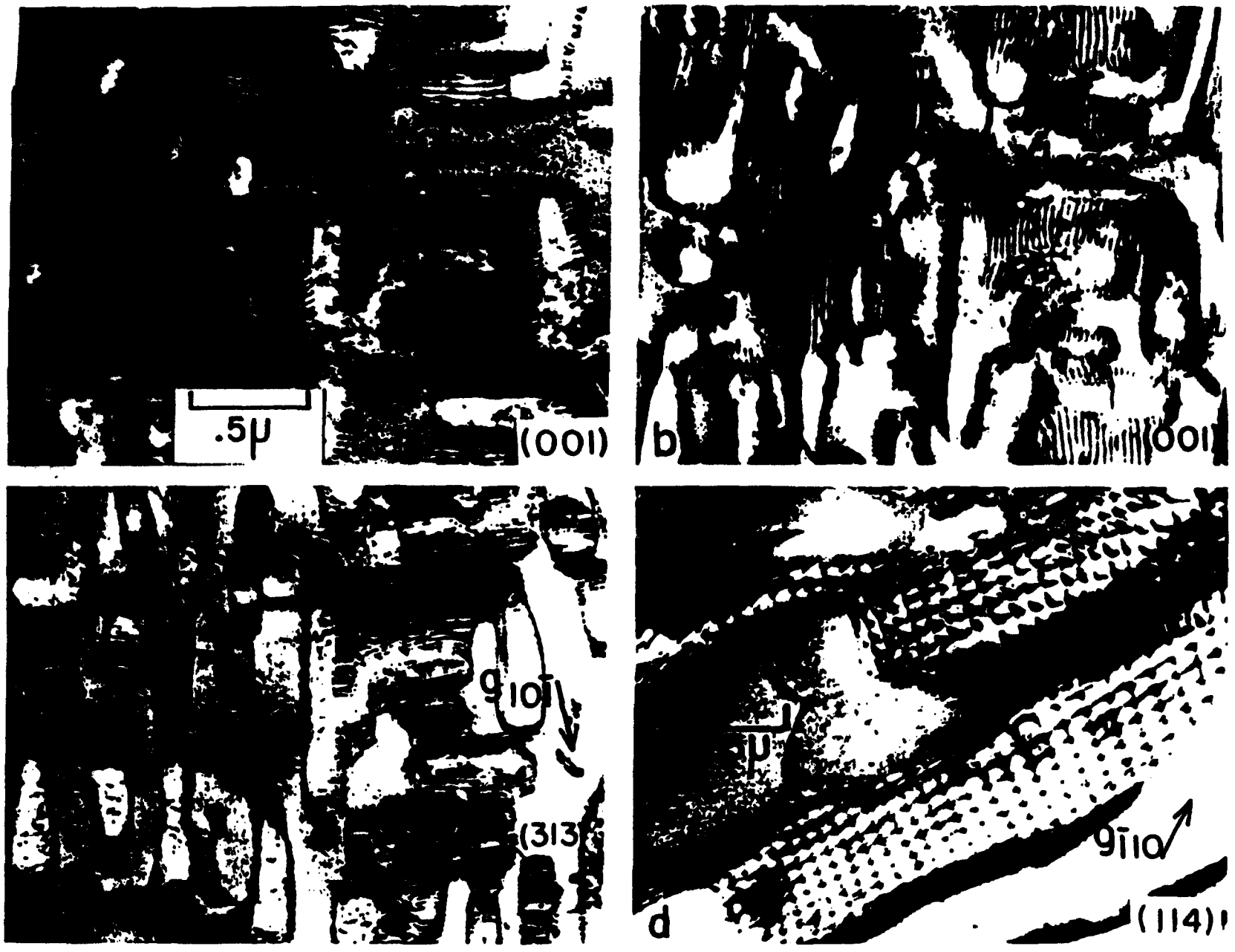


Fig. 1—Transmission electron micrographs of the β'-β alloy in the heat treated condition. The lattice mismatch between the β-precipitates and β' matrix is accommodated by two orthogonal sets of $a_0\langle 100\rangle$ interfacial dislocations.

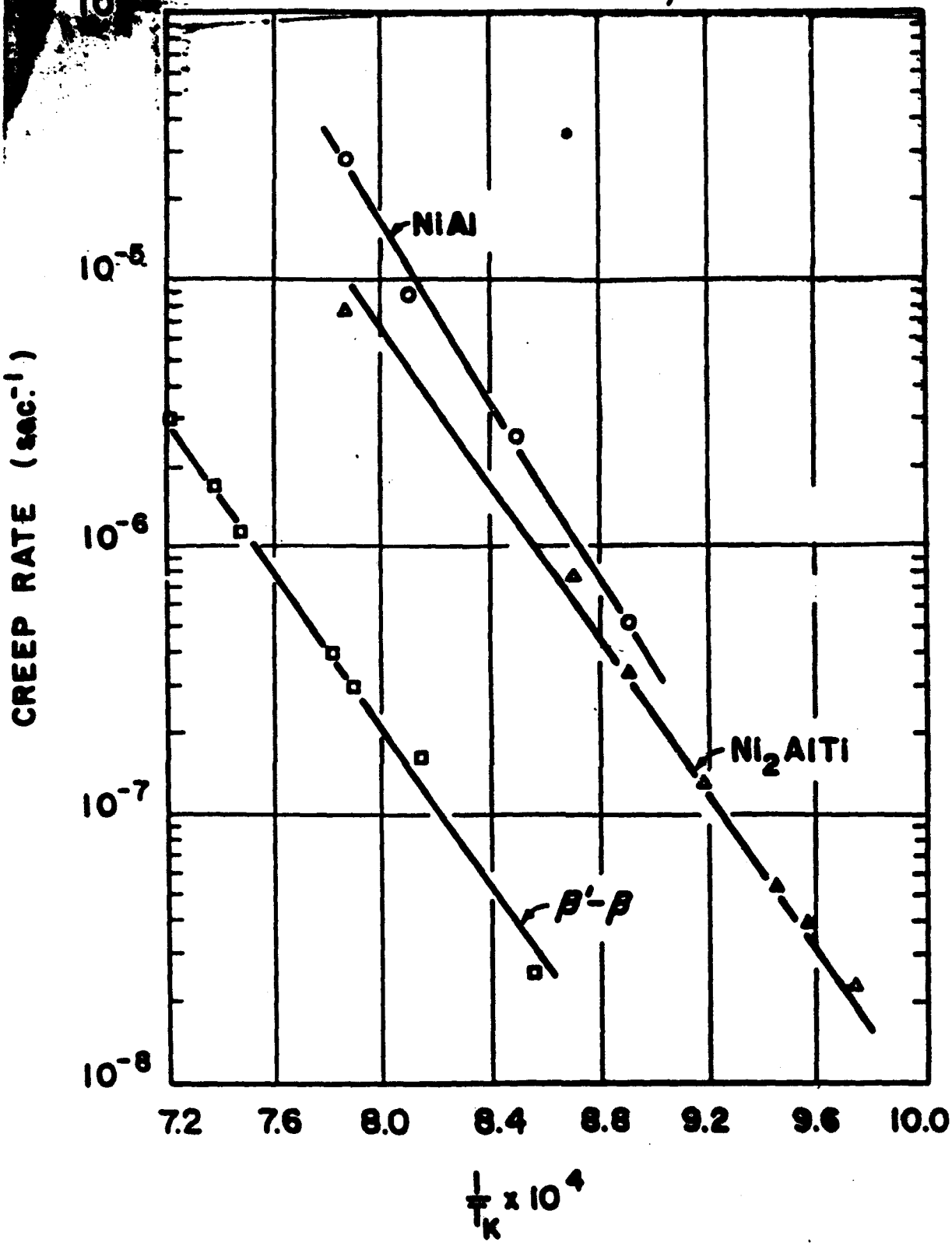
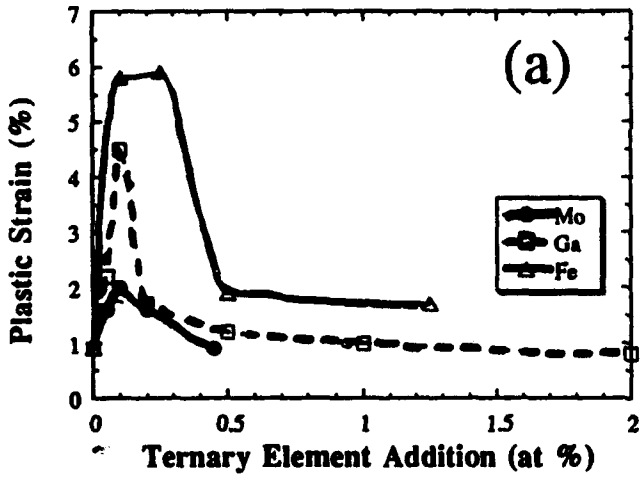
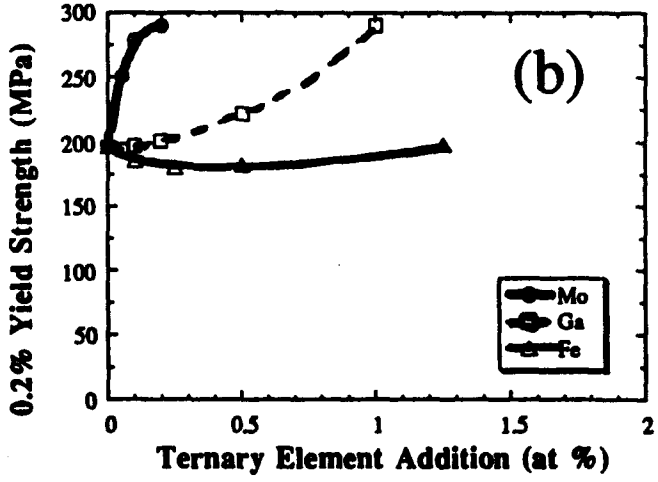


Fig. 3—Arrhenius plot of $ln\ \dot{\epsilon}$ *vs* $1/T_k$ for β'-β specimens crept at 137.9 MN/m^2. Data for [001] axis NiAl single crystals crept at 48.3 MN/m^2 and polycrystalline Ni_2AlTi creep at 68.9 MN/m^2 is included for comparison.

"Micro-Alloying Effect"





ISSUES

Alloying Effects: What is the principal strengthening effect? What are the opportunities for improved properties? What are the mechanisms of microalloying effects?

Dislocation Core Effects: To what extent does the dislocation core structure influence properties? How can the core structure be modified?

Mechanism of DBTT: Does climb occur in NiAl at 300°C (0.30 Tm)?

Technology Issues:

- Can a design methodology for brittle materials be adopted (impact properties)? Can the unique attributes of NiAl be taken advantage of in an advanced design?
- Single crystal growth/casting including core technology requires investment.
- Machining, fabrication, and joining requires additional work.

4. **Promise versus Reality for High Temperature Applications of Gamma TiAl - A Perspective**

P. Martin
Rockwell Science Centre, USA

Outline of the Presentation

P. MARTIN

- Comparison of TiAl with other aluminides and superalloys
- Physical metallurgy of TiAl as it affects microstructure
- Some mechancial properties of an 'advanced' near-γ composition
- Future directions for research in this class of alloys

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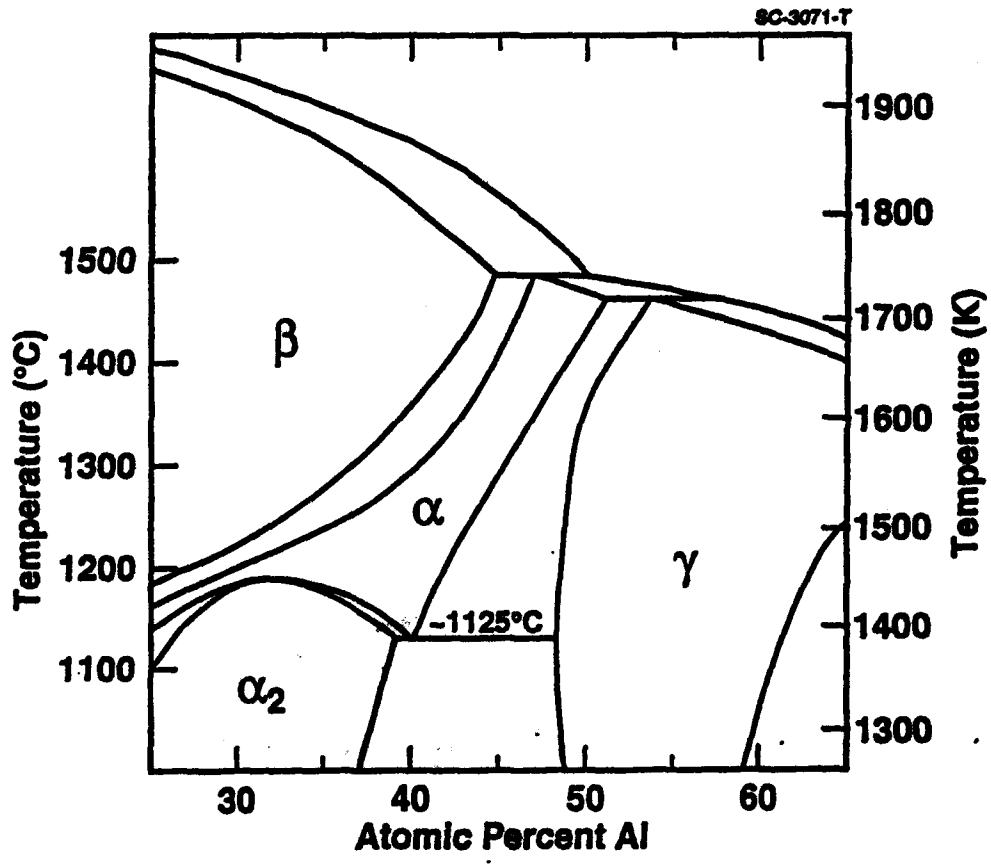
Ti-Al Binary Phase Diagram



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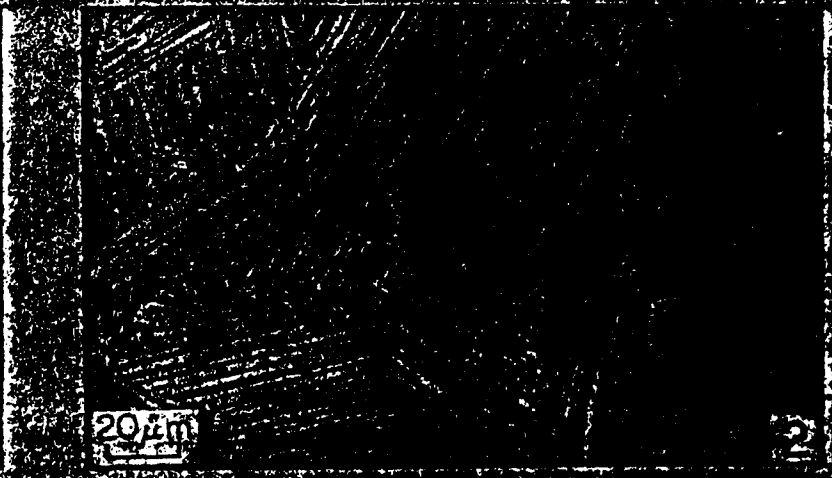
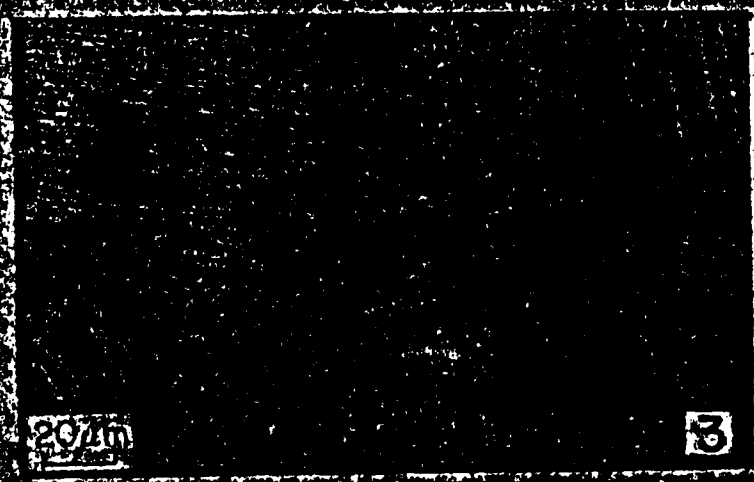
Ti-48Al-2Cr-2Nb
Cast Plus HIP

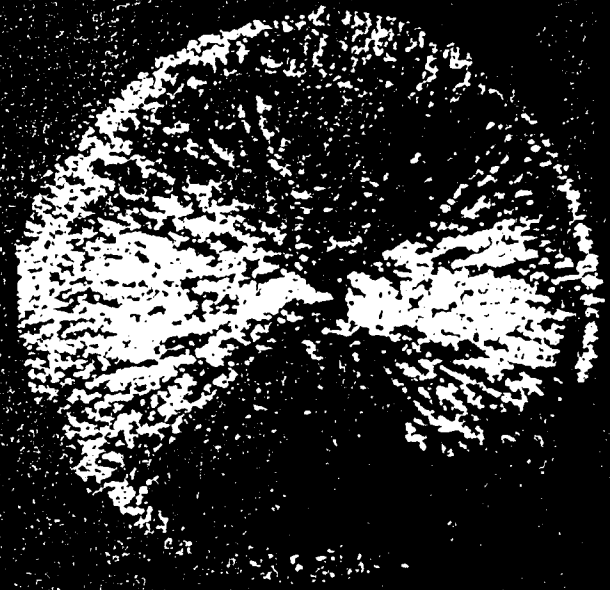




	YS (KSI)	PLASTIC ELONG. (%)
1. 1350°C/10 HR	[illegible]	[illegible]
2. 1350°C/0.5 HR	[illegible]	[illegible]
3. 1350°C/0.5 HR	[illegible]	[illegible]
1000°C/12 HR		

Macrostructure of 8.2 cm Ingots

Ti-45.6Al-1.9Nb-1.9Cr

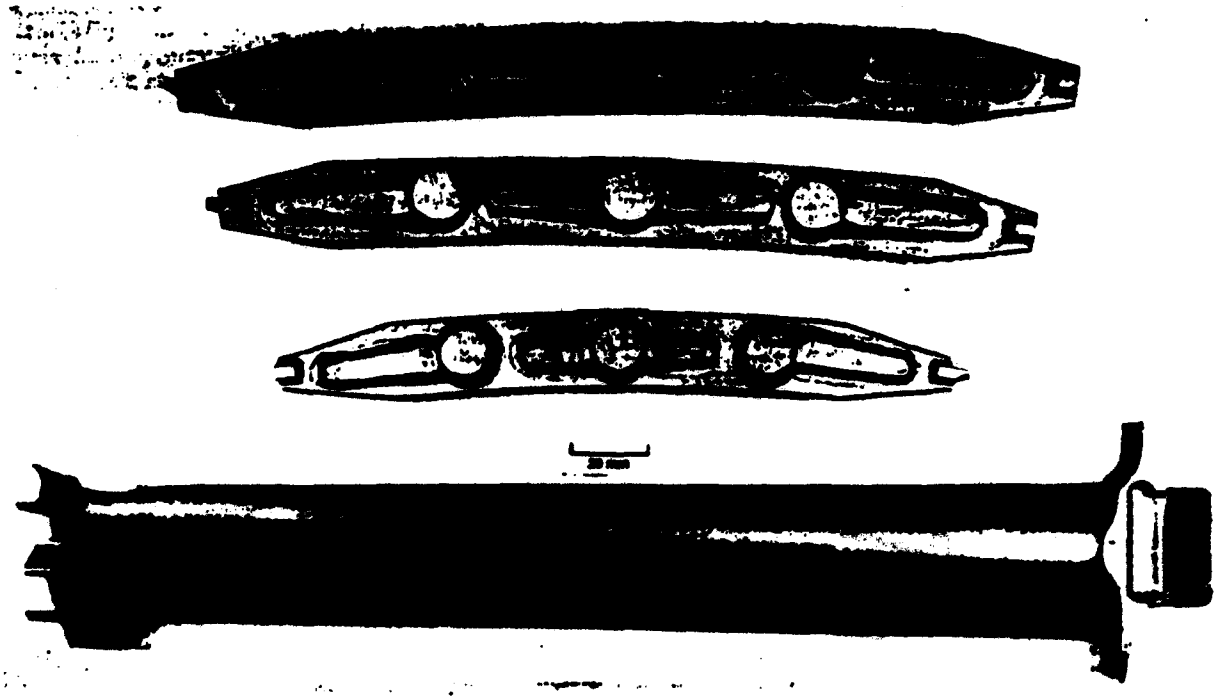


Ti-46.7Al-1.9Nb-1.9Cr

HIGH TEMPERATURE ALLOY COMPARISON

	Ti-Base	Ti_3Al	TiAl	Superalloys
DENSITY ($\#/FT^3$)	.16	.152	.136	.30
STIFFNESS (10^6 PSI)	16	21	25.5	30
MAX. TEMP. - CREEP (^oF)	1000	1500	1650	2000
MAX. TEMP. - OXIDATION (^oF)	1100	1200	1750	2000
DUCTILITY - R.T. (%)	~20	2-4	1-3	3-10
DUCTILITY - OPERATING (%)	HIGH	5-12	5-12	10-20

Cast γ Replacements for IN-718 in the GE90



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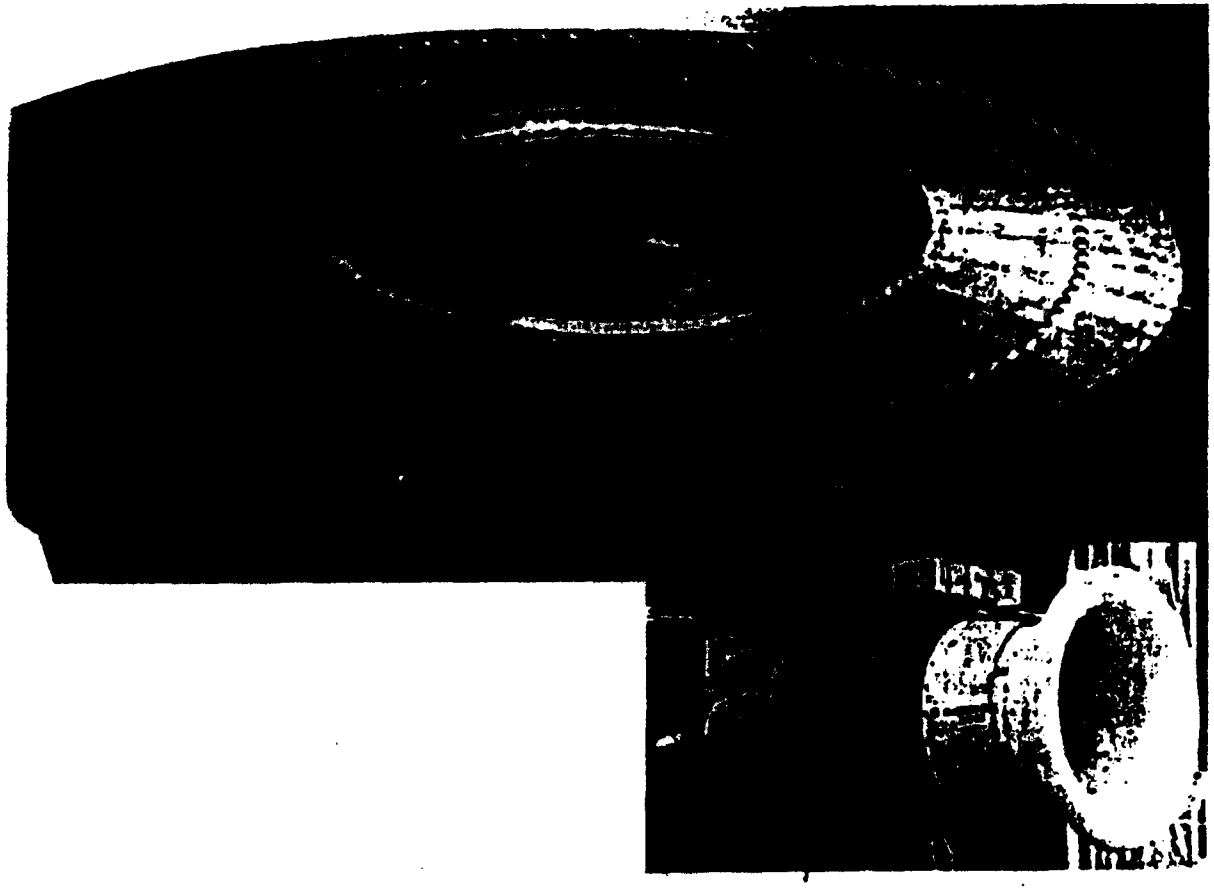
LPT Blade-Set Prior to GE90 Test

SCP.0781E.011194



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Applications for γ-TiAl in the U.S.

- Gas turbine engines
  - Static structure
  - Rotating components
- Hypersonic airframes, e.g. NASP
  - Supporting structure
  - Skin
- Internal combustion engines, e.g. valves
- Spacecraft structure and/or engines

Olds Quad-Four γ Exhaust Valves

SCP.0780E.011194

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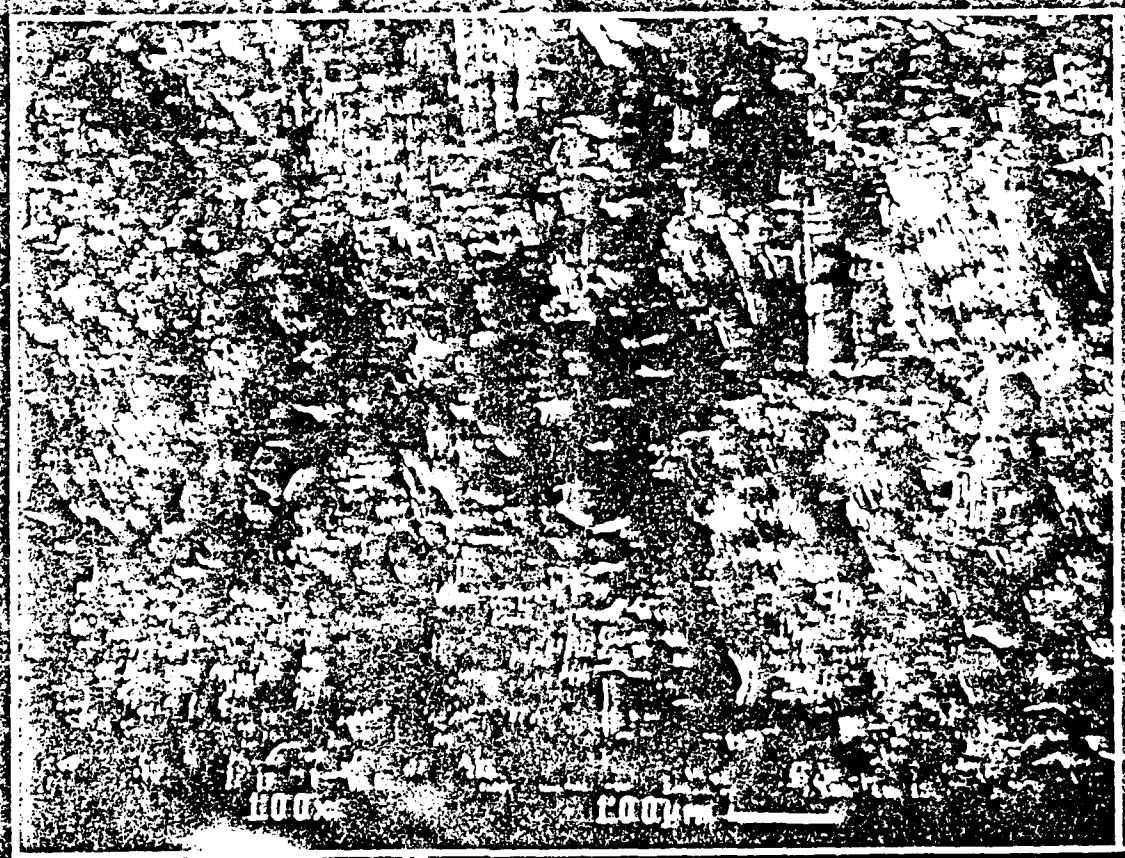
MULTIPLE ALLOYING ADDITIONS TO NEAR-GAMMA TITANIUM ALUMINIDES

Ductility	Oxidation Resistance	Strength
Cr	W	W
V	Ta	Ta
Mn	Nb	Si
	Si	O
		Lower Al

Materials

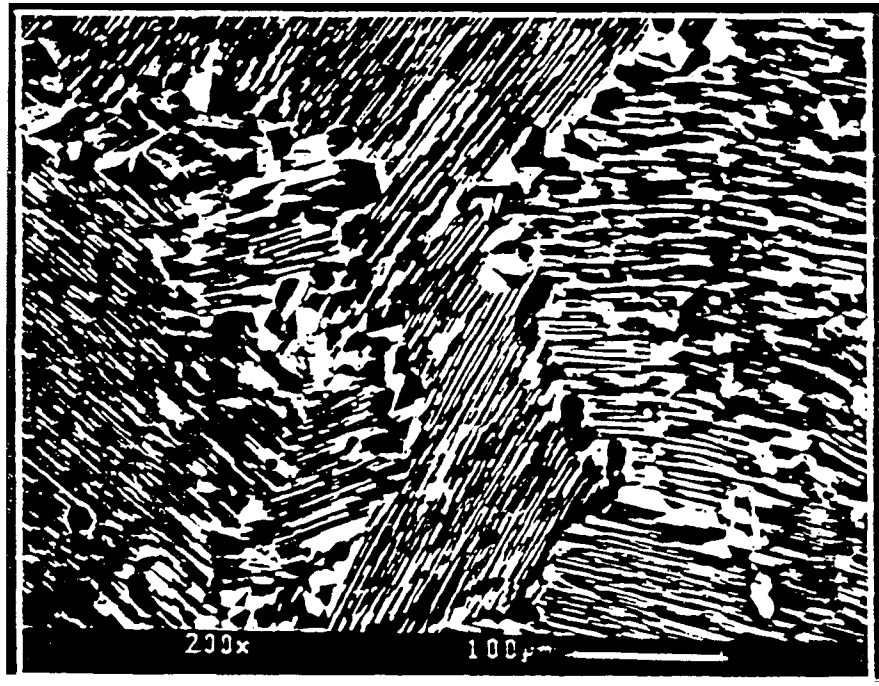
- Induction skull melt at Duriron Co., Inc:
  - 8.2 cm diameter - 14 kg ingots
  - 15.2 cm diameter - 23 kg ingots
- HIP at 1260°C / 4 hours / 172 MPa
- Three alloy types (atomic percent):
  - Ti-46.5±Al-2Nb-2Cr (with and w/o 1Ta)
  - Ti-46Al-2Cr-4Ta
  - Ti-46Al-5Nb-1W

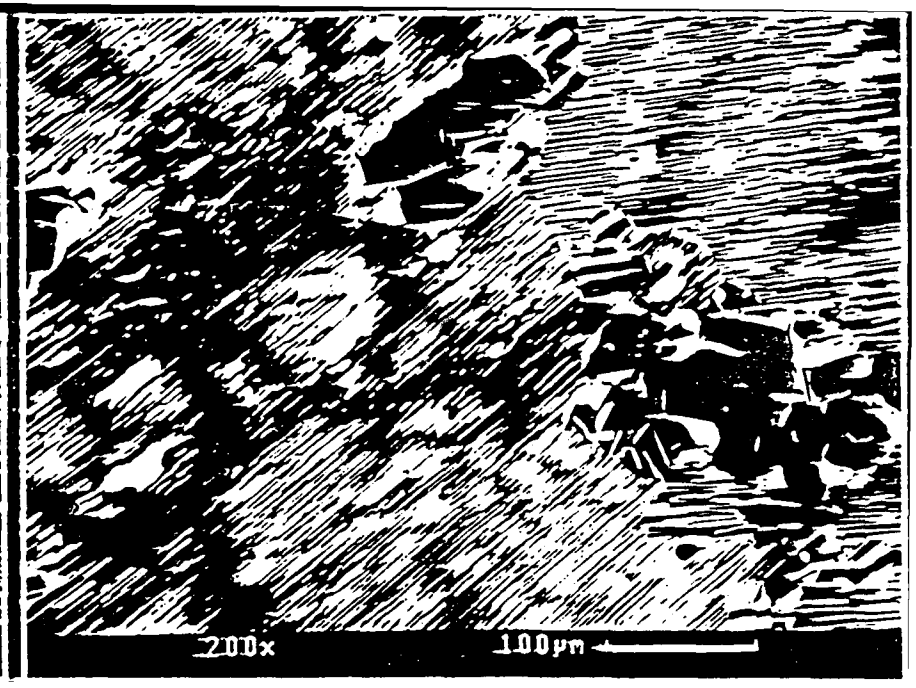
Microstructure of As-HIP'ed 8.2 cm Ingot



Ti-46.7Al-1.9Nb-1.9Cr

Polished Section Backscattered Electrons


200x
100μm


200x
100μm

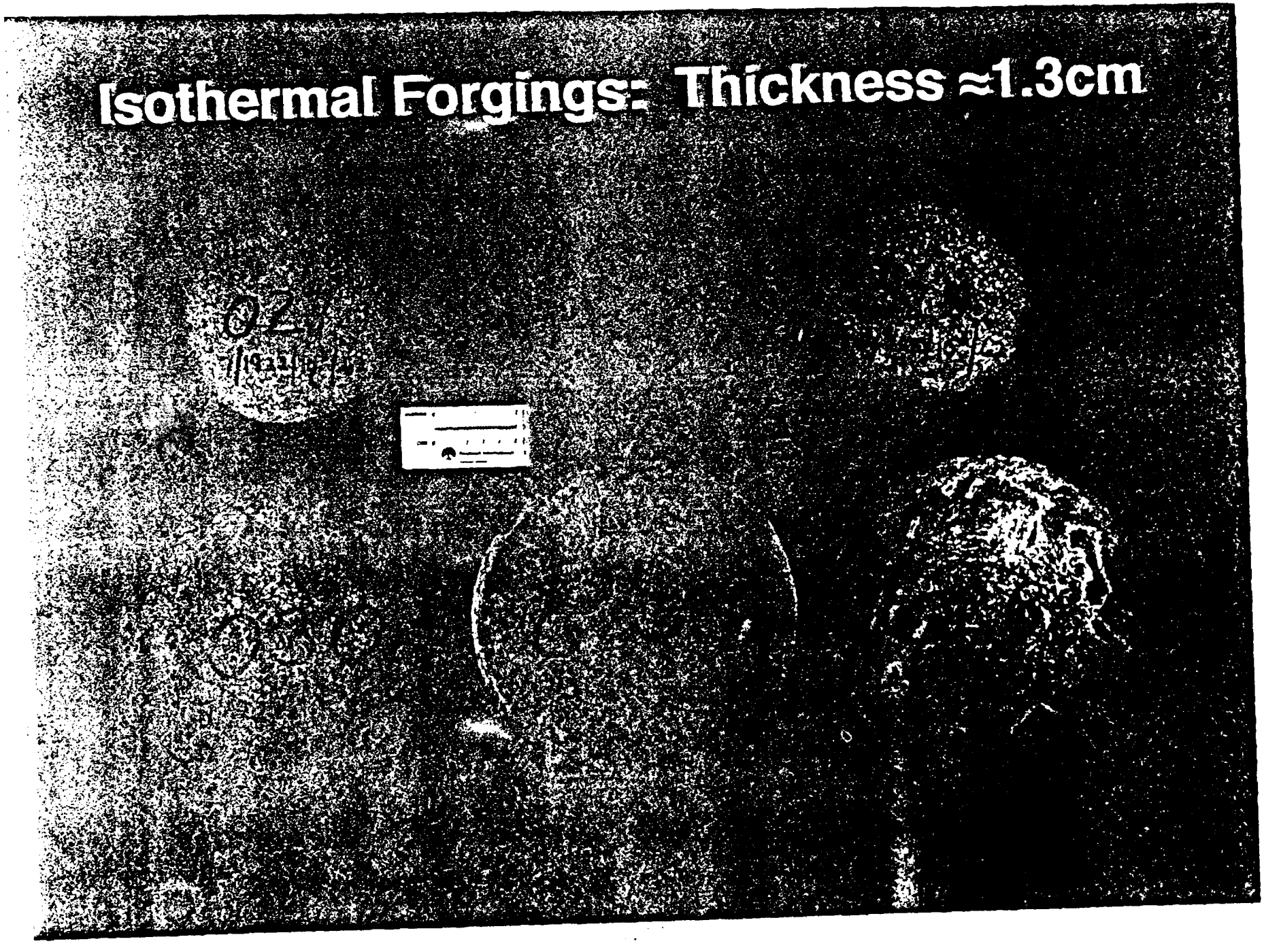
Microstructure of As-HIP'ed 8.2 cm Ingot

Ti-46.5Al-2.1Cr-4.1Ta

Ingot Microstructure after T_α+30°C / 2 hours

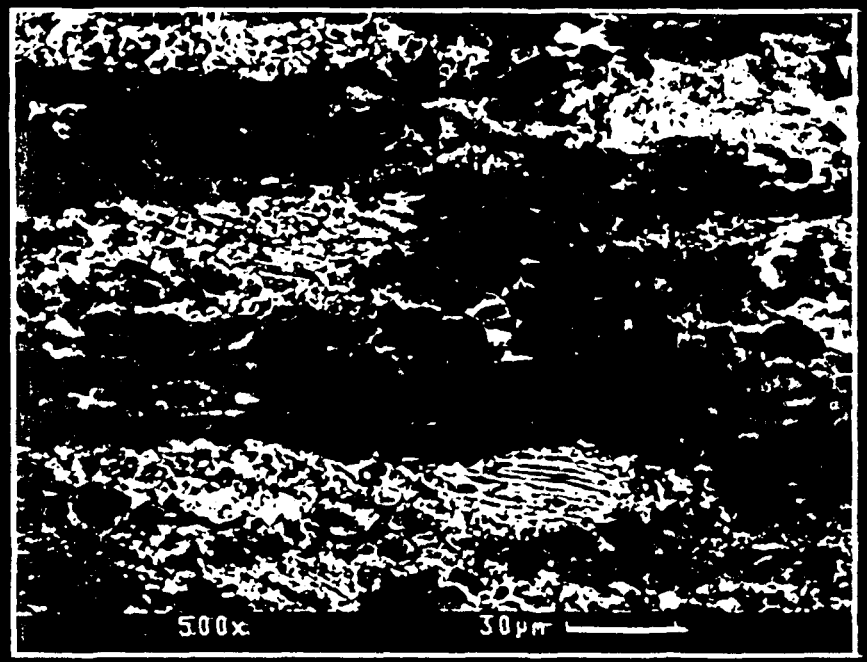
Ti-46.9Al-1.9Nb-2.2Cr-1Ta

Ti-45.6Al-5.2Nb-1.1W


Isothermal Forgings: Thickness ≈1.3cm

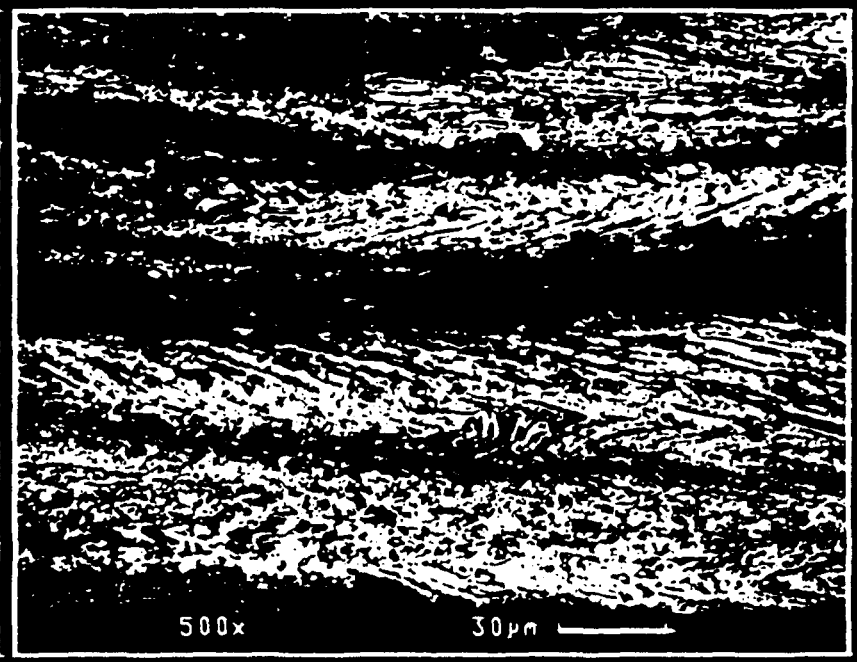
As-Forged Microstructure: 85% at 10^{-3} sec^{-1}

1150°C



Ti-46.9Al-1.9Nb-2.2Cr-1Ta

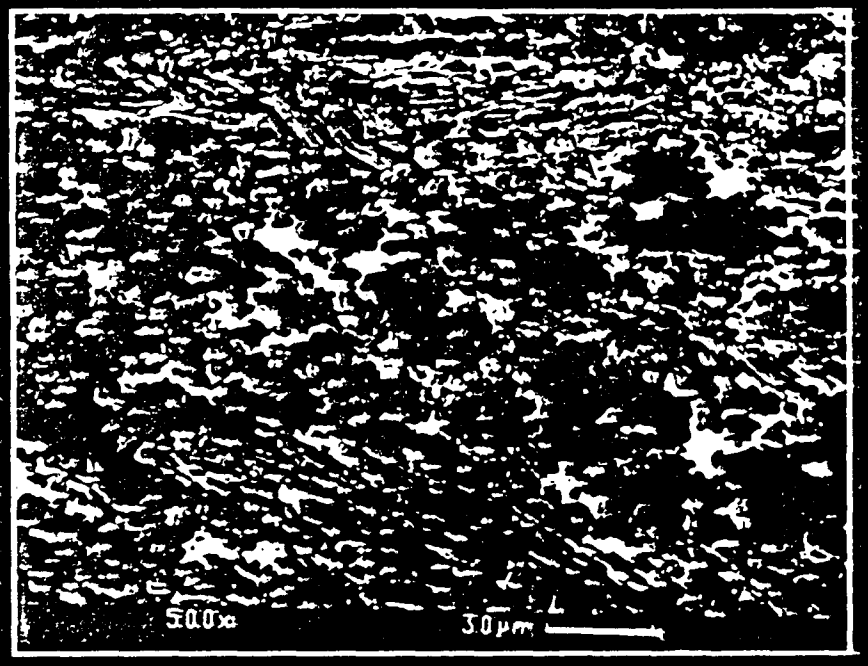
1050°C



Ti-46.3Al-1.8Nb-2.1Cr-1Ta

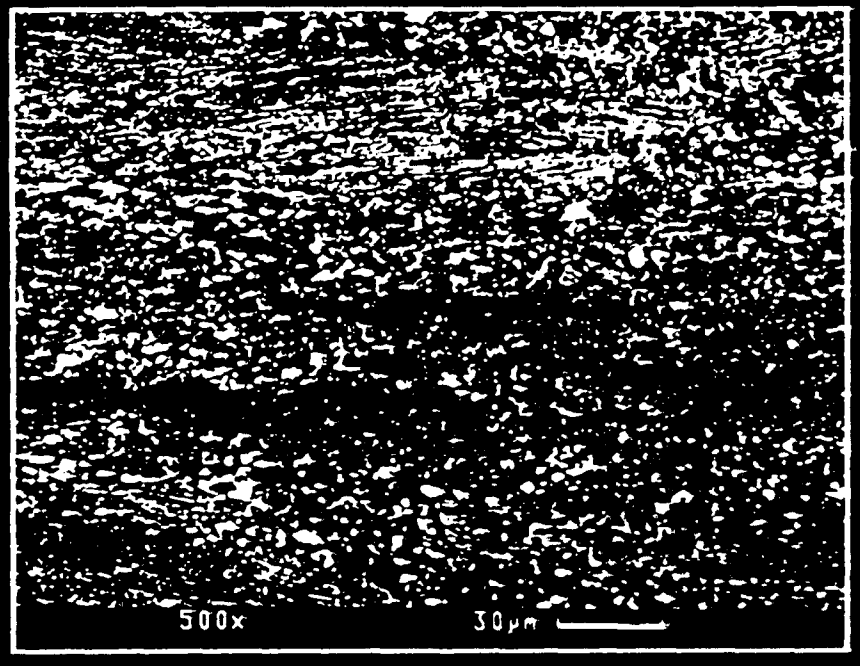
As-Forged Microstructure: 85% at 10^{-3} sec^{-1}

1150°C



Ti-45.6Al-2Nb-2.2Cr-1Ta

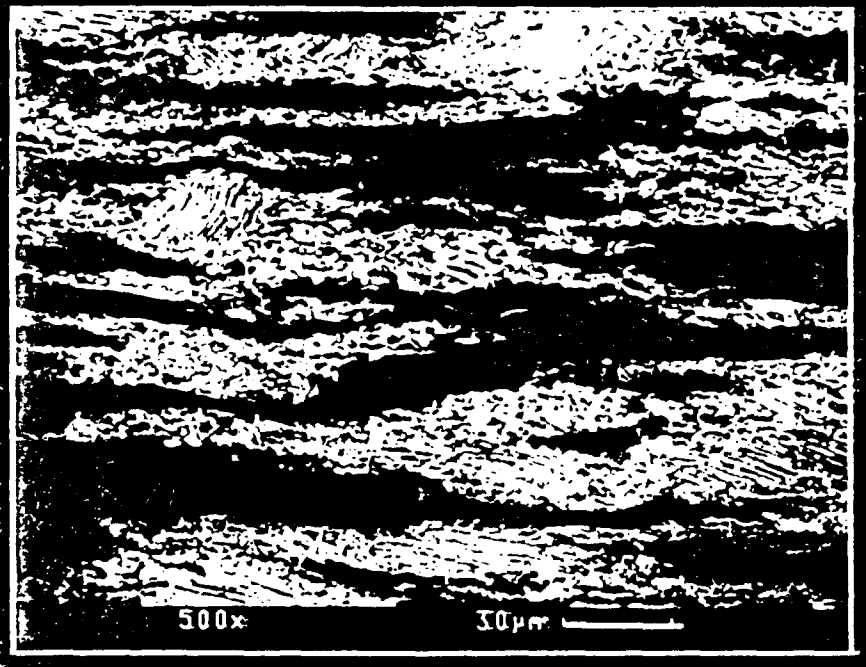
1150°C



Ti-46.5Al-2.1Cr-4.1Ta

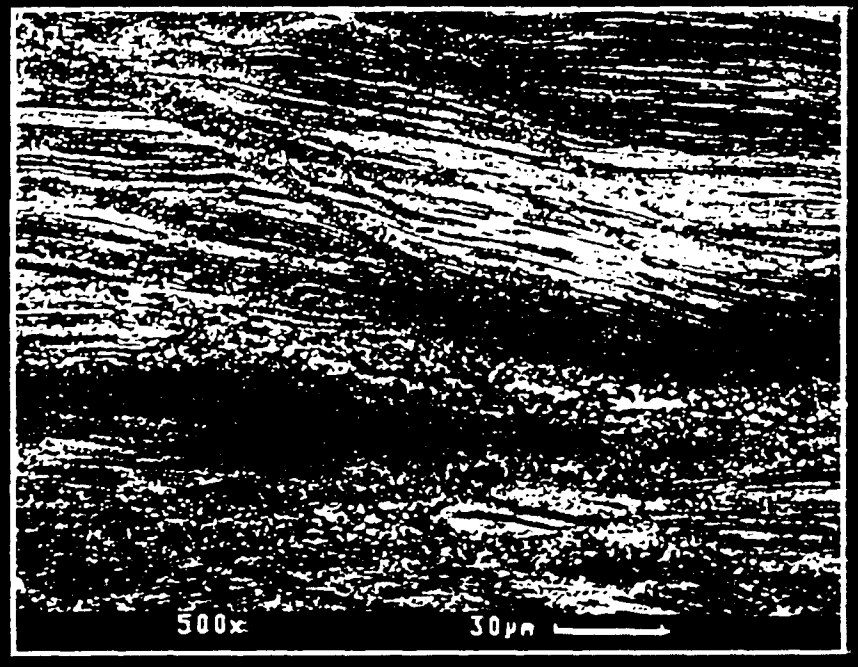
As-Forged Microstructure: 85% at 10^{-3} sec^{-1}

1150°C



Ti-45.6Al-5.2Nb-1.1W

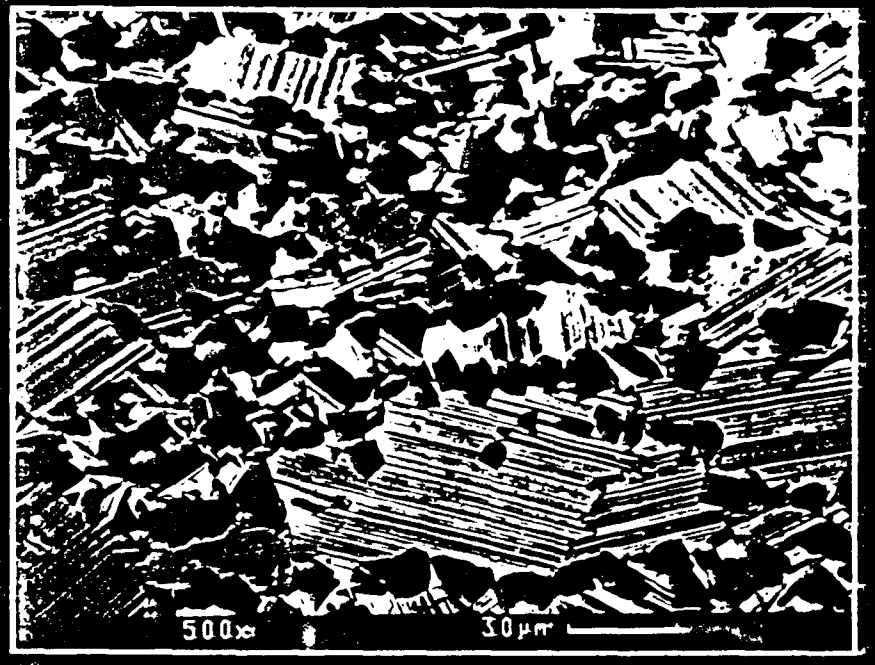
1050°C



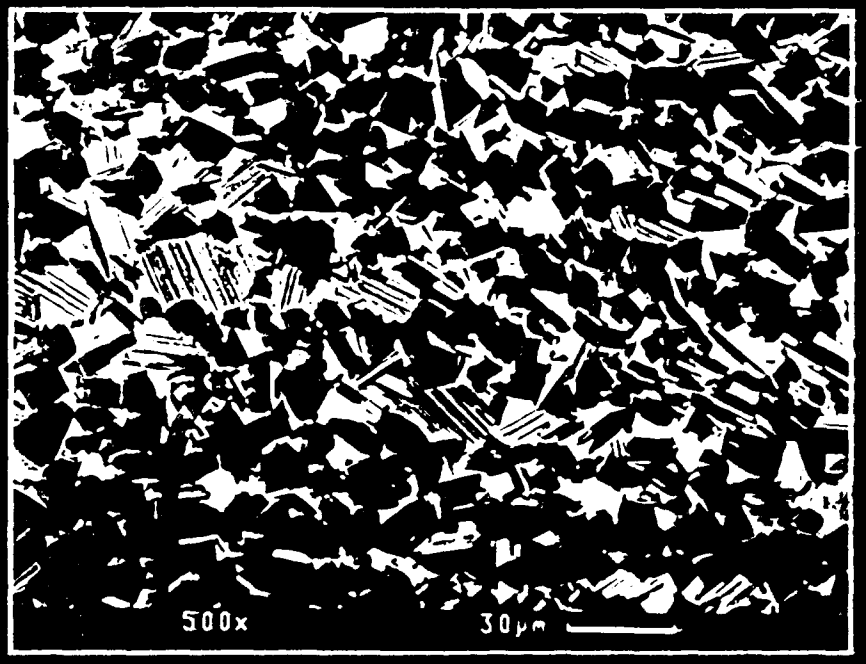
Ti-45.9Al-5.1Nb-1W

Forged and Heat Treated Microstructure

T_α-25°C / 2 hrs.

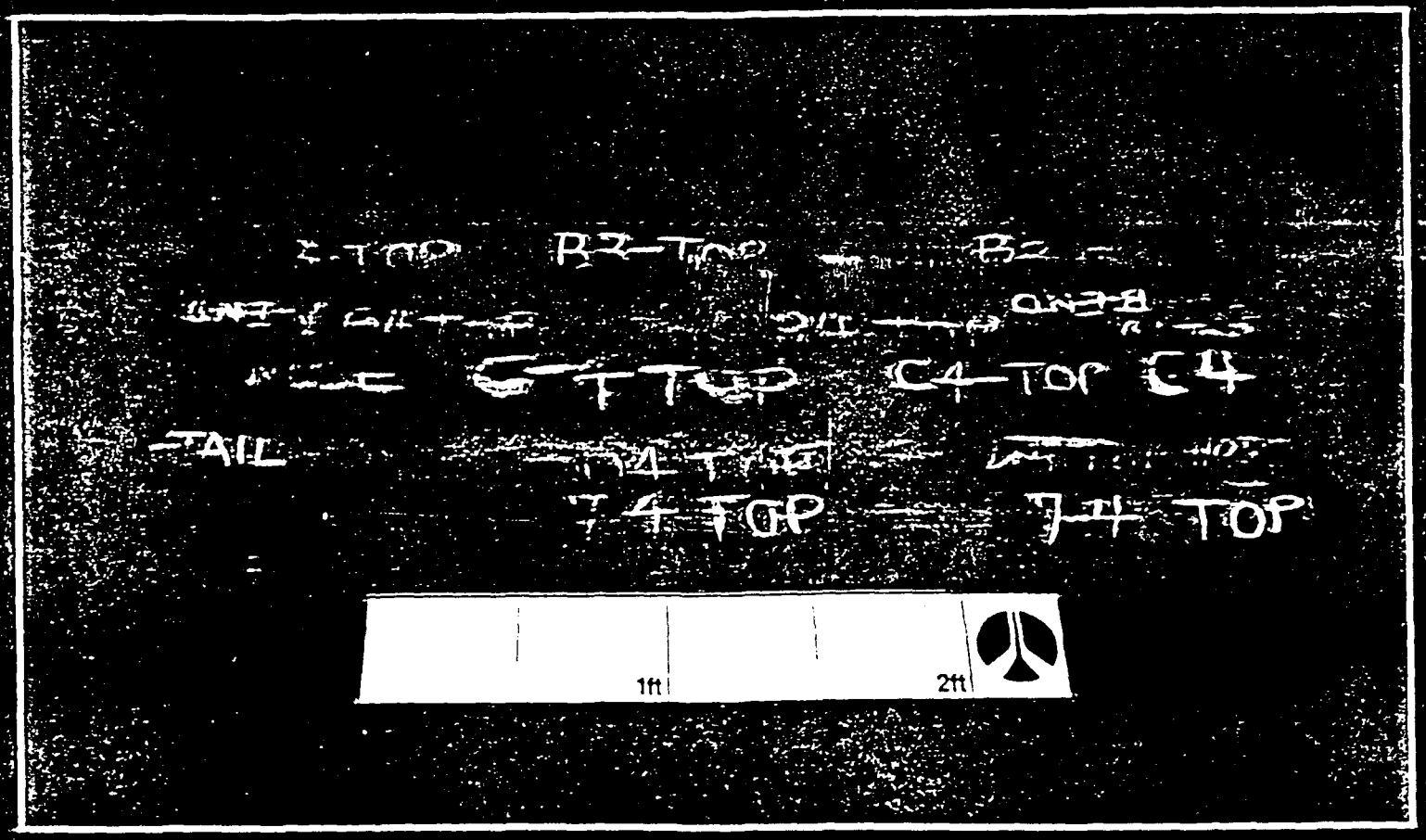


T_α-50°C / 2 hrs



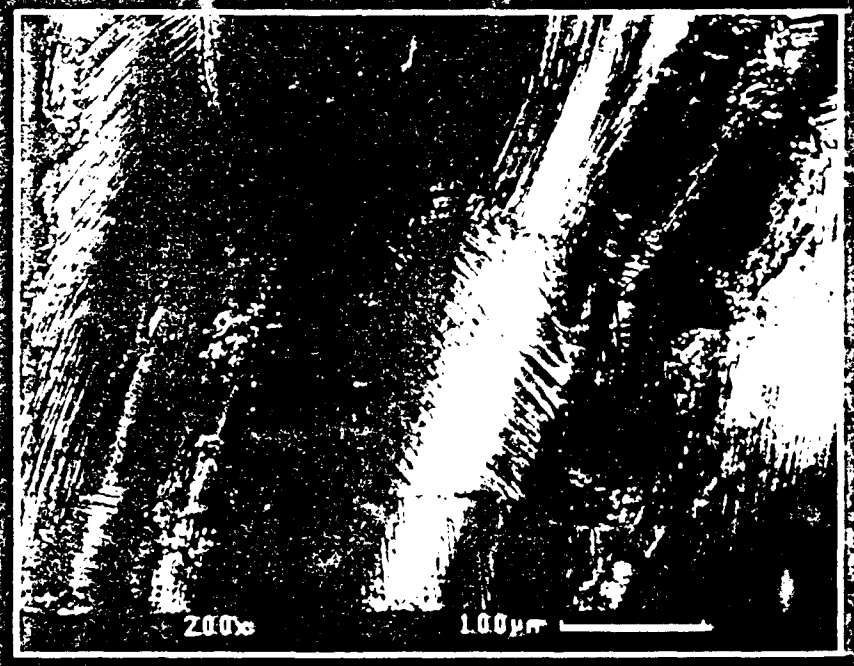
Ti-46.1Al-1.9Nb-1.7Cr

15.2 cm Ingots Following Extrusion



As-Extruded Longitudinal Microstructure

Ti-47.1Al-2.1Nb-2.1Cr



Ti-45.6Al-1.8Cr-3.8Ta

Extruded and Heat Treated Microstructure

1245°C / 24 hrs.

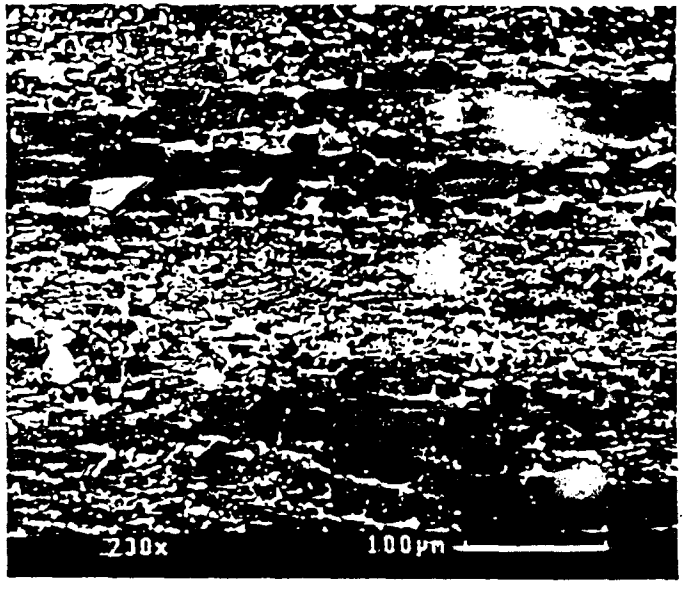
Ti-45.6Al-1.8Cr-3.8Ta

1225°C / 24 hrs.

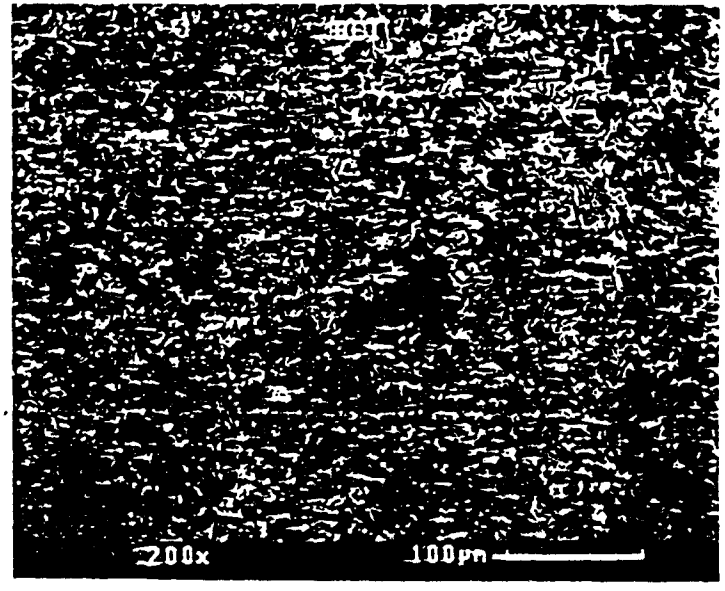
Ti-44.9Al-5Nb-1W

Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

First forging: recrystallization response



Forged + 1200°C / 1 hr.



Forged + 1300°C / 1 hr.

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Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Second isothermal forging:

63% : 1100°C : 10^{-3} sec^{-1}

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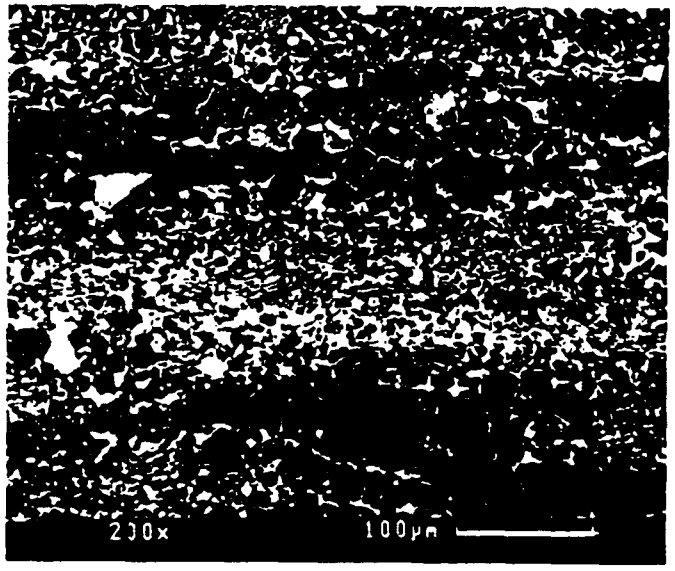
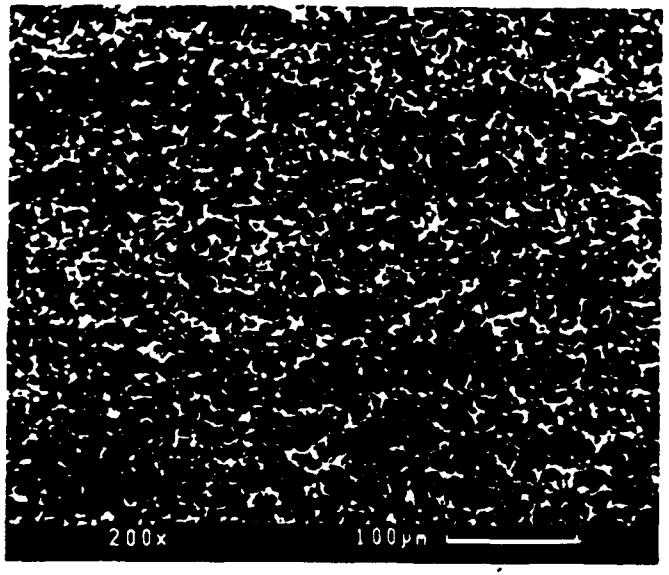
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

"Banding" Susceptibility



First forging: 1200°C / 1 hr.



Second forging: 1200°C / 1 hr.

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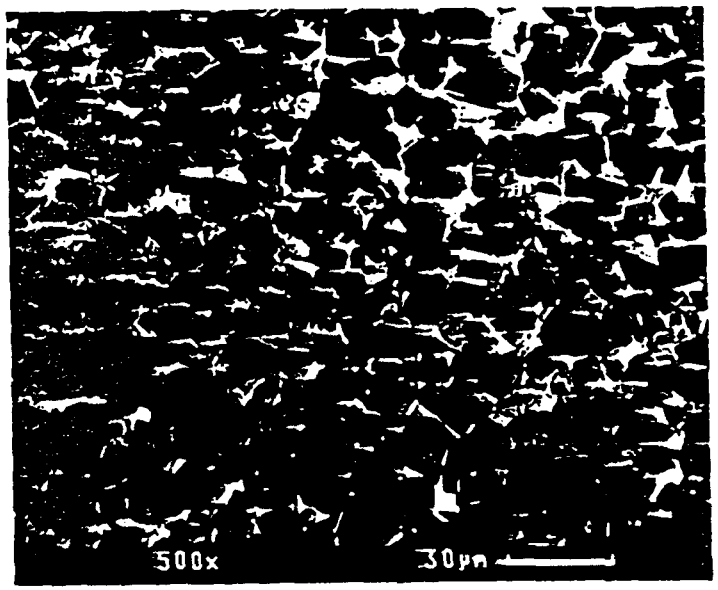
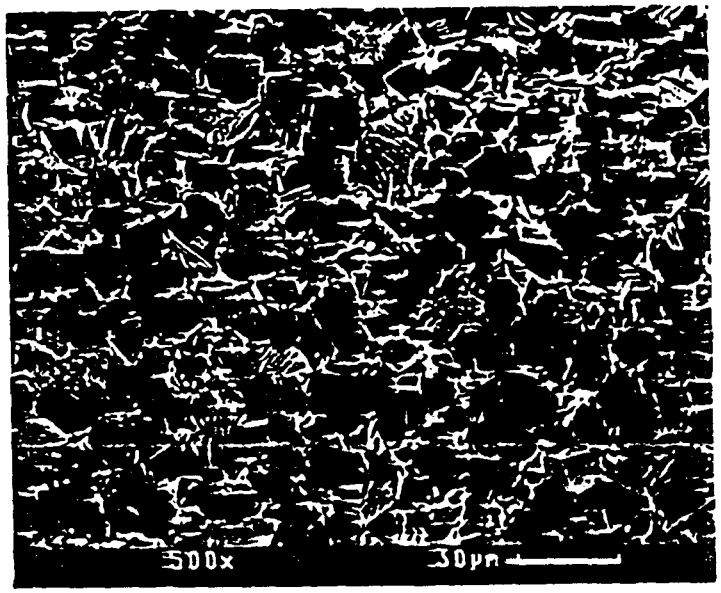
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Recrystallization response after second forging: Equiaxed and Duplex



1250°C / 1 hr.



1310°C / 1 hr.

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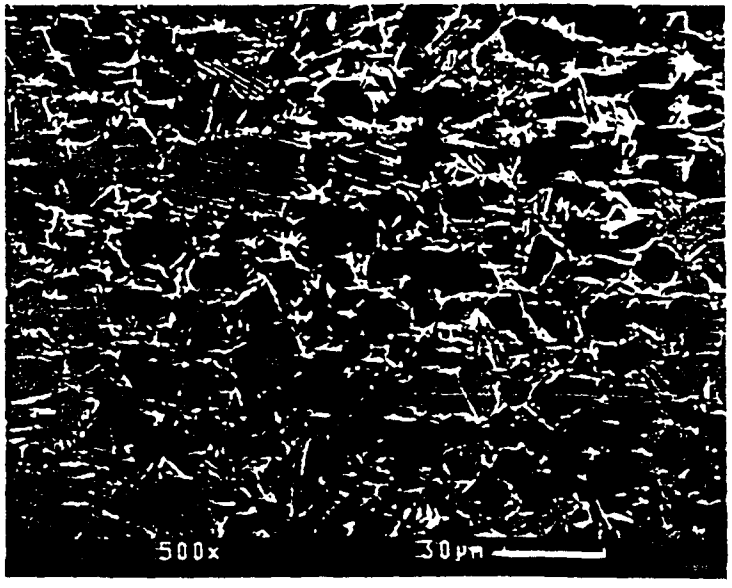
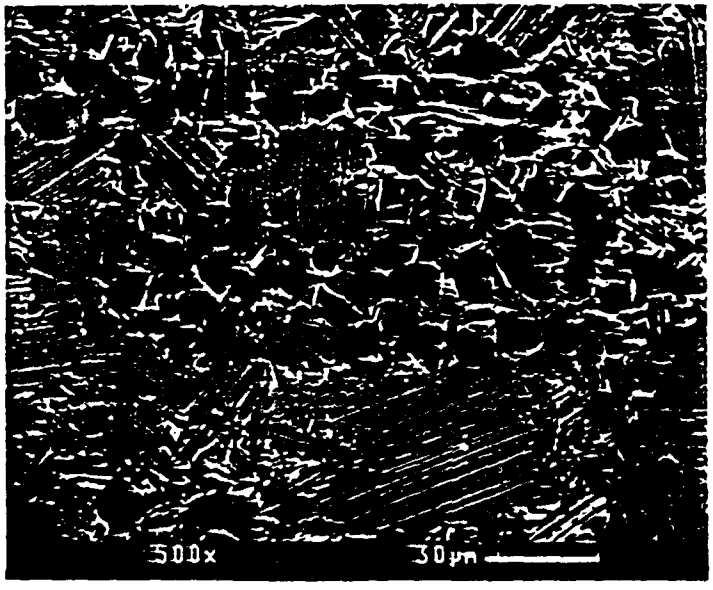
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Recrystallization response after second forging: Duplex



1320°C / 1 hr.



1330°C / 1 hr.

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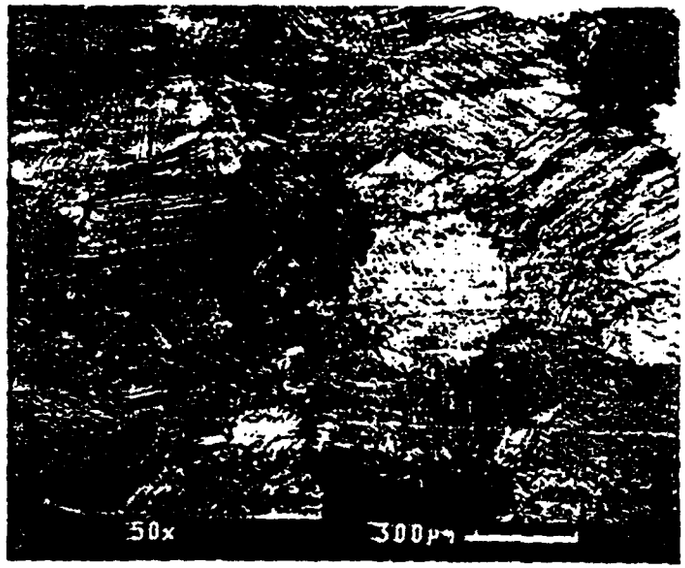
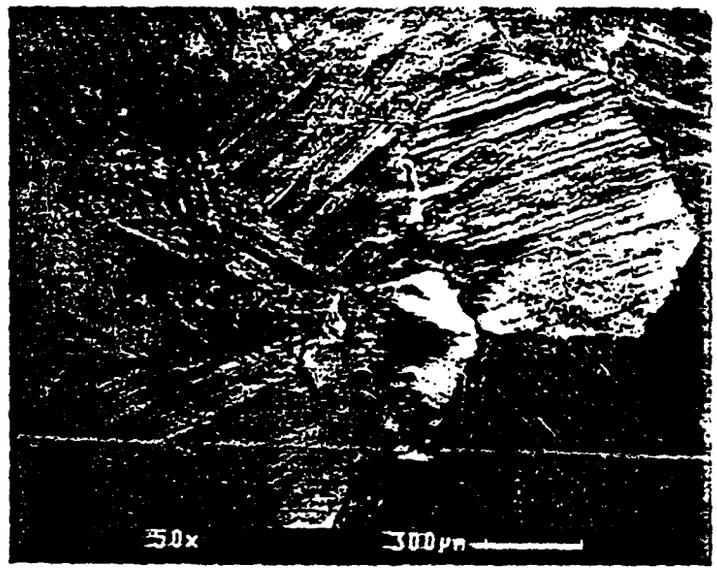
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Recrystallization response after second forging: Fully lamellar



1340°C / 0.25 hr.



1340°C / 1 hr.

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Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Room Temperature tensile properties

Heat Treatment	Microst. Type	Yield (MPa)	Ultimate (MPa)	Plastic Elong. (%)	RA (%)
1250/1+950/8	Equiaxed	501	528	1.2	1.1
1330/1+950/8	Duplex	498	560	1.1	1.4

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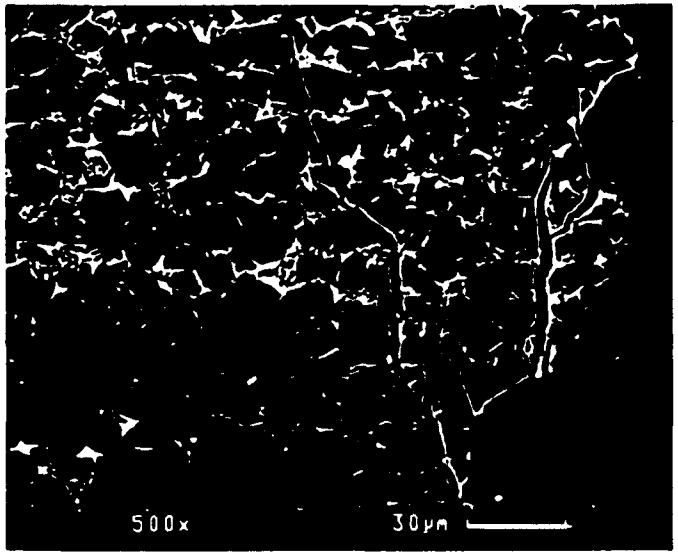
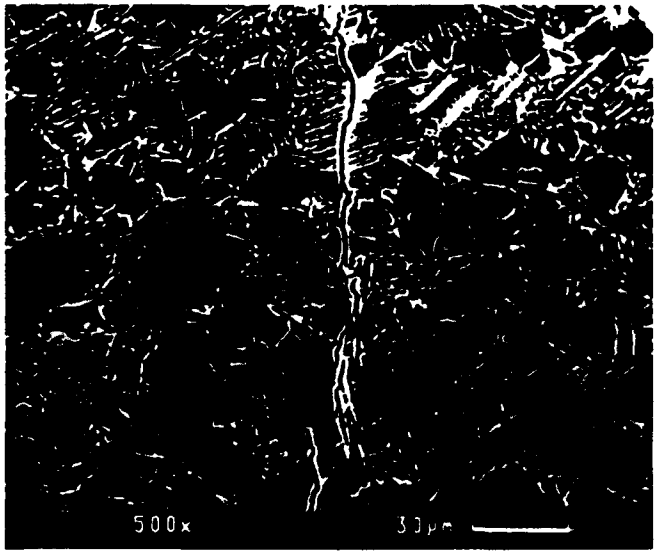
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo

Room temperature tensile fracture path:



1250°C/1hr.+950°C/8hr.



1330°C/1hr.+950°C/8hr.

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Conclusions

- Peritectic solidification determines the macro and microstructures of ingots
- Heat treatment above T_α can eliminate interdendritic γ without true homogenization
- Isothermal forging can refine the structure
- Static recrystallization near T_α can lead to homogeneous chemistry
- Extrusion can result in recrystallized α grains with remnant casting segregation

Directions for Future Work

- Refine the processing-microstructure-mechanical property envelope <u>especially</u> using existing <u>full scale</u> facilities (large ingot, primary breakdown and mill product conversion)
- Expand the range of product forms available for component manufacture; e.g. investment casting, shaped forging and extrusion
- Begin introducing TiAl into existing turbo-machinery in simple components to gain designer confidence - stress lower weight at constant stiffness and strength wrt IN718
- Stress lower cost processing approaches: e.g. casting and economy-of-scale in wrought

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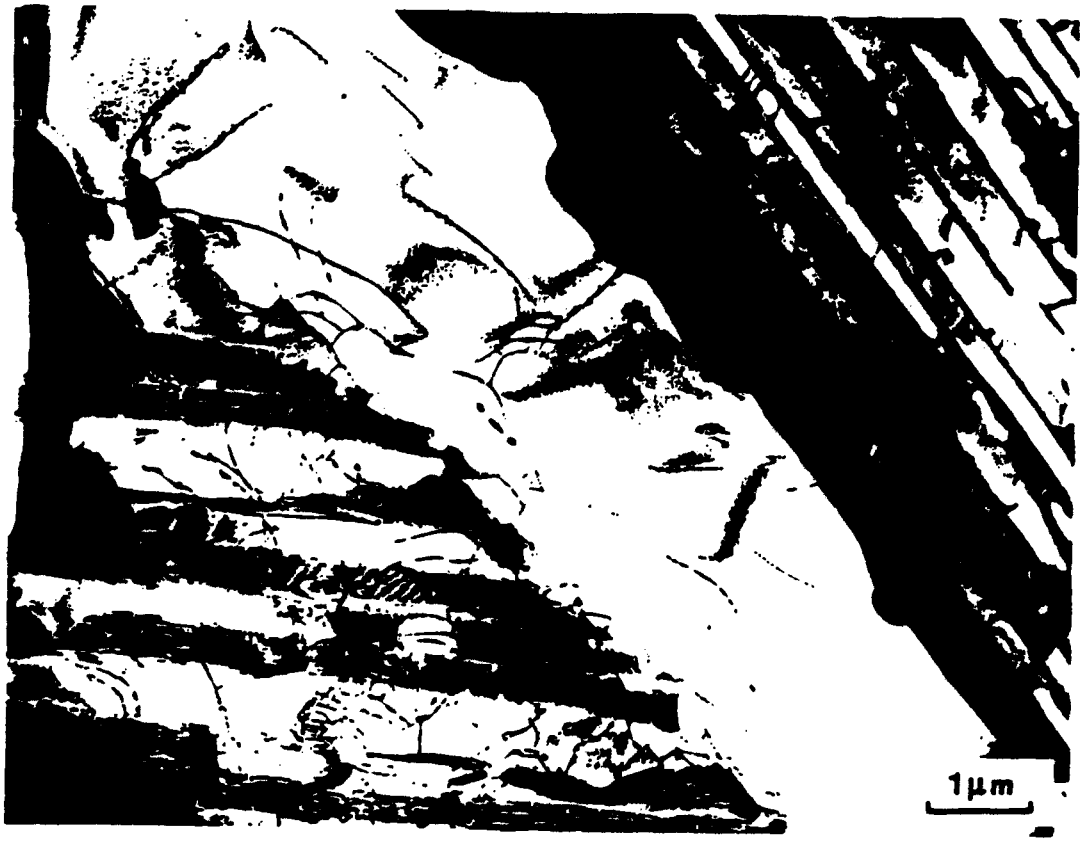
Microstructure and properties of Ti-48Al-2Nb-2Cr-1Mo



Second forging + 1330°C / 1 hr. + 950°C / 8 hr.

Rockwell International
Science Center

5. Technology and Applications of Ni_3Al Based Materials

V. Sikka
Oak Ridge National Laboratory, USA

TECHNOLOGY AND APPLICATIONS OF Ni_3Al-BASED MATERIALS*

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Presentation at
Defence Metallurgical Research Laboratory
Hyderabad, India

February 5, 1994

*Research sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Concepts (AIC) Mateials Program, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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SEVERAL ATTRIBUTES MAKE Ni_3Al-BASED ALLOYS SUITABLE FOR HIGH-TEMPERATURE APPLICATIONS.

- OXIDATION RESISTANCE
- CARBURIZATION RESISTANCE
- HIGH-TEMPERATURE STRENGTH

oral

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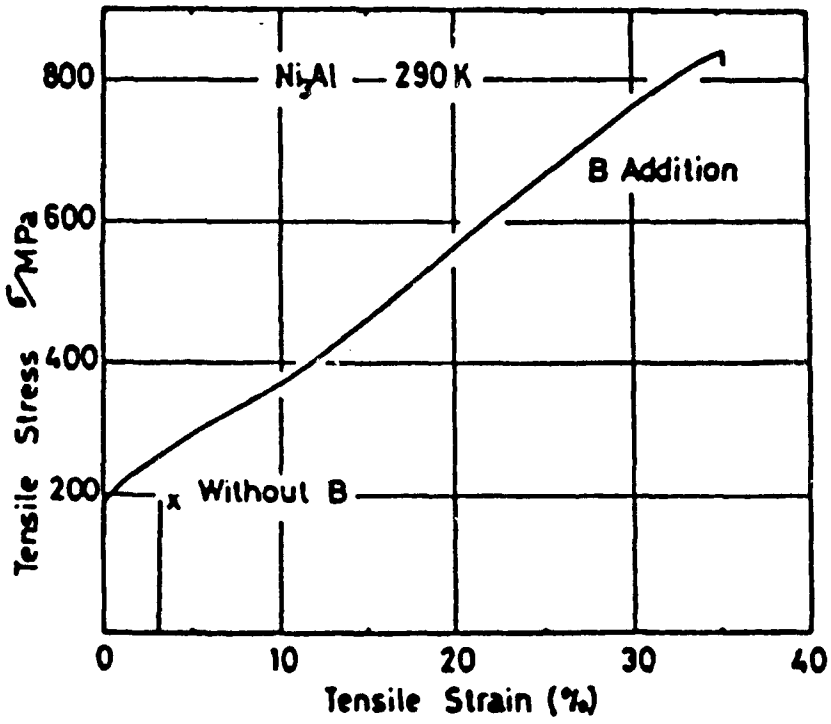
DUCTILIZATION EFFECT OF BORON ON Ni_3Al
(Aoki and Izumi 1979)



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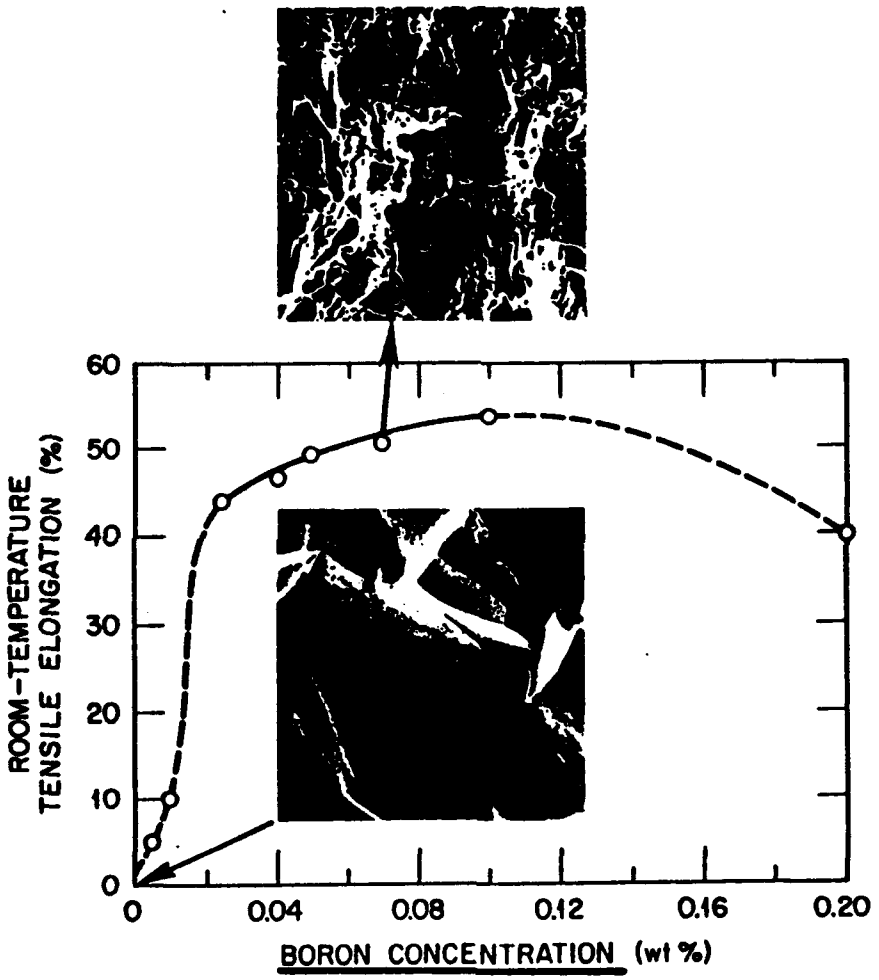
ORNL-DWG 85-18477R

MICROALLOYING WITH BORON DRAMATICALLY IMPROVES THE TENSILE DUCTILITY AND SUPPRESSES BRITTLE GRAIN-BOUNDARY FRACTURE IN Ni_3Al (24 at. %)



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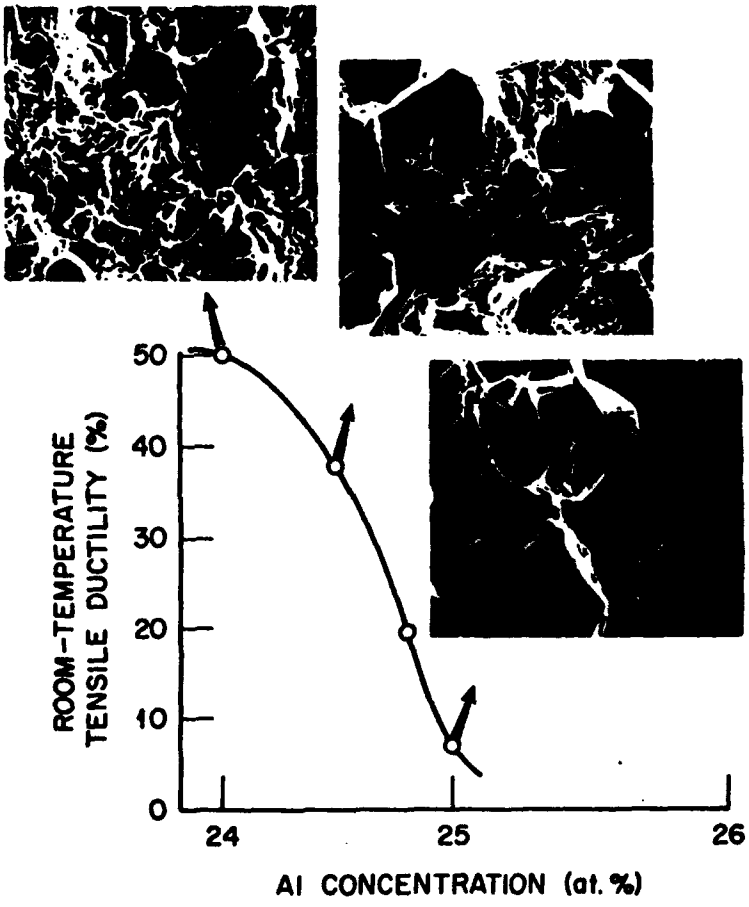
ORNL-DWG 86-18476

INCREASING Al CONTENT FROM 24 TO 25% SHARPLY DECREASES TENSILE DUCTILITY AND PROMOTES GRAIN-BOUNDARY FRACTURE IN Ni_3Al ALLOYS DOPED WITH 0.2% BORON



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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.

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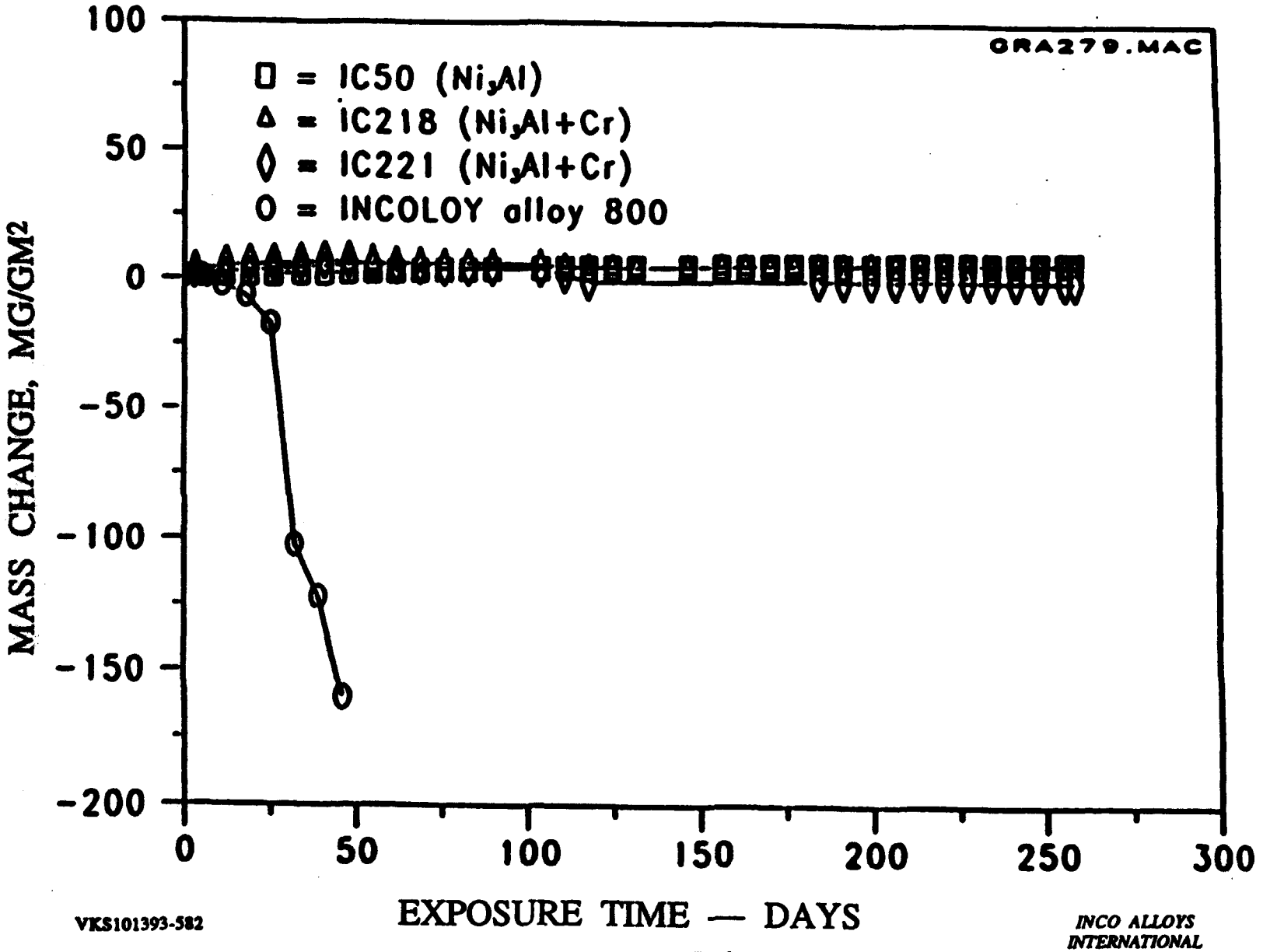
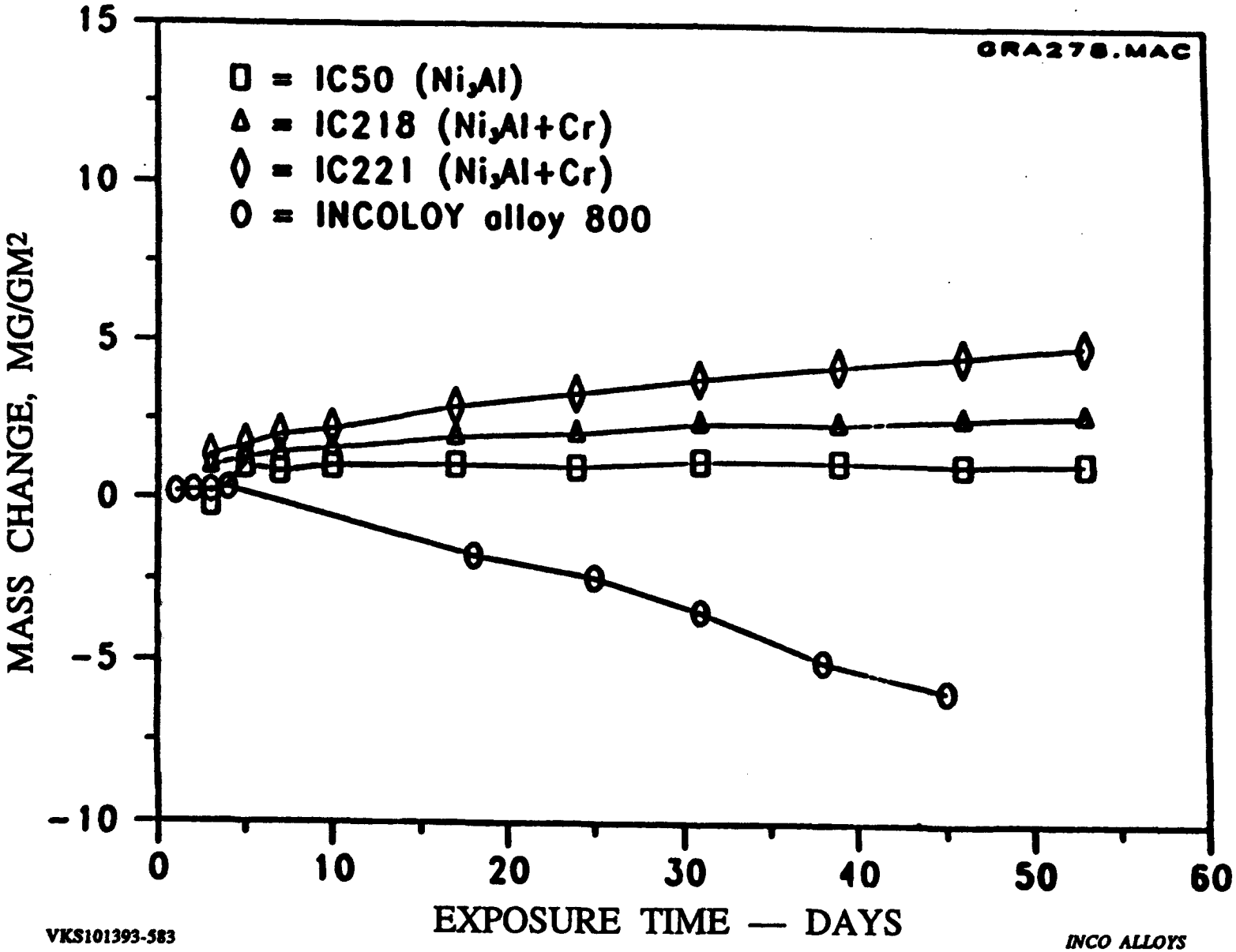
MASS CHANGE IN AIR + 5% WATER VAPOR AT 1100°C



VKS101393-582

INCO ALLOYS INTERNATIONAL

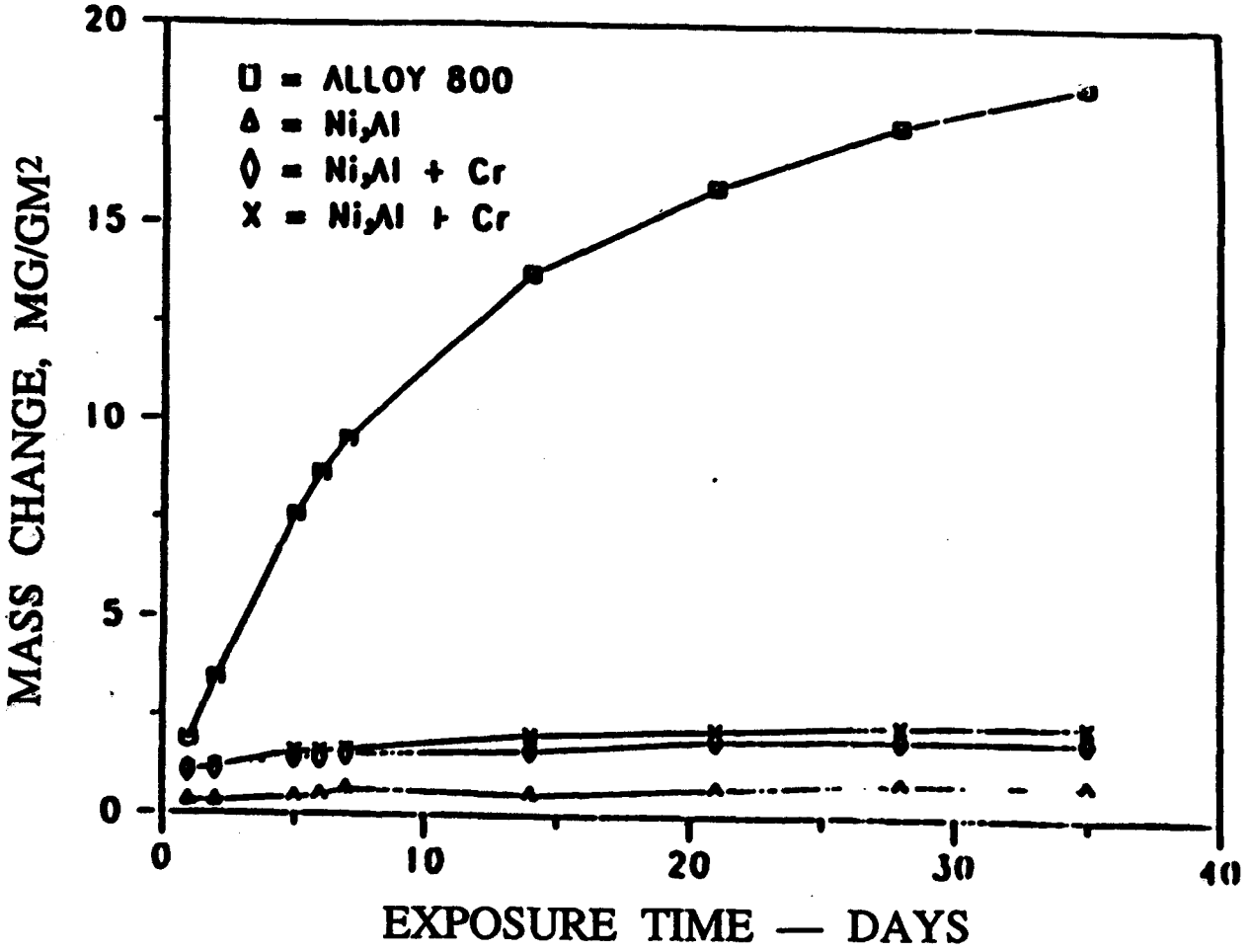
MASS CHANGE IN AIR + 5% WATER VAPOR AT 1000°C



VKS101393-583

INCO ALLOYS INTERNATIONAL

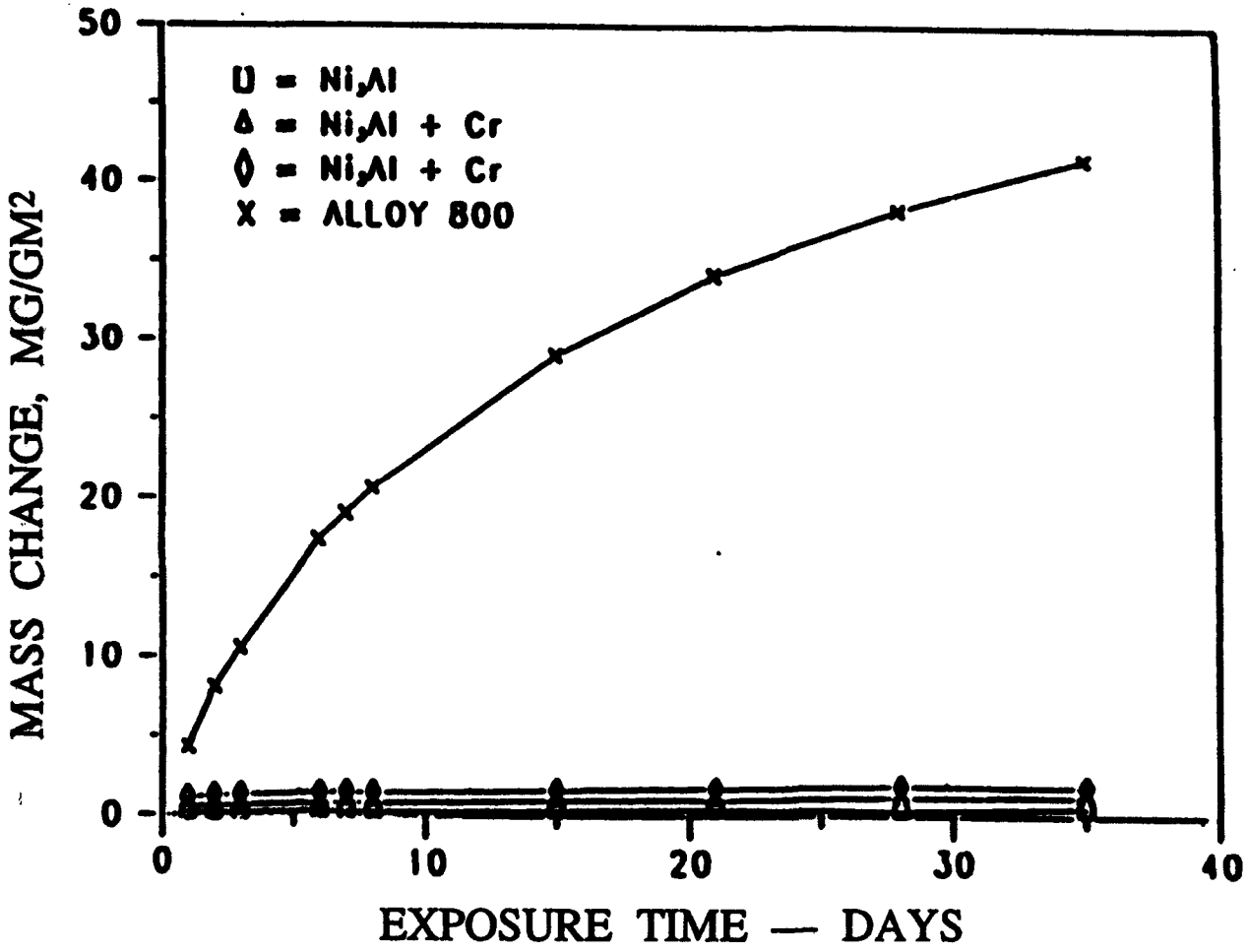
MASS CHANGE IN H_2-5.5% CO_2 AT 1000°C



VKS101393-585

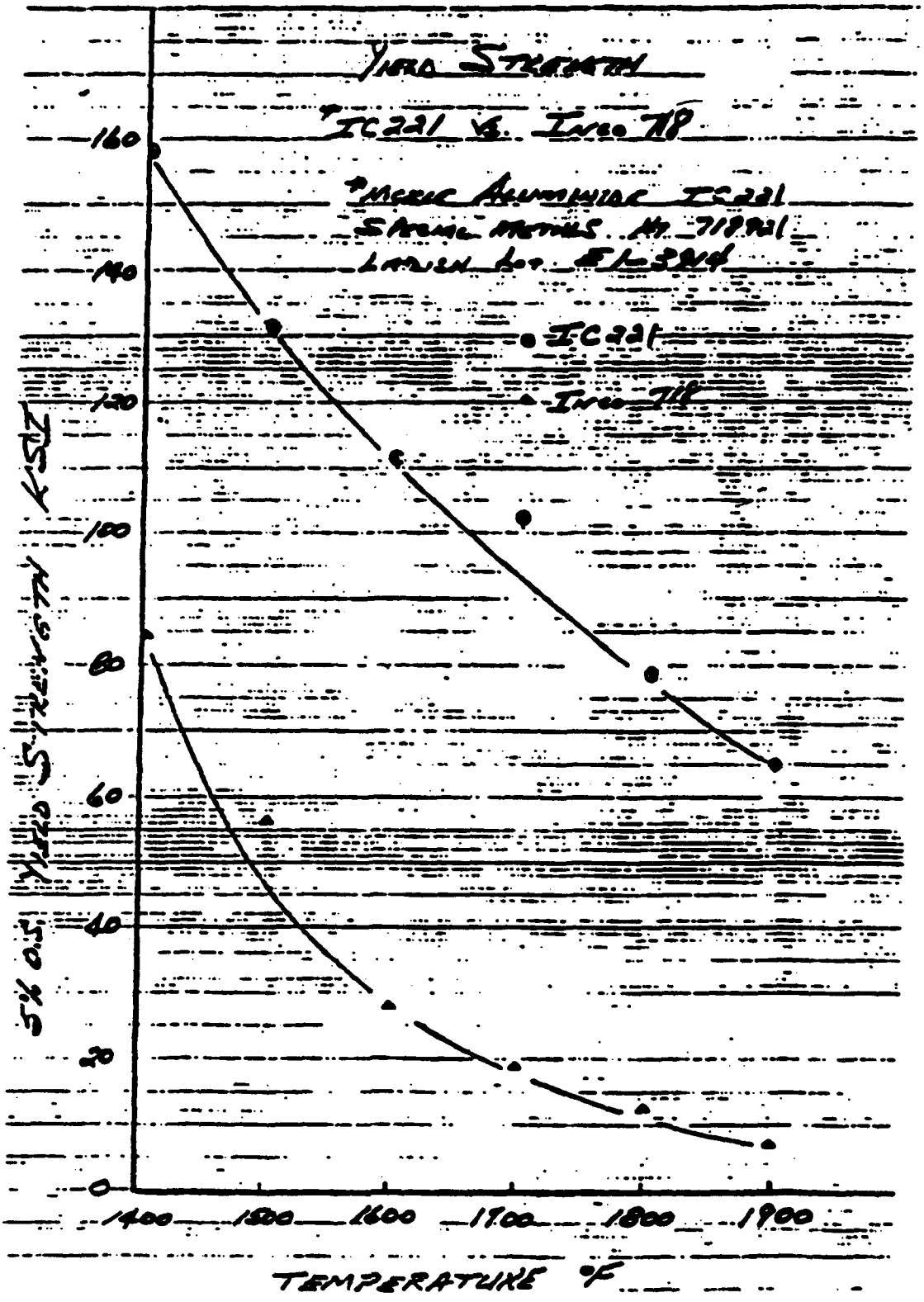
INCO ALLOYS INTERNATIONAL

MASS CHANGE IN H_2-1% CH_4 AT 1000°C



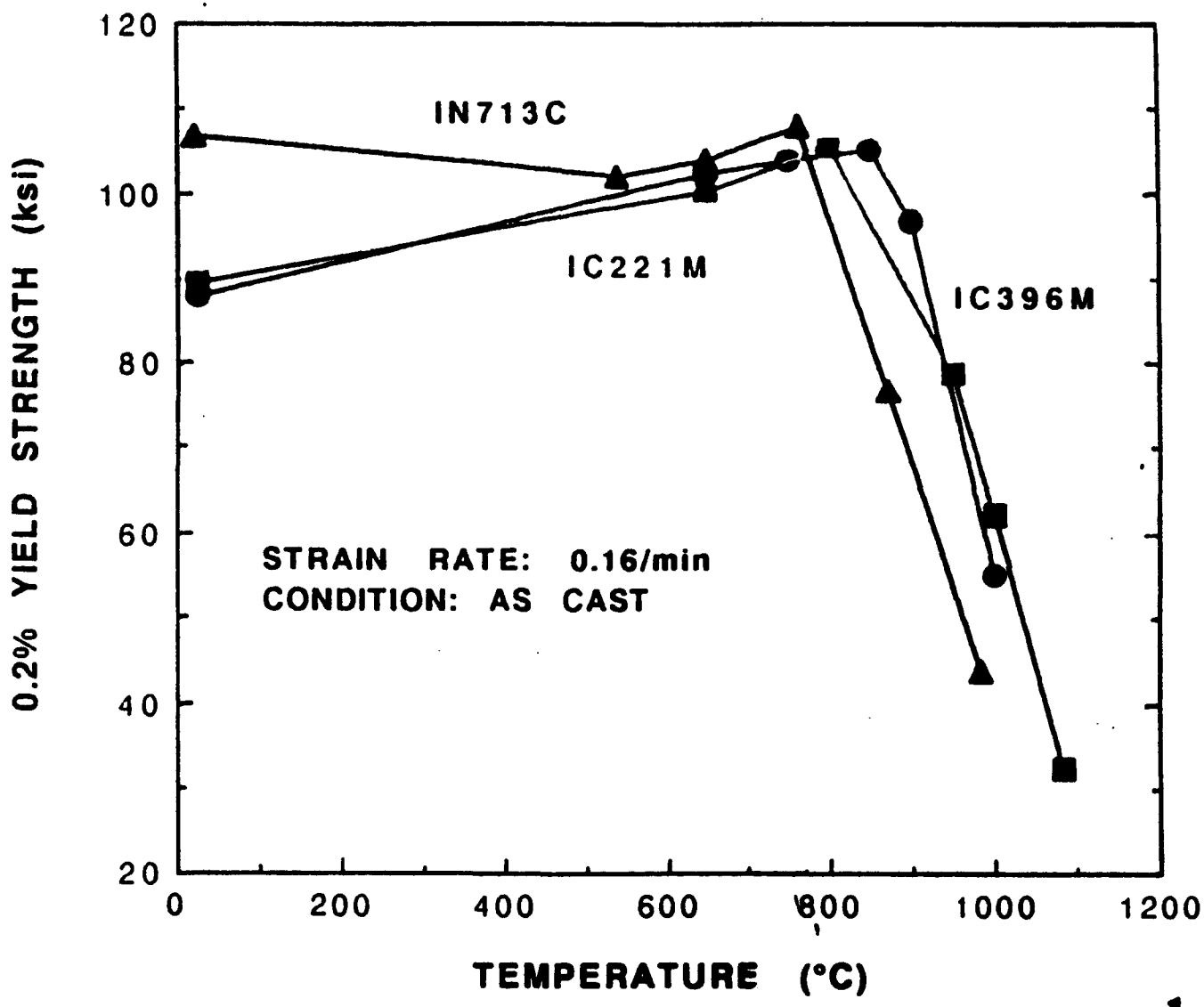
VKS101393-584

INCO ALLOYS INTERNATIONAL



Yield Strength
*IC221 vs. Inco 718
*Nickel Aluminide IC221
Special Metals Ht 718921
Latrobe Lot E1-3914
IC221
Inco 718
5% O.S. Yield Strength KSI
160
140
120
100
80
60
40
20
0
1400
1500
1600
1700
1800
1900
Temperature °F

YIELD STRENGTH OF IN-713, IC-221M, AND IC-396M



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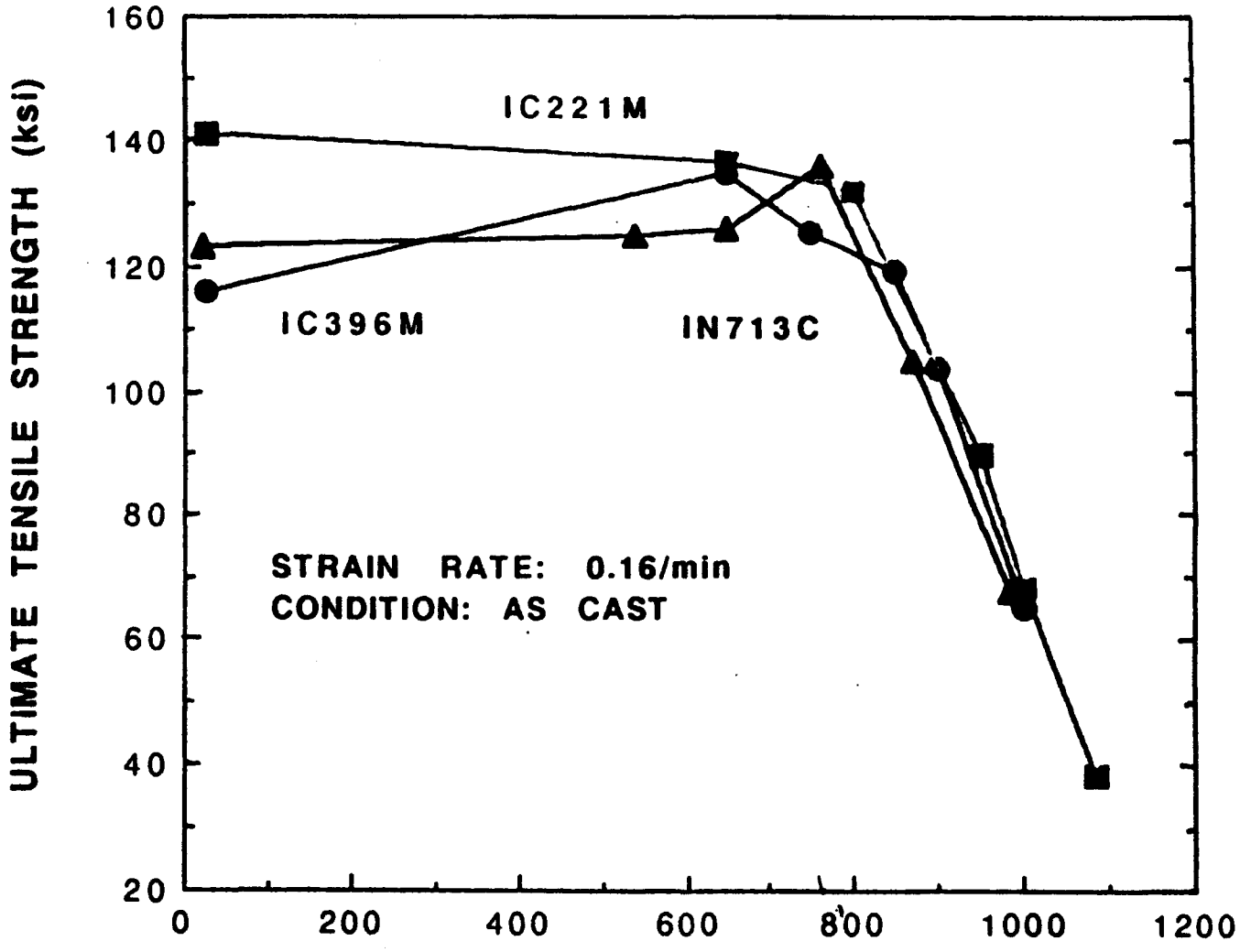
ULTIMATE TENSILE STRENGTH OF IN-713C, IC-221M, AND IC-396M



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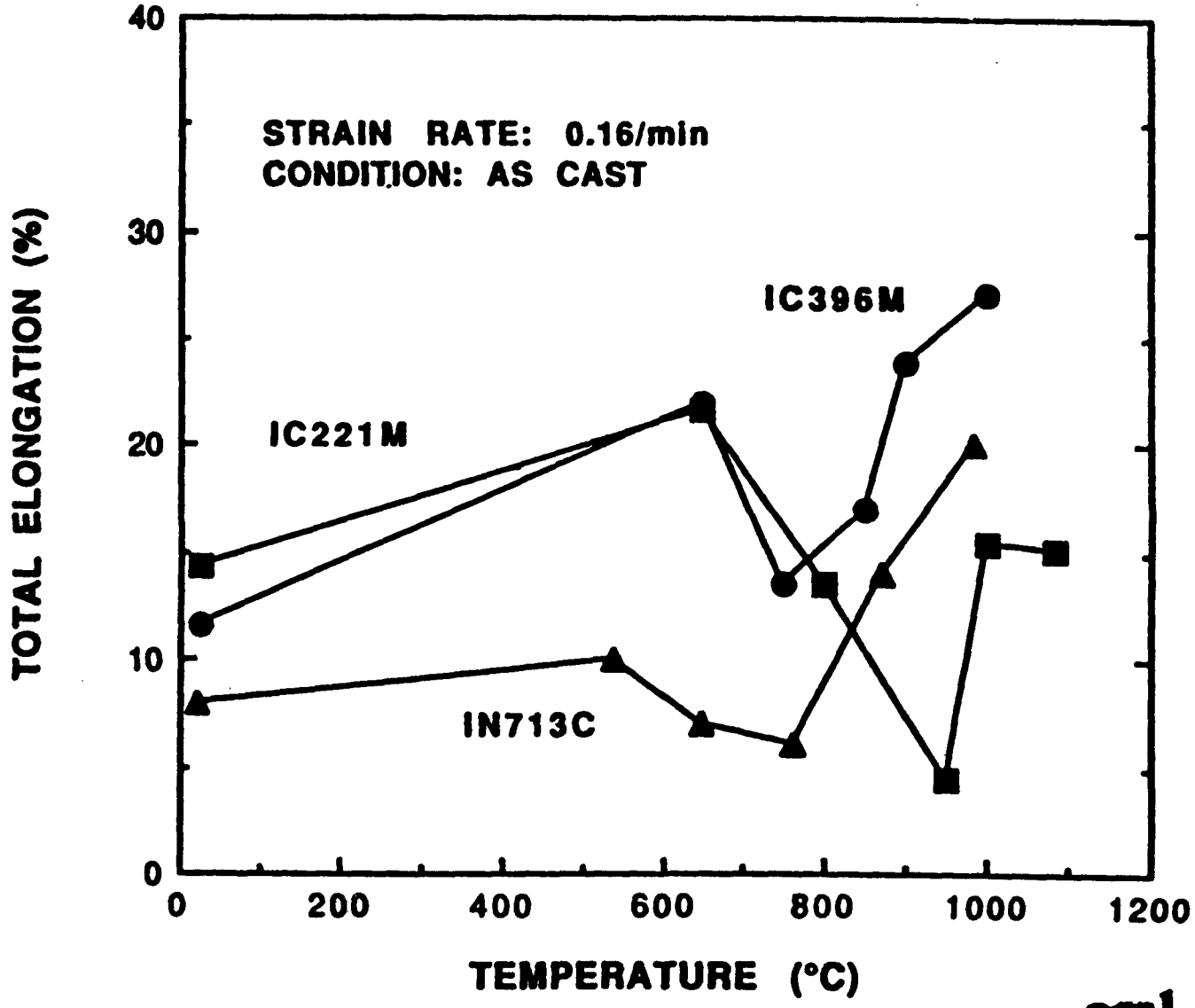
TOTAL ELONGATION OF IN-713C, IC-221M, AND IC-396M



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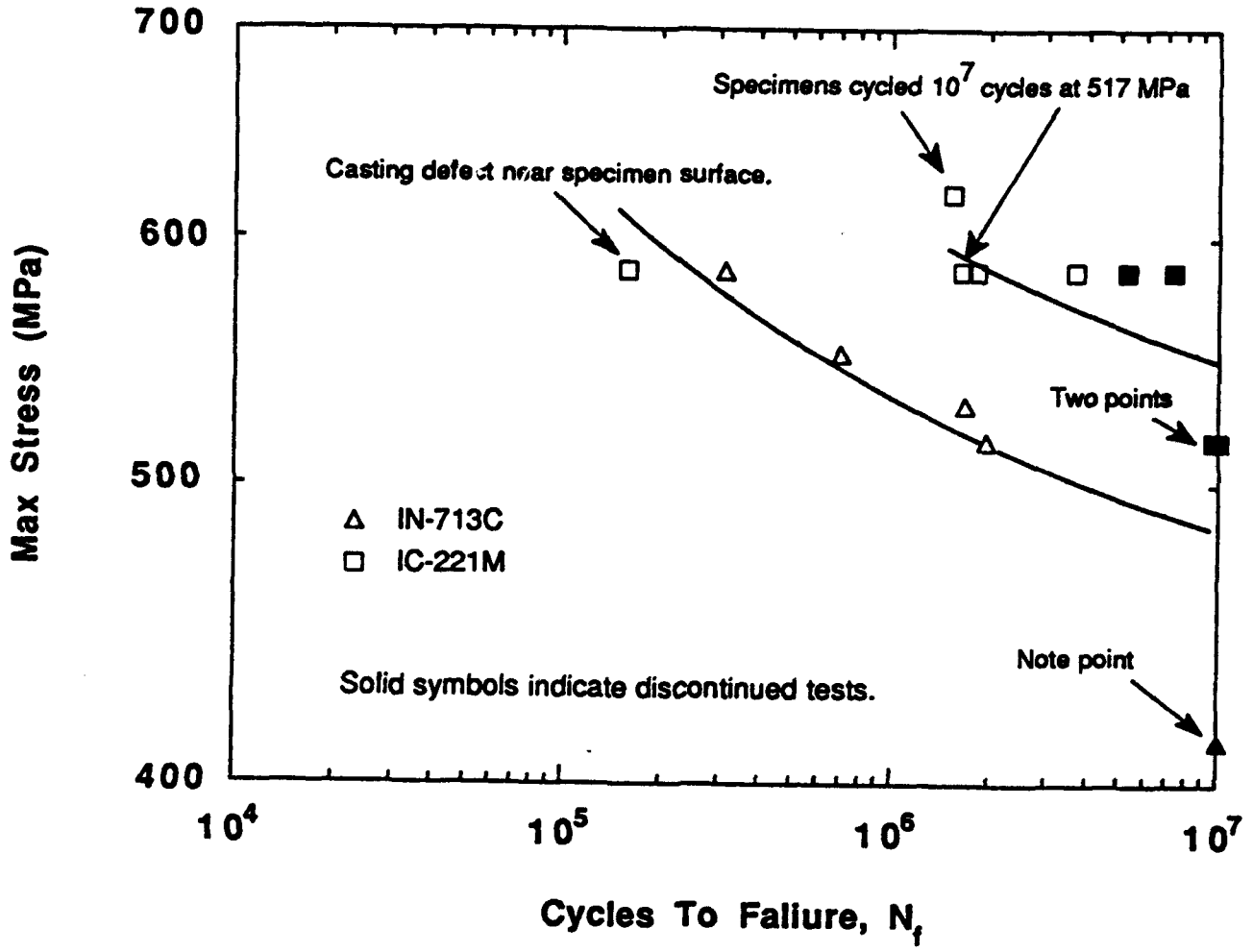
FATIGUE PROPERTIES OF NICKEL ALUMINIDE ARE NEARLY AN ORDER OF MAGNITUDE BETTER THAN ALLOY IN-713C.



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NICKEL-ALUMINIDE APPLICATIONS

- HEAT-TREATING FURNACES
  - TRAYS AND FIXTURES
  - ROLLERS
  - WALKING BEAMS
  - RADIANT TUBES
  - INSTRUMENT-PROTECTIVE TUBES

NICKEL-ALUMINIDE APPLICATIONS (CONTINUED)

- AUTOMOTIVE
  - TURBOCHARGERS
  - CATALYTIC CONVERTER SUBSTRATES
  - HIGH-TEMPERATURE FASTENERS

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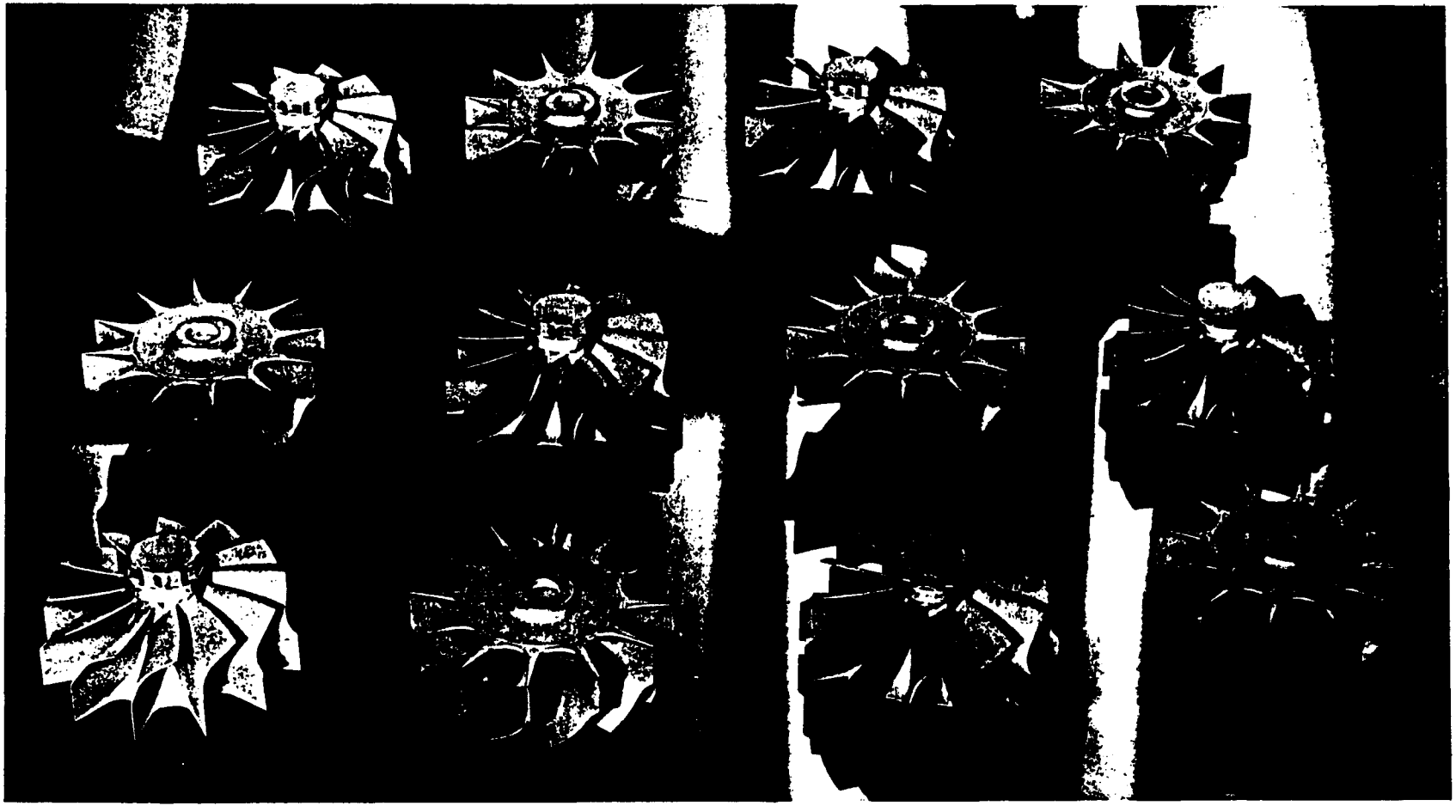
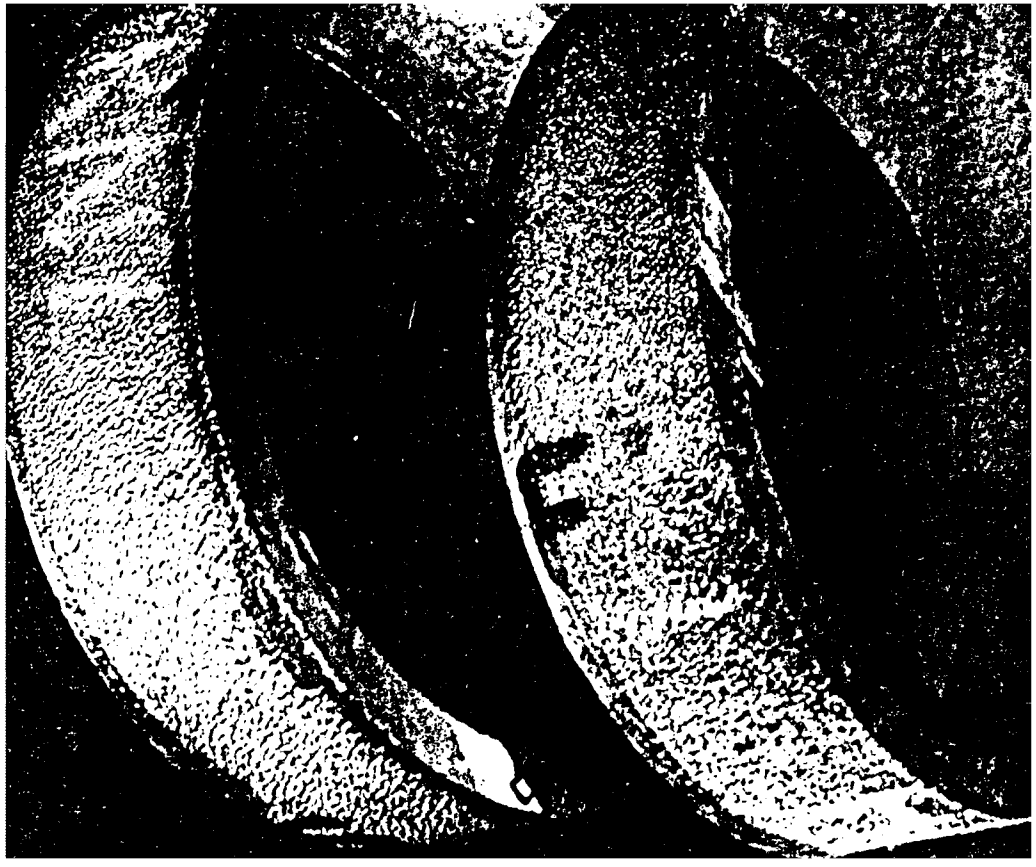
NICKEL-ALUMINIDE APPLICATIONS (CONTINUED)

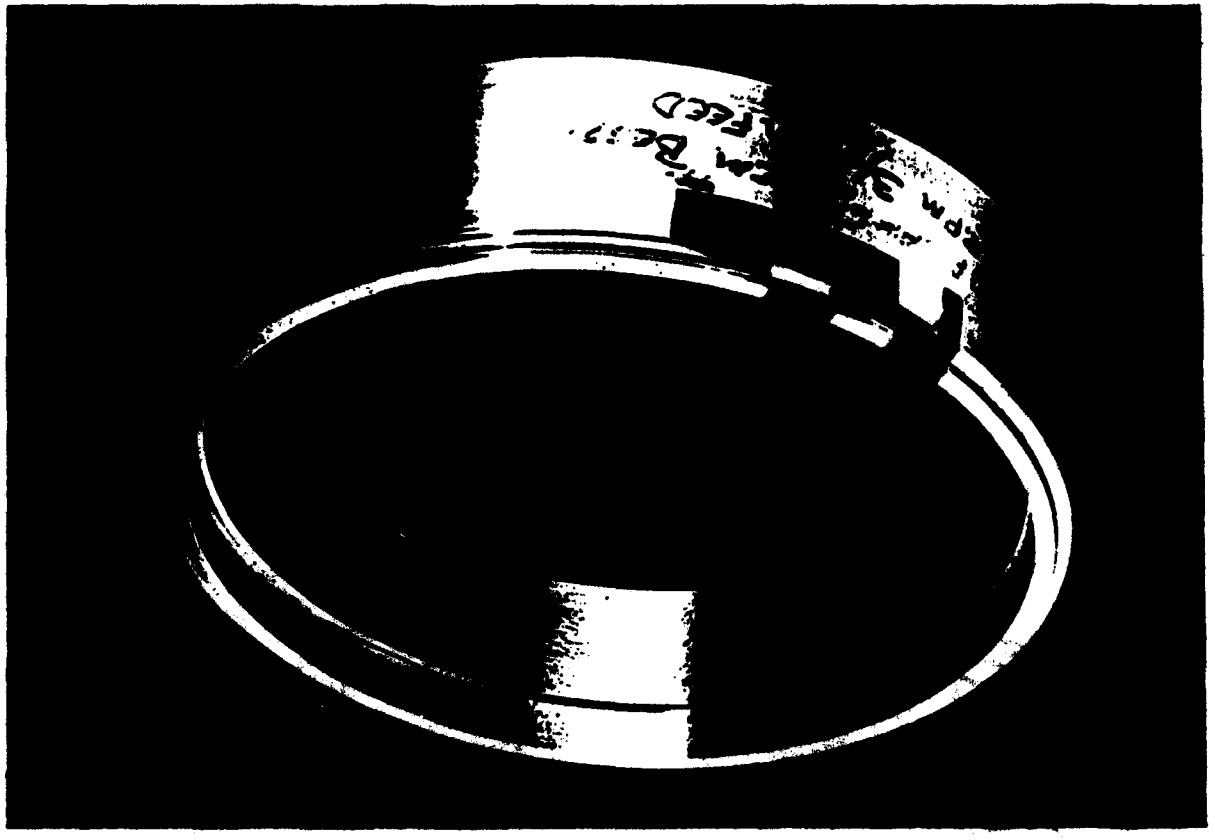
- MANUFACTURING
  - — HOT-PRESSING DIES
  - — HOT-FORGING DIES
  - — PERMANENT MOLDS FOR CASTING

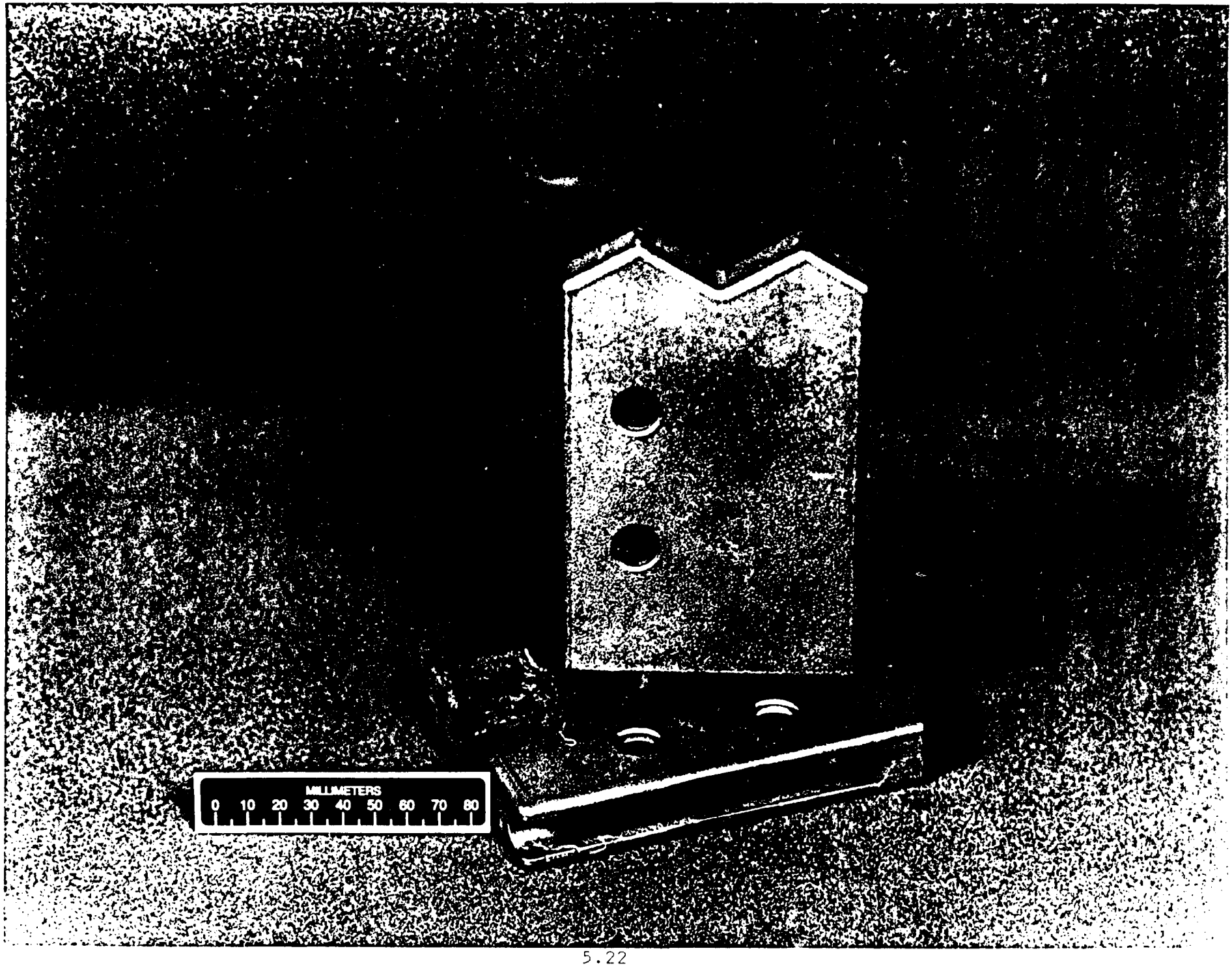
NICKEL-ALUMINIDE APPLICATIONS (CONTINUED)

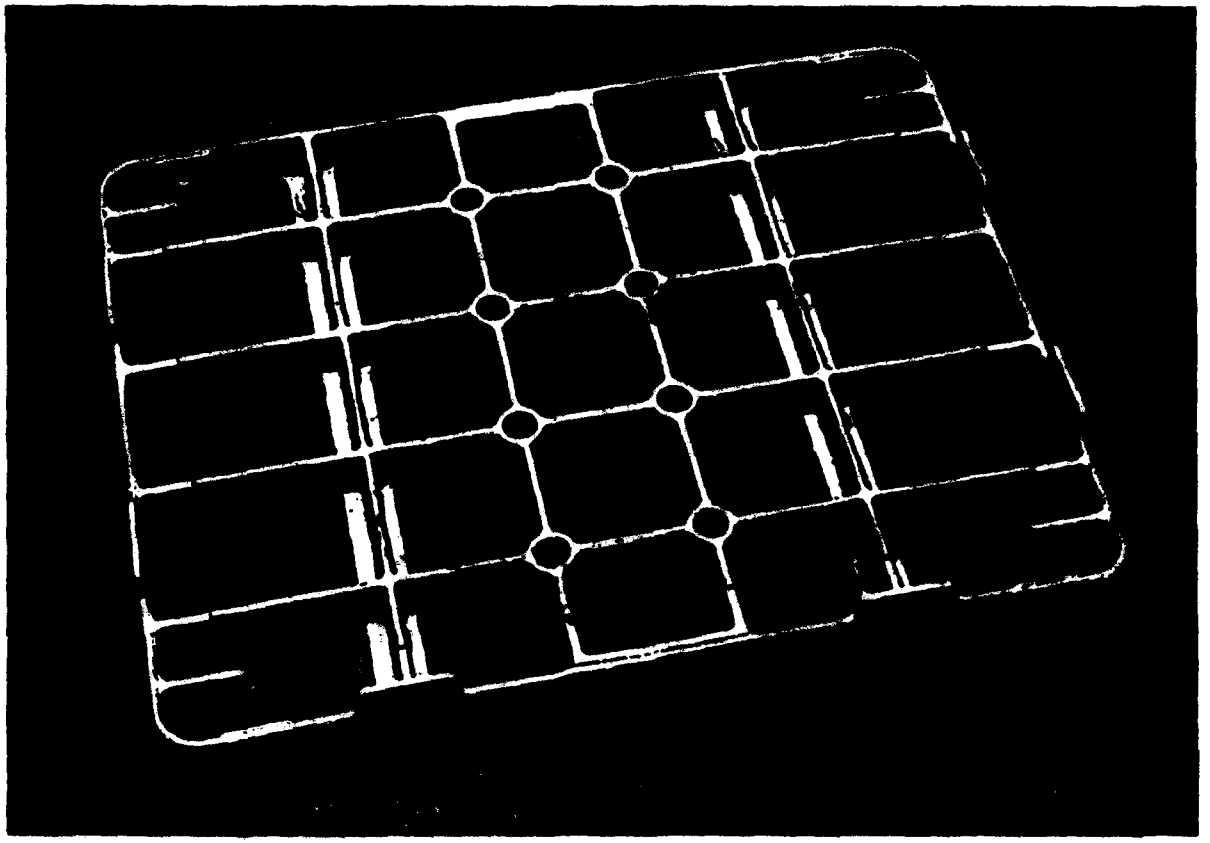
- ENERGY
  - — BLADES FOR HYDROTURBINES
  - — SUPERHEATER TUBES
  - — FUEL-CELL COMPONENTS








MILLIMETERS
0 10 20 30 40 50 60 70 80



5.23

DIRECT-CAST SHEET OF 1- TO 2-MM-THICK BY 300-MM-WIDE NICKEL-ALUMINIDE ALLOYS IC-50 AND IC-218. SHEET CASTING WAS CARRIED OUT AT ALLEGHENY LUDLUM CORPORATION (BRACKENRIDGE, PENNSYLVANIA).

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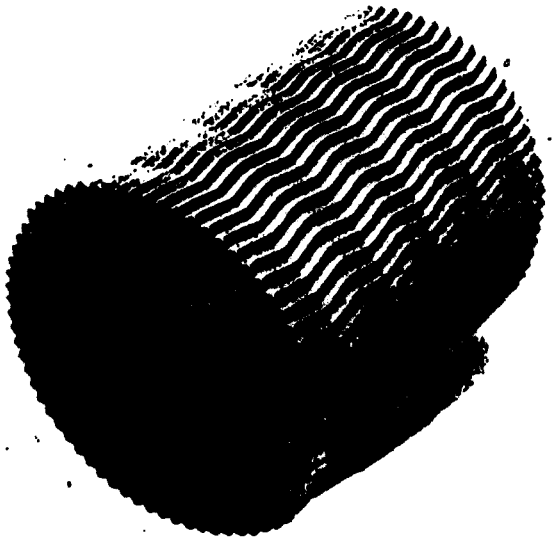
PROTOTYPE CATALYTIC CONVERTER FABRICATED OUT OF FOIL OF NICKEL-ALUMINIDE ALLOY, IC-50.



YEAR: 1992

VKS102692-2

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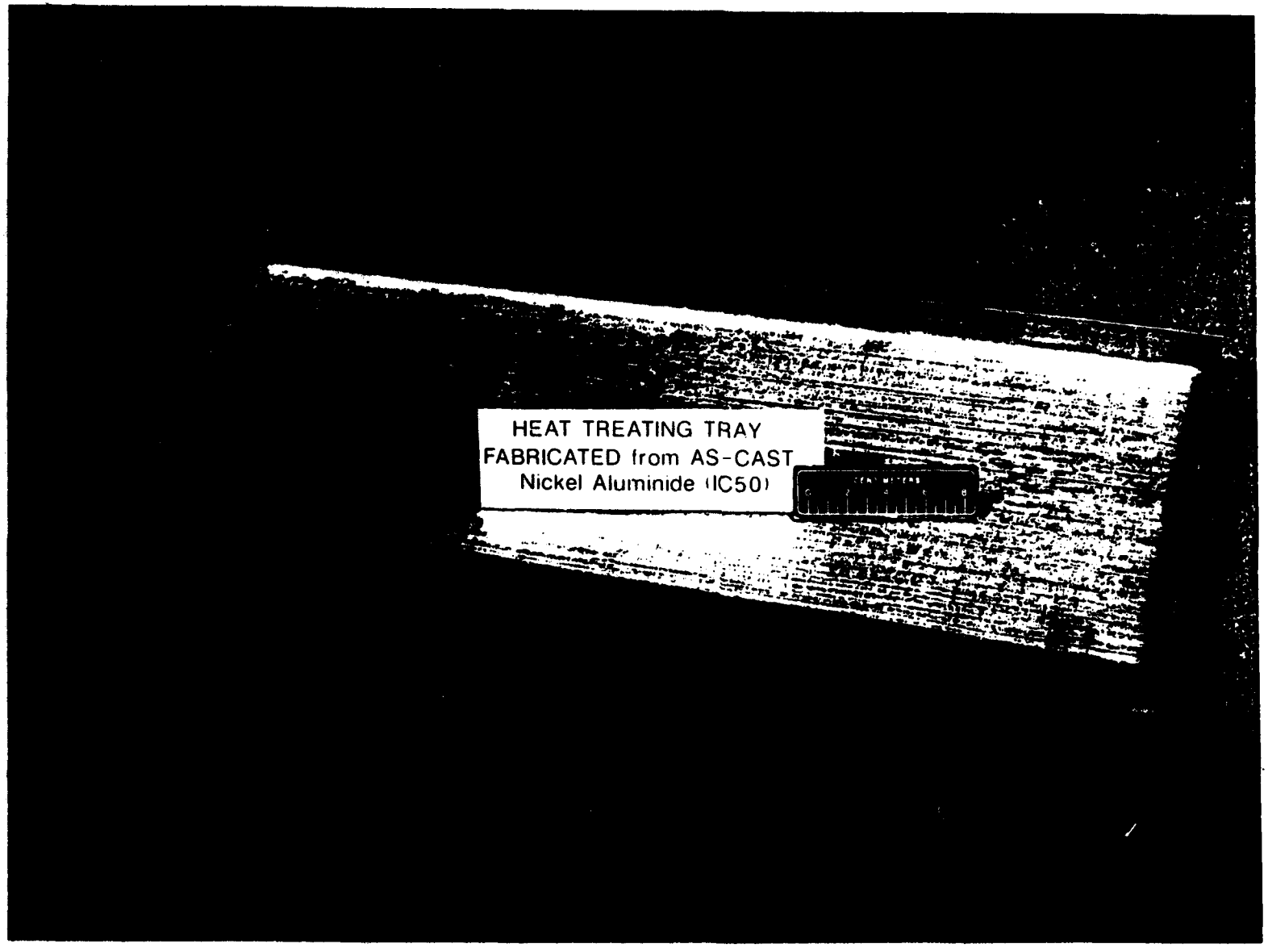
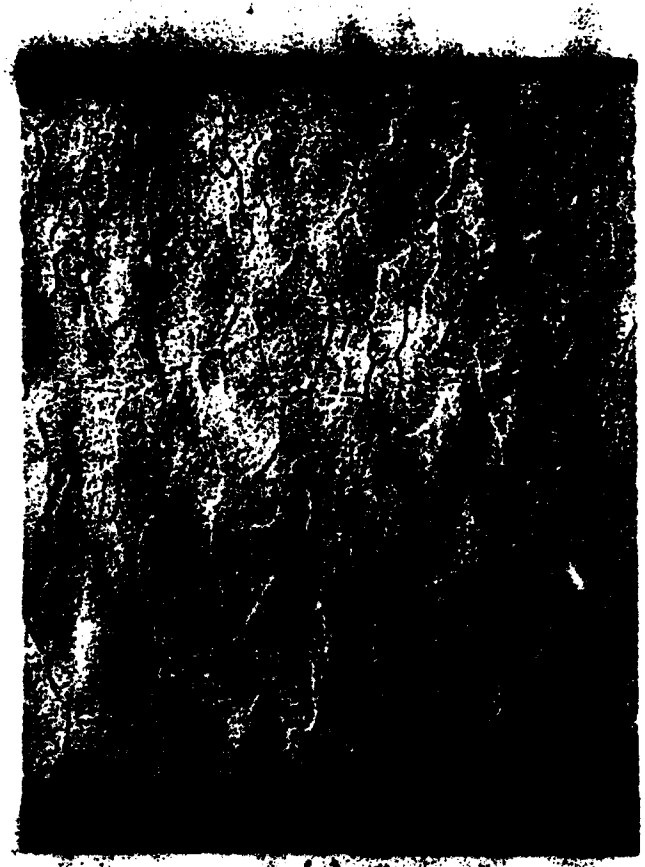
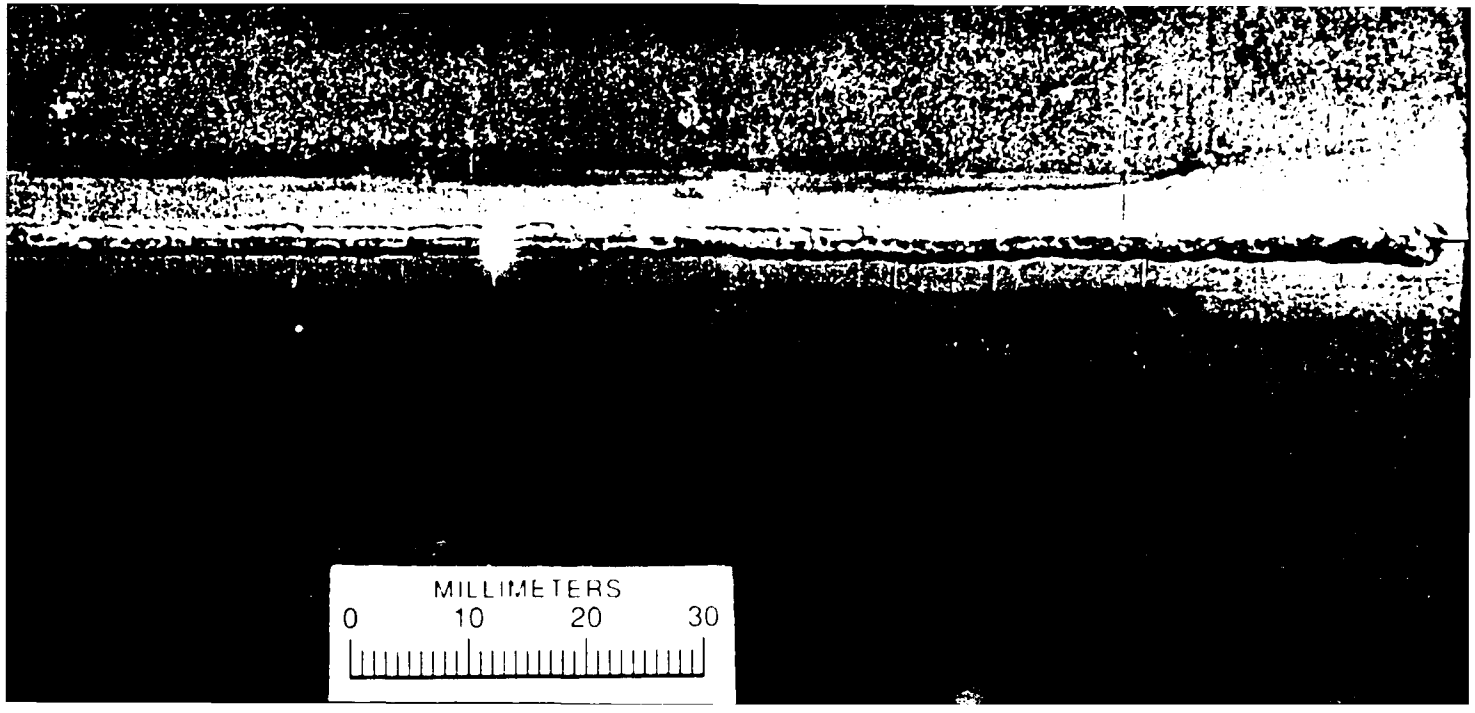

HEAT TREATING TRAY
FABRICATED from AS-CAST
Nickel Aluminide (IC50)

COMPARISON OF AS-CAST MICROSTRUCTURE OF (a) IC50 AND (b) IC218 SHEETS FABRICATED BY ALLEGHENY LUDLUM STEEL CORPORATION. MAGNIFICATION: 100×.



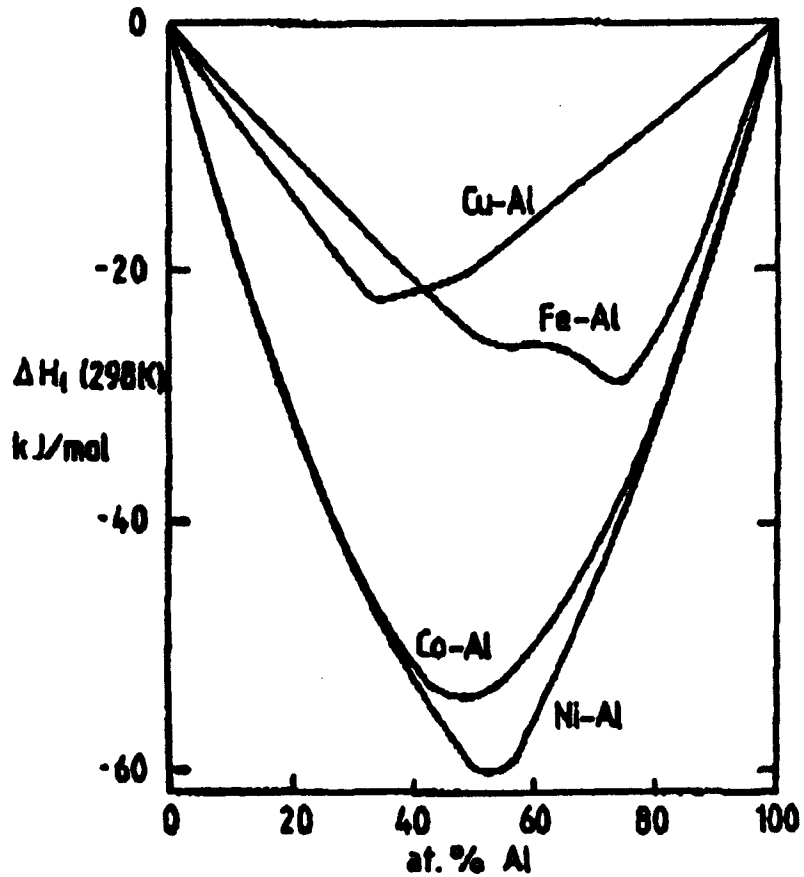
(a)

(b)


MILLIMETERS
0
10
20
30

IC 50 MARKED WITH FELT TIP AND CLEANED IN FERRIC CHLORIDE

EXTENT OF EXOTHERMIC REACTION IN ALUMINUM BINARY SYSTEMS WITH TRANSITION METALS: IRON, COBALT, NICKEL, AND COPPER



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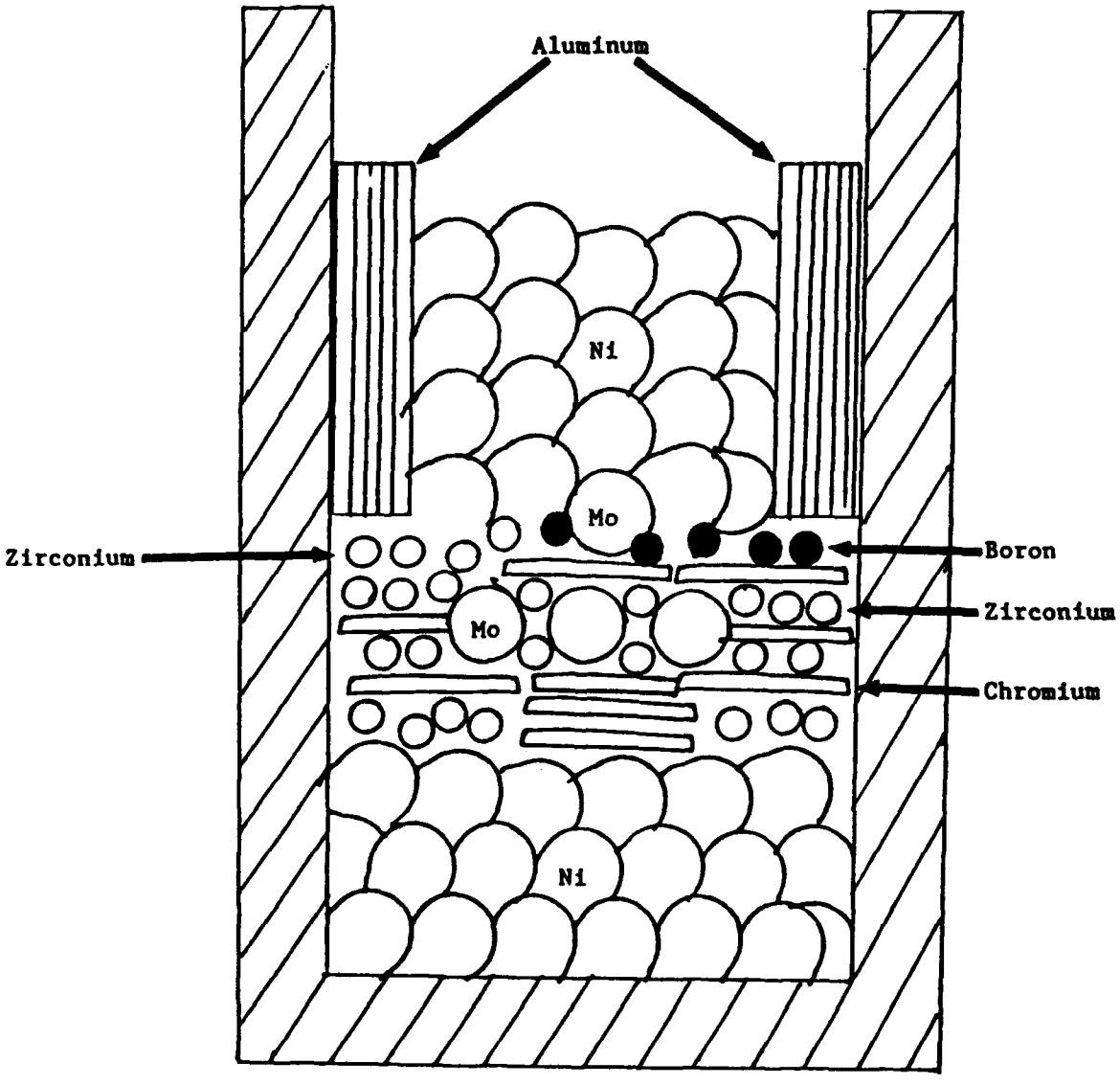
oral

FURNACE-LOADING SEQUENCE TO TAKE ADVANTAGE OF HEAT OF FORMATION OF Ni_3Al DURING THE MELTING OF NICKEL-ALUMINIDE ALLOYS. SIMILAR LOADING SEQUENCE, REPLACING NICKEL BY IRON AND BY TITANIUM, WILL WORK FOR THE MELTING OF IRON AND TITANIUM ALUMINIDES.



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EFFECT OF HOLDING TIME ON THE CHEMICAL ANALYSIS OF A NICKEL-ALUMINIDE ALLOY, IC-221M, AIR MELTED WITH AN ARGON GAS COVER

Element	Weight percent	
	Holding time (min)	
	0	8
Ni	81.2	81.2
Al	7.61	7.59
Cr	7.66	7.63
Mo	1.42	1.43
Zr	1.46	1.47
B	0.009	0.009
Nb	0.02	0.02
Ti	0.14	0.14
C	0.009	0.010
S	0.001	0.001
N	0.006	0.006
O	0.011	0.010
Fe	0.44	0.44
Si	0.04	0.04

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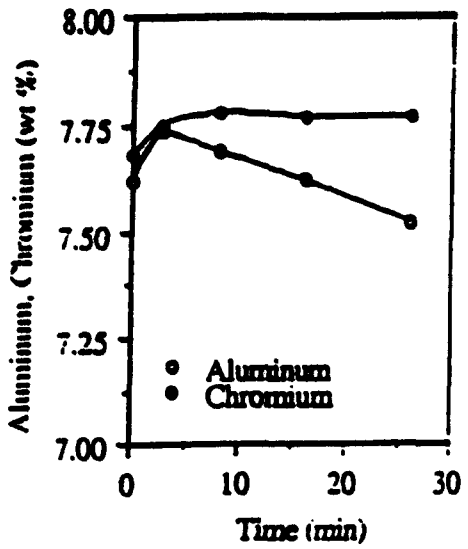

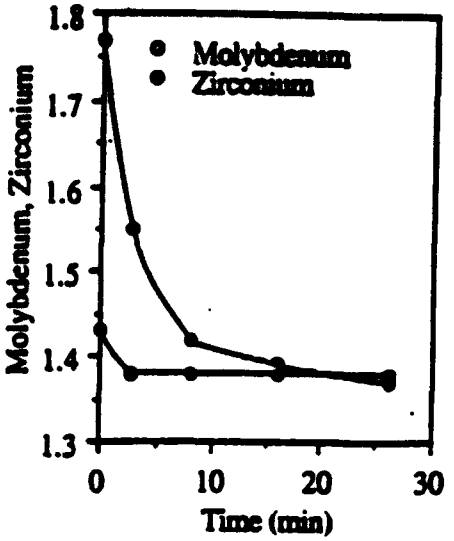

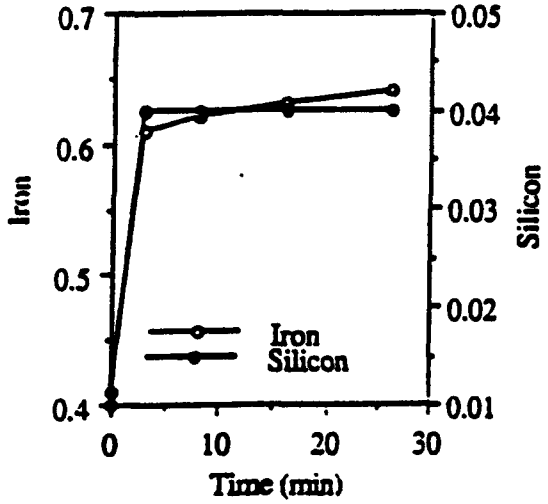

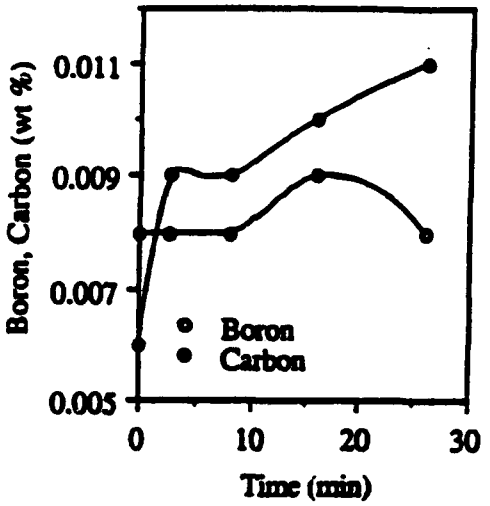

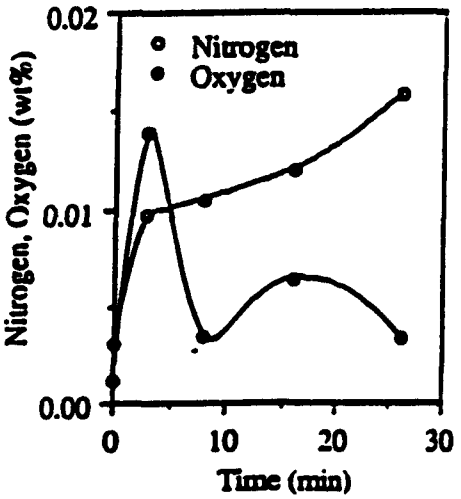

5.33

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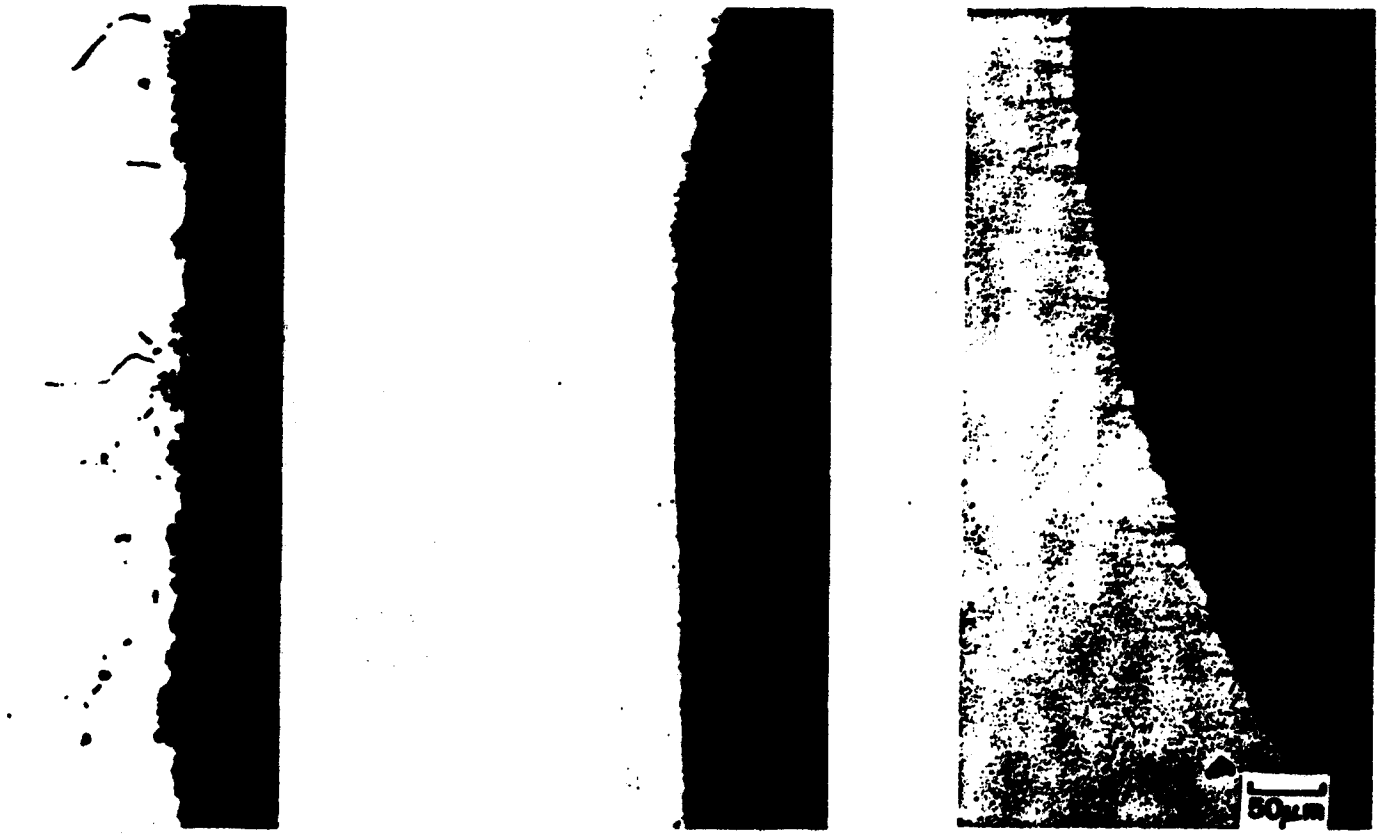


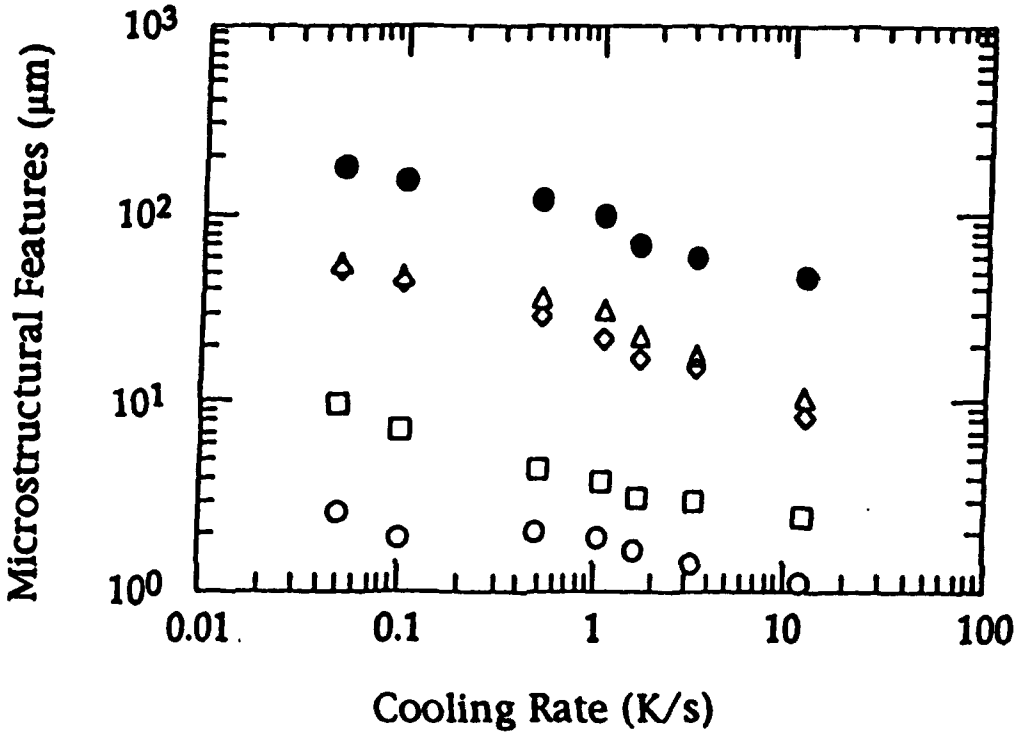
(*a*) (*b*) (*c*)

Surface reaction of nickel-aluminide alloy with mold material and methods of eliminating: (*a*) nickel aluminide of 1.7 wt % Zr cast in an alumina silicate mold, (*b*) same composition cast in a clay graphite crucible, and (*c*) same composition modified by hafnium and cast in zircon shell with a cobalt-aluminate wash.

EFFECT OF ZIRCONIUM CONTENT IN NICKEL-ALUMINIDE ALLOY ON SURFACE REACTION WITH THE INVESTMENT MOLD SHELL MATERIAL

Alloy Zirconium content (wt %)	Reaction depth (mm)
0.85	0
1.28	0.051
1.70	0.076

SIZE OF VARIOUS MICROSTRUCTURAL FEATURES AS A FUNCTION OF COOLING RATE FOR NICKEL-ALUMINIDE ALLOY IC-396M CONTAINING 0.85 WT % Zr.



○ = Radius of γ′ cells (R γ′ cell)

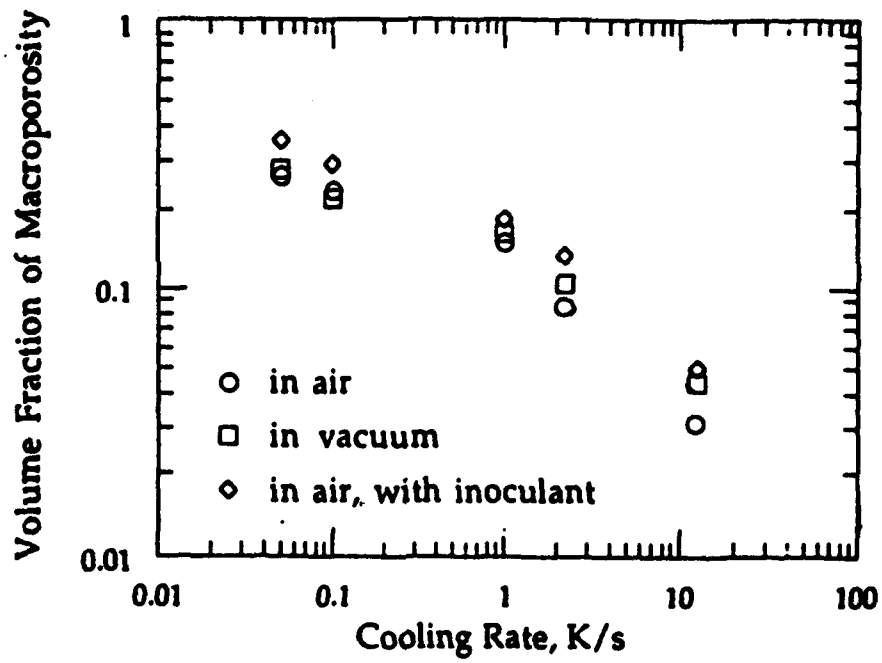
◊ = Radius of γ′ particles (R γ′)

● = Secondary dendrite arm spacing (λ2)

□ = Radius of microporosity ($R_{micropone}$)

Δ = Radius of macroporosity ($R_{macropone}$)

EFFECT OF COOLING RATE ON THE MACROPOROSITY VOLUME FRACTION OF A NICKEL-ALUMINIDE ALLOY IC-221M CONTAINING 1.7 WT % Zr.



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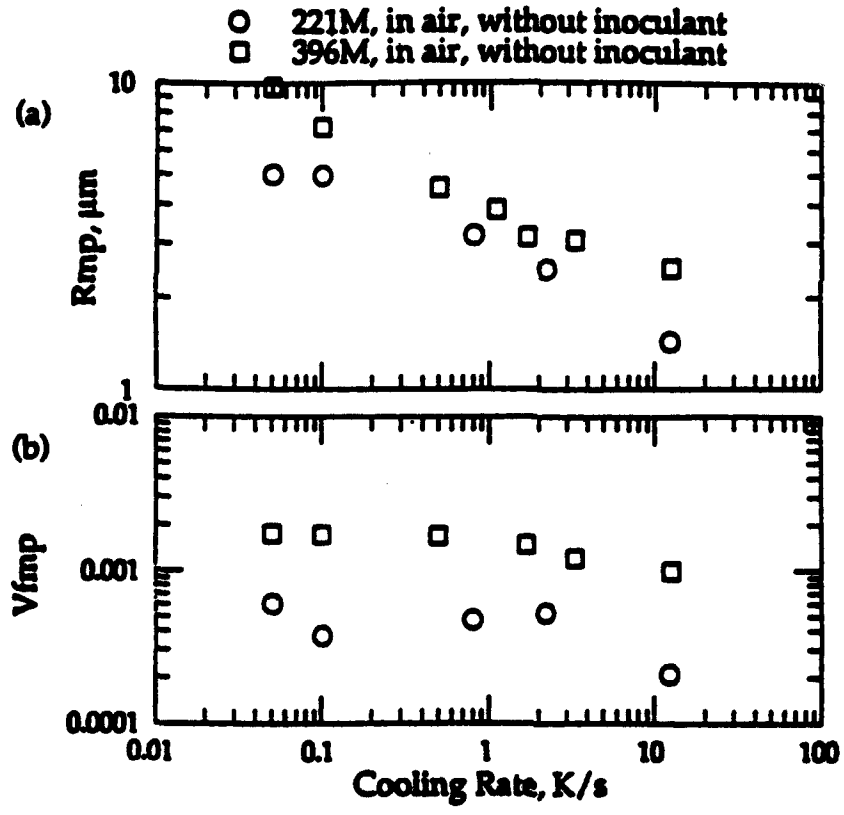
EFFECT OF COOLING RATE ON THE MACROPOROSIY VOLUME FRACTION OF A NICKEL-ALUMINIDE ALLOY IC-221M CONTAINING 1.7 WT % Zr.

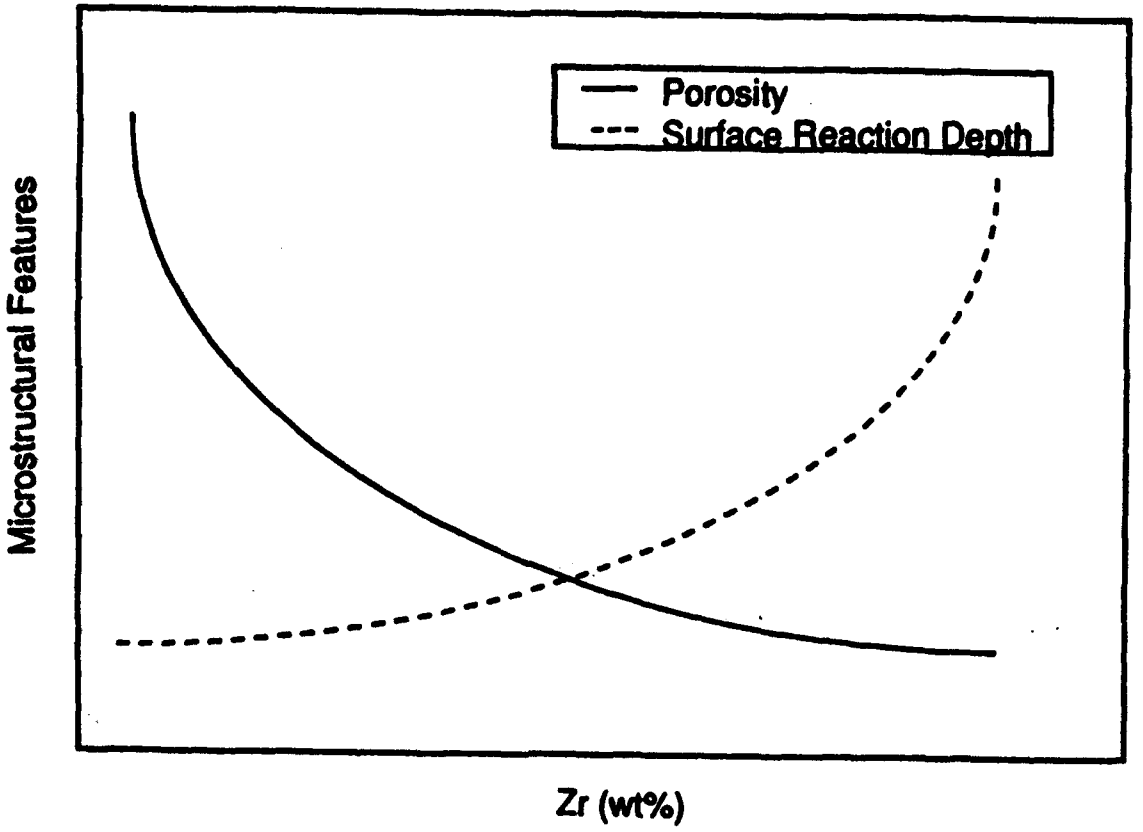


VEB013194-689

5.37 (a)

oral

SCHEMATIC REPRESENTATION OF EFFECTS OF ZIRCONIUM CONTENT ON MICROPOROSITY AND SURFACE REACTION DEPTH FOR NICKEL-ALUMINIDE ALLOYS.



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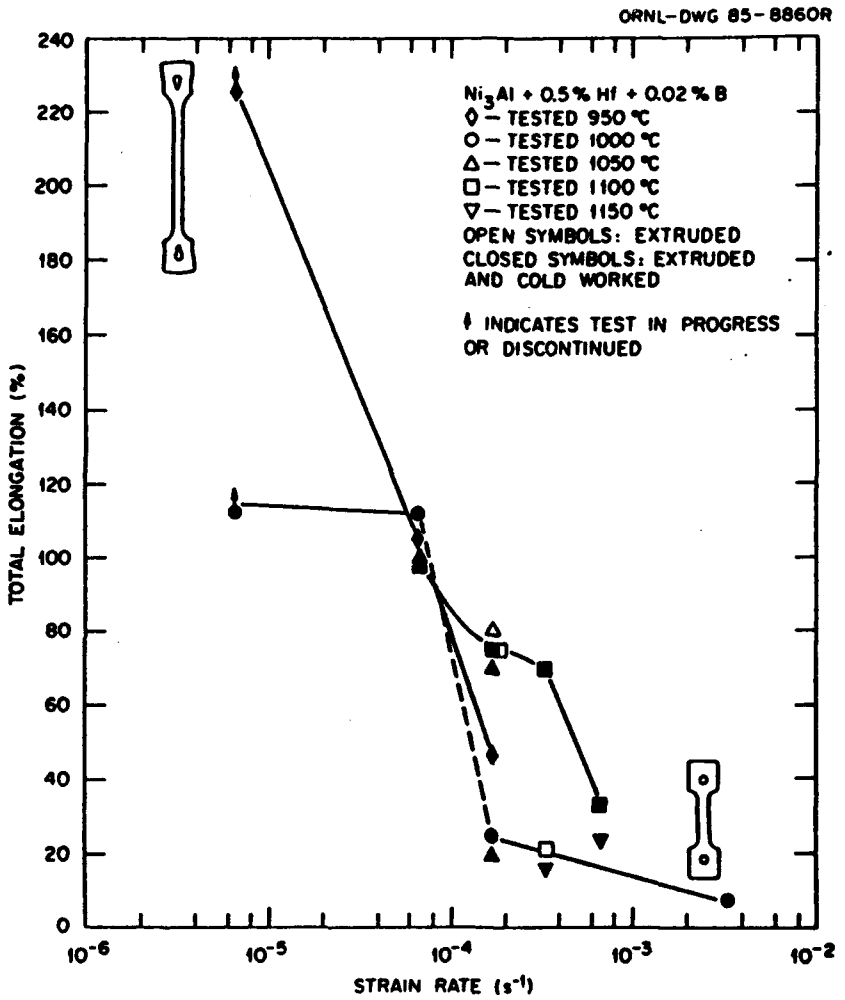
EFFECT OF STRAIN RATE AND TEST TEMPERATURE ON TENSILE DUCTILITY OF Ni_3Al ALLOY CONTAINING 0.5 WT % Hf AND 0.02% B.



VKS013194-693

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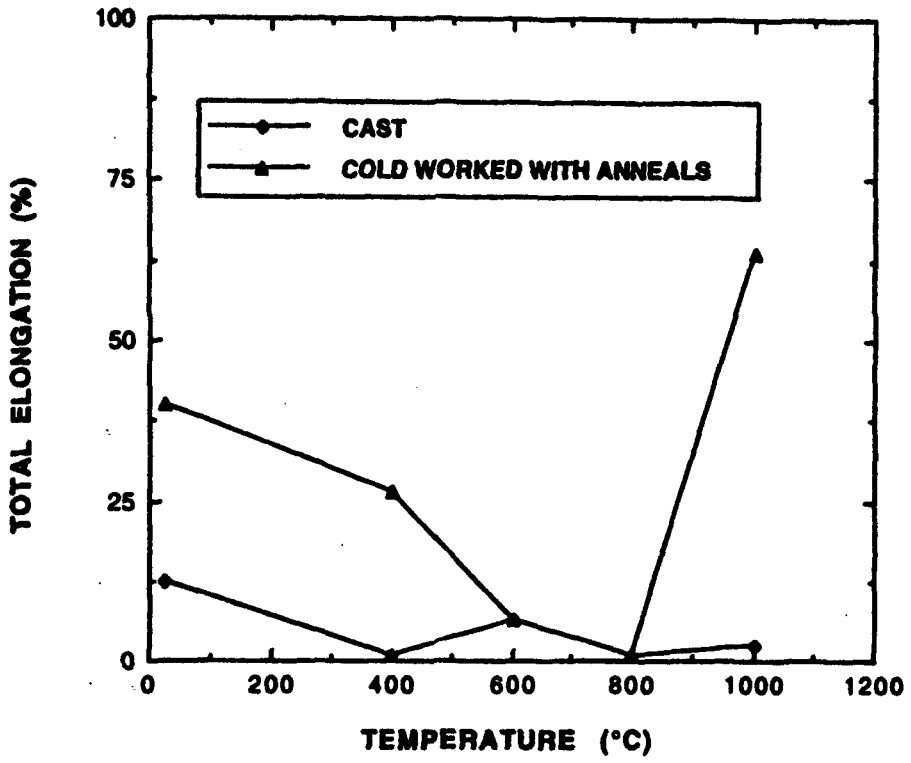
EFFECT OF GRAIN REFINEMENT BY COLD WORKING WITH INTERMEDIATE ANNEALS ON DUCTILITY OF Ni_3Al-BASED ALLOY IC-50. TESTS WERE CONDUCTED IN AIR AT A STRAIN RATE OF $3 \times 10^{-3}\ S^{-1}$.



VKS013194-695

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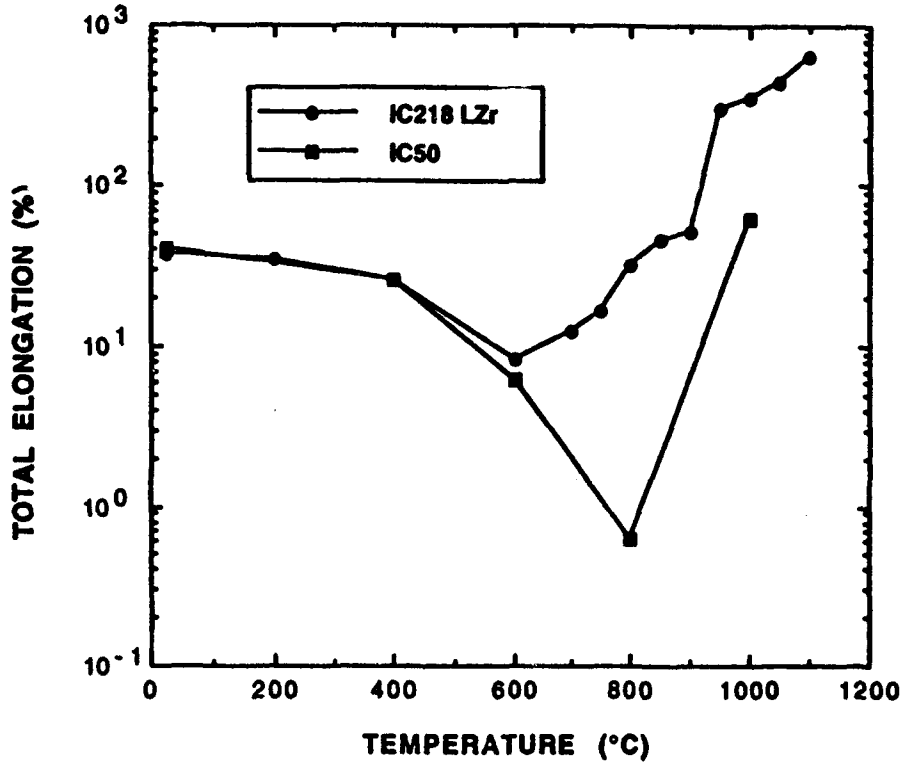
EFFECT OF CHROMIUM IN REDUCING THE DYNAMIC-OXYGEN-EMBRITTLEMENT EFFECT IN Ni_3Al-BASED ALLOYS. BOTH ALLOYS WERE TESTED IN AIR AT A STRAIN RATE OF $6.7 \times 10^{-4}\ S^{-1}$ IN THE WROUGHT CONDITION.



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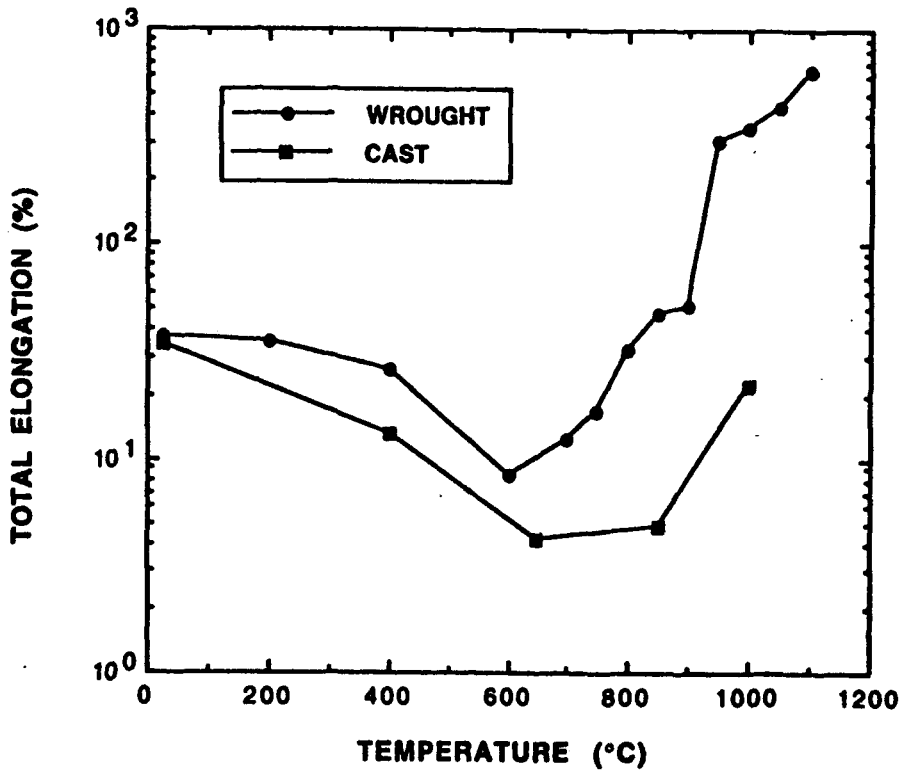
EFFECT OF GRAIN-STRUCTURE REFINEMENT THROUGH HOT WORKING FOLLOWED BY COLD WORKING ON DUCTILITY OF Ni_3Al-BASED ALLOY IC-218LZr. ALL OF THE SPECIMENS WERE TESTED IN AIR AT A STRAIN RATE OF $6.7 \times 10^{-4}\ S^{-1}$.



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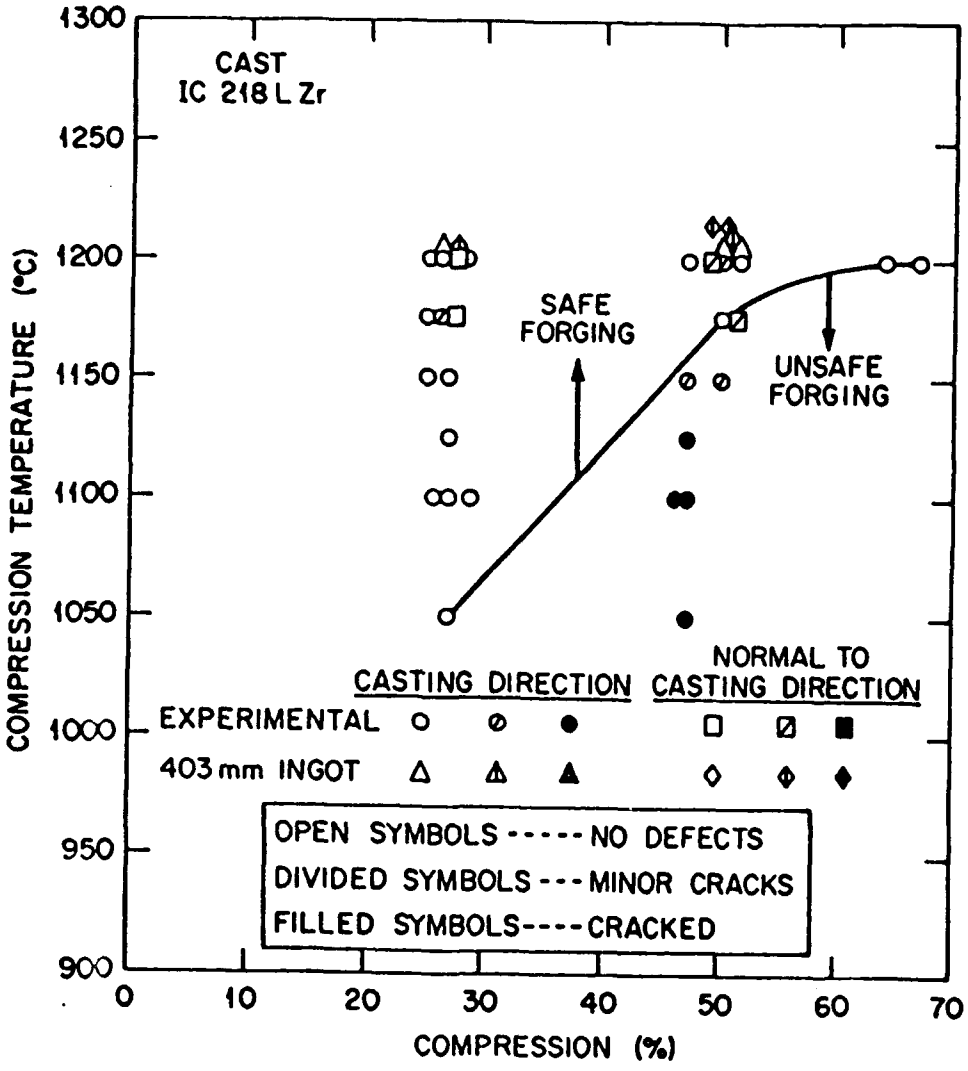
HOT-COMPRESSION RESPONSE OF SAMPLES TAKEN FROM THE EXPERIMENTAL (75-MM-DIAM) AND COMMERCIAL (403-MM-DIAM) INGOTS OF Ni_3Al ALLOY CONTAINING CHROMIUM (IC-218LZr).



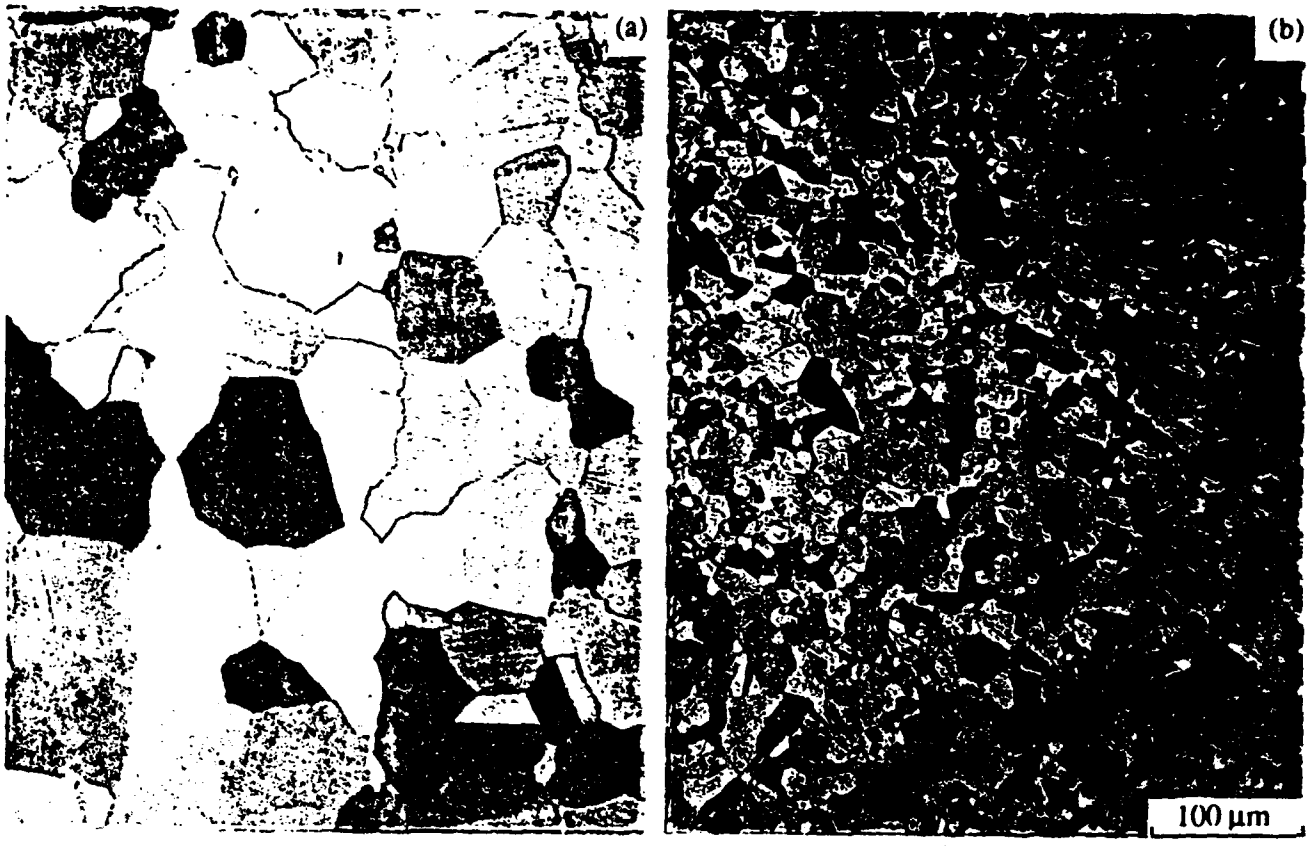
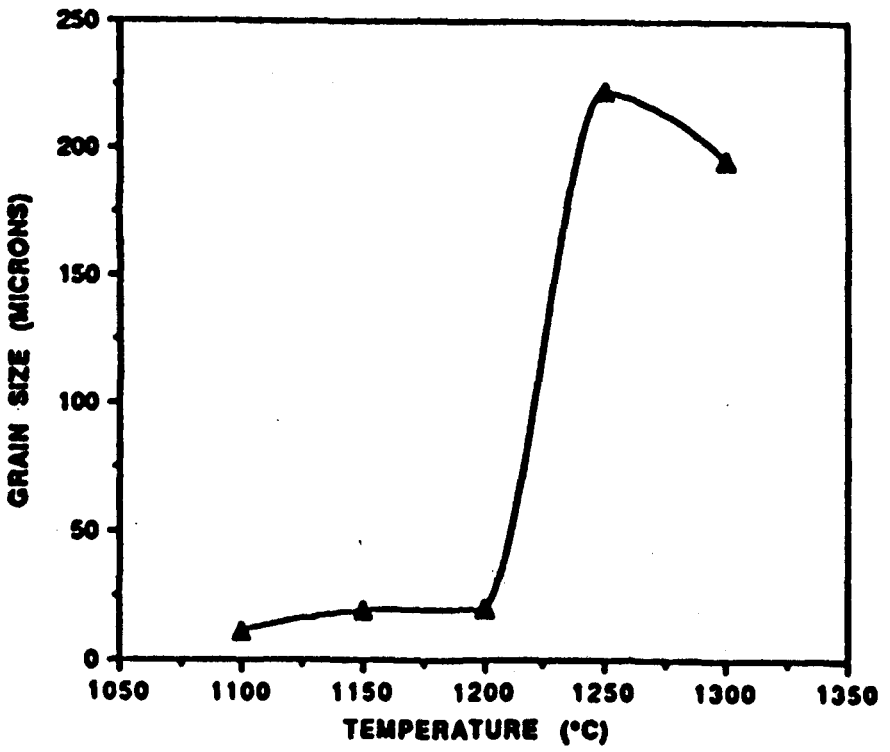


Fig. 12. IC-218LZr ingot: (a) as-extruded condition and (b) cold worked 58% and annealed at 1100°C for 1 h.

GRAIN SIZE AS A FUNCTION OF TEMPERATURE FOR NI_3AL-BASED ALLOY IC-218LZr. THE 57% COLD-WORKED SAMPLES WERE ANNEALED FOR 1 H AT INDICATED TEMPERATURES.



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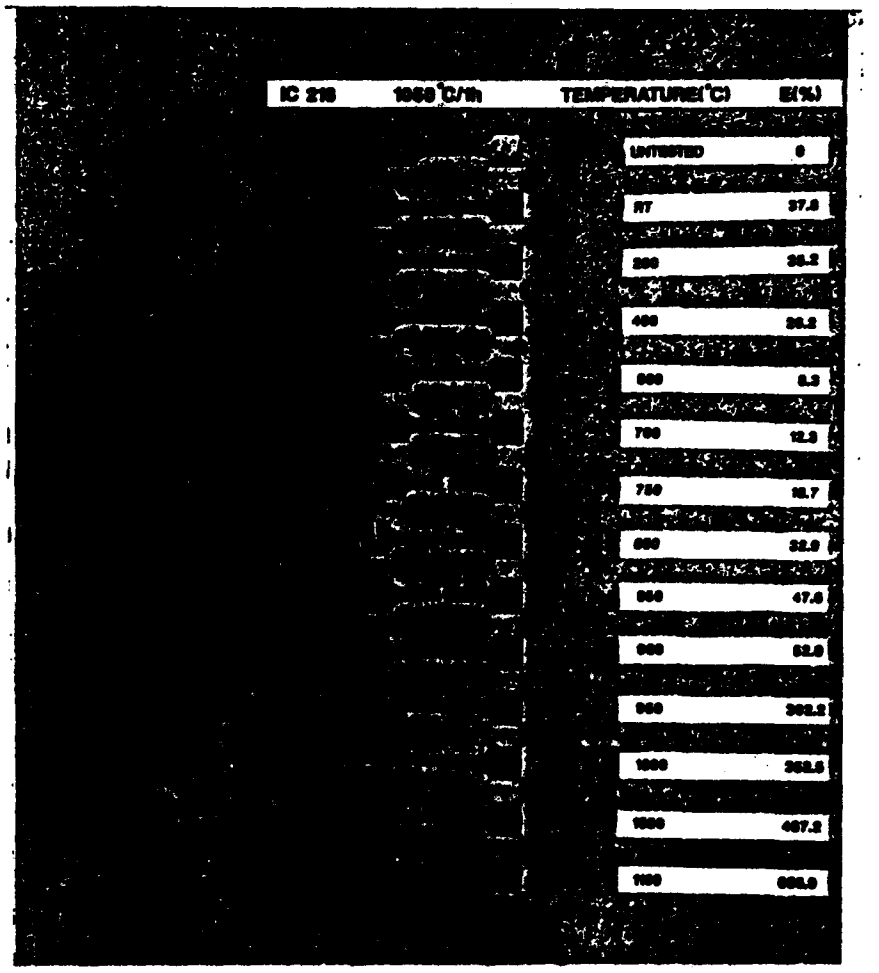
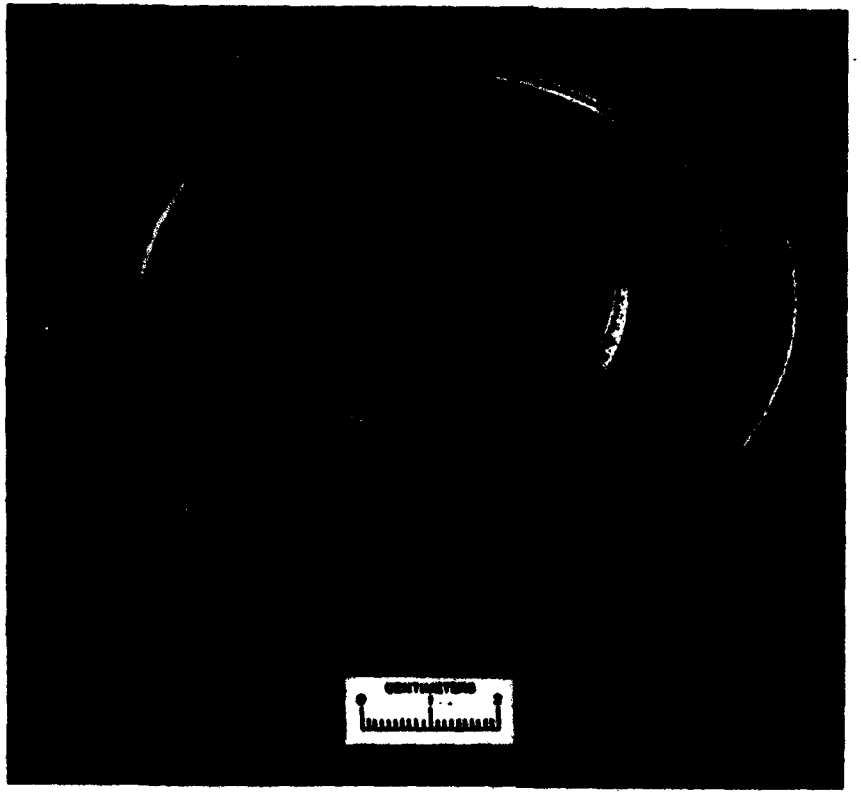
SUPERPLASTICITY IS OBSERVED IN Ni_3Al CONTAINING Cr.



YEAR: 1986

SUPERPLASTICITY CONDITIONS OF TEMPERATURE AND STRAIN RATE, BASED ON THE TENSILE TEST, ARE CONFIRMED BY FORMING OF A PROTOTYPE DISC AT LADISH.



YEAR: 1986

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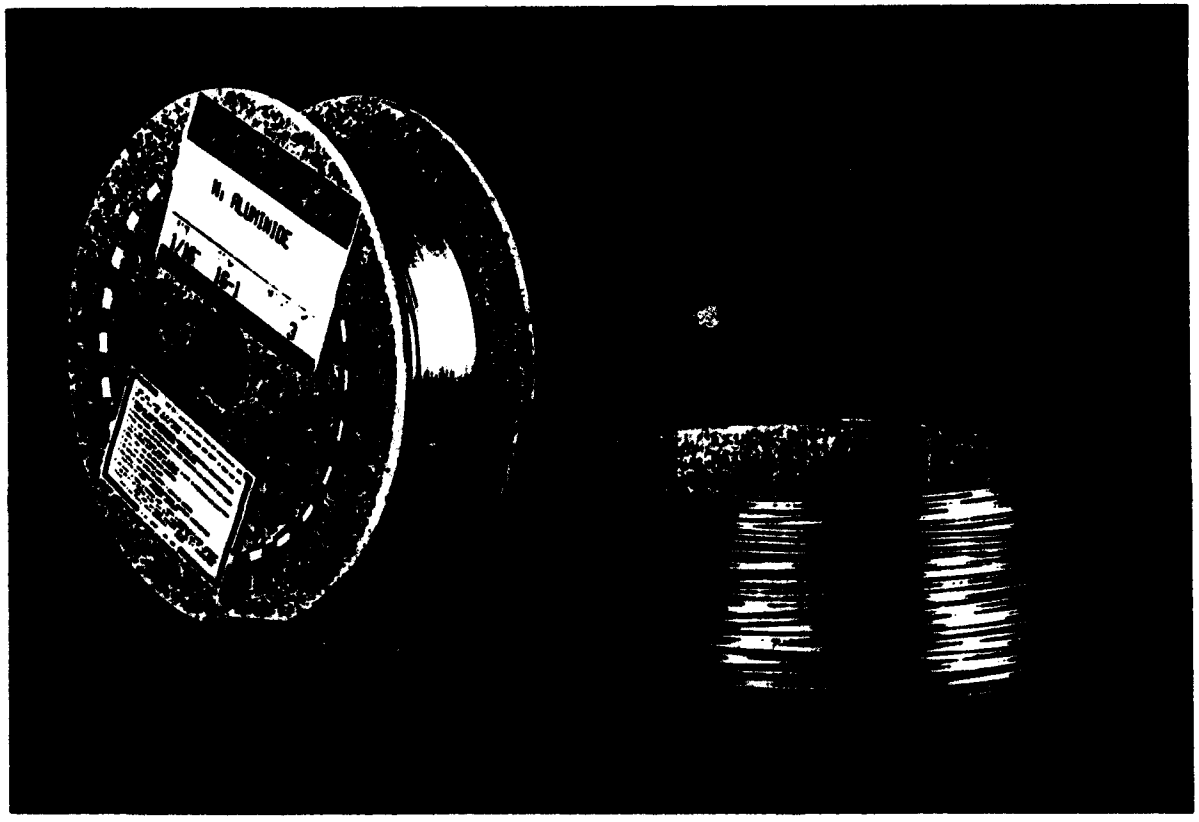
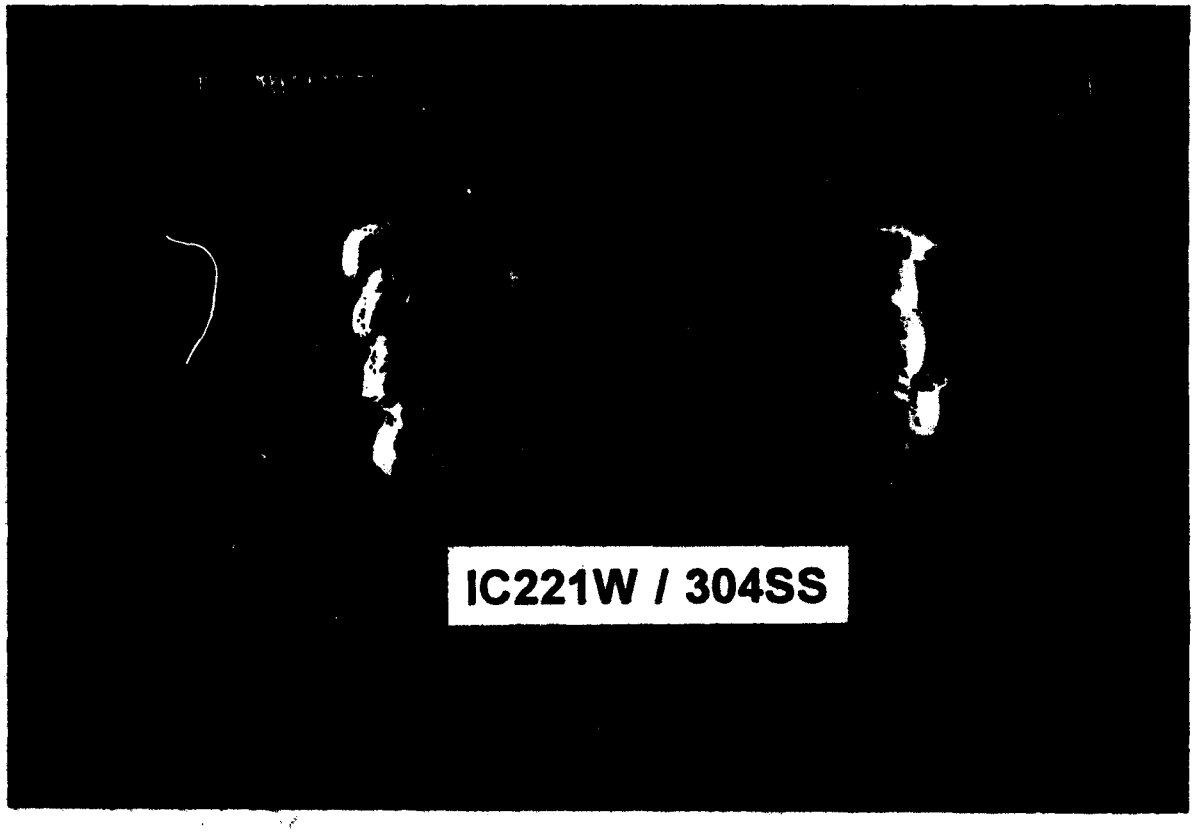
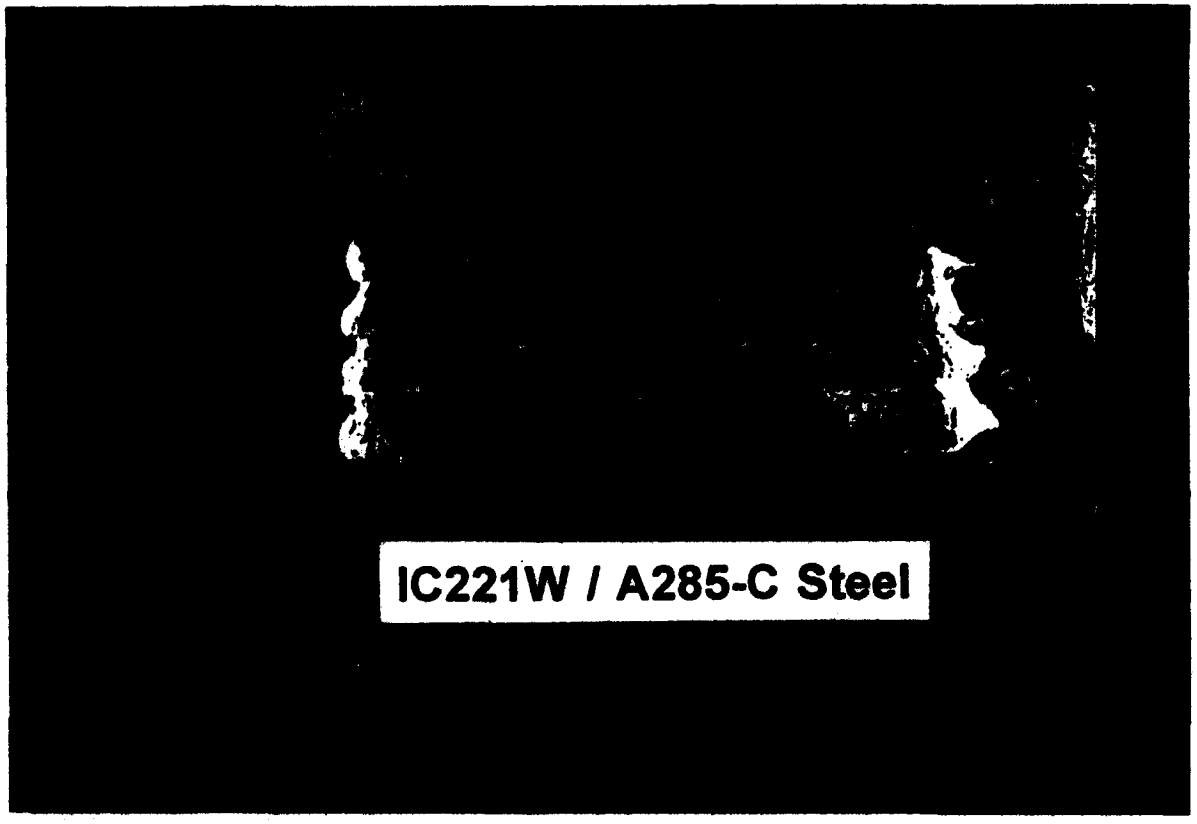
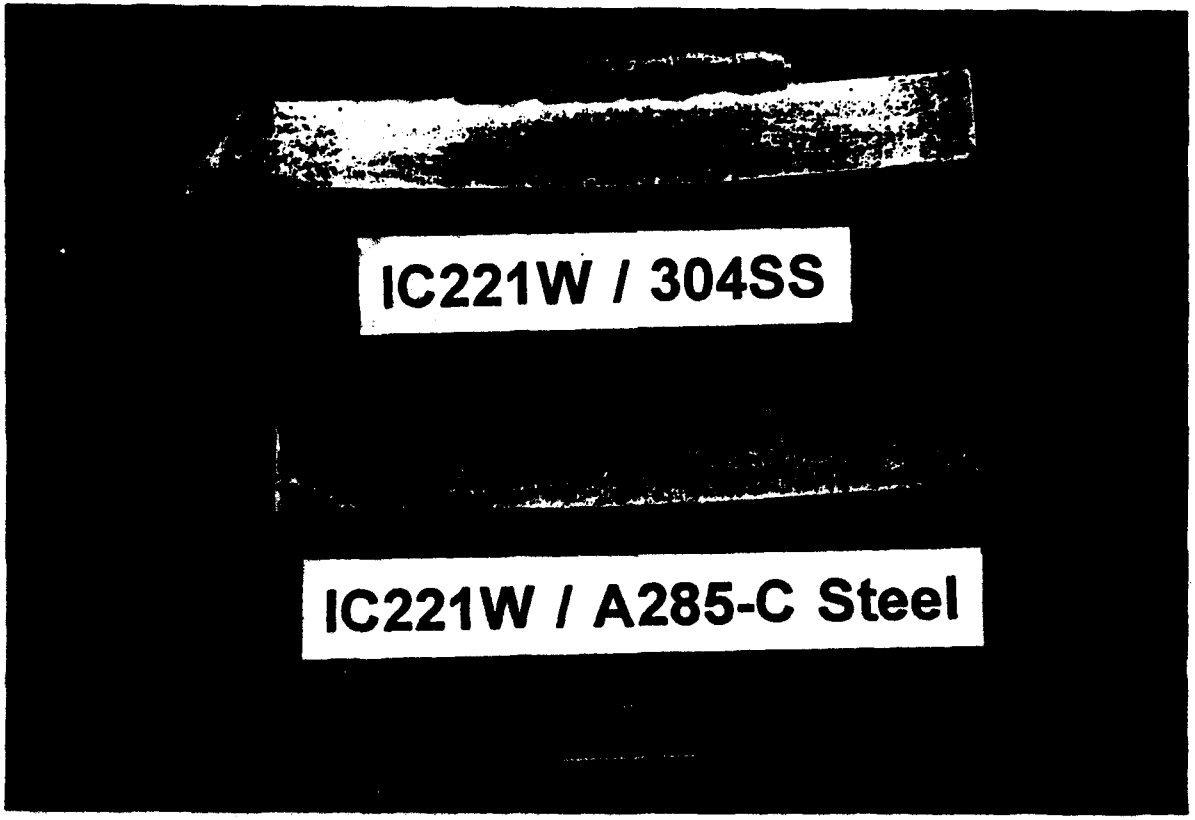
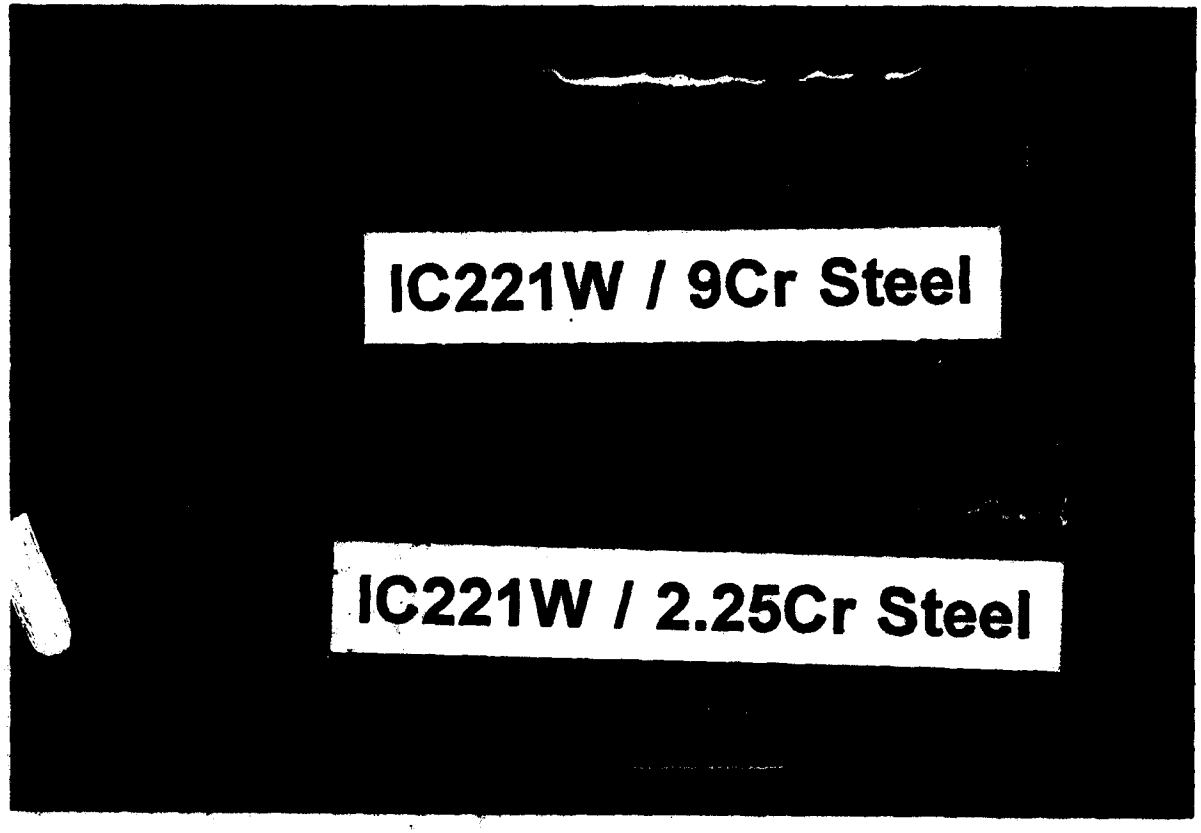



IC221W / 304SS


IC221W / A285-C Steel


IC221W / 304SS
IC221W / A285-C Steel


IC221W / 9Cr Steel
IC221W / 2.25Cr Steel

DEVELOPMENT AND COMMERCIALIZATION OF A NEW MATERIAL REQUIRE COMPREHENSIVE INFORMATION PACKAGE

- SPECIFICATIONS
- PROCESSING
- MECHANICAL PROPERTIES
- WELDMENT PROPERTIES
- CORROSION DATA
- PROTOTYPING
- COMPONENT FABRICATION
- MELTING AND CASTING
- PHYSICAL PROPERTIES
- WELDING
- HIGH-TEMPERATURE OXIDATION
- SPECIAL DATA
- COMPONENT FABRICATION
- SPECIFICATION APPROVAL BY ASTM
- BOILER AND PRESSURE VESSEL CODE BY ASME

NICKEL-ALUMINIDE LICENSEES

- AMETEK SPECIALTY METAL PRODUCTS DIVISION
- ARMCO RESEARCH & TECHNOLOGY
- CAST MASTERS
- CUMMINS ENGINE COMPANY, INC.
- HARRISON ALLOYS
- HOSKINS MANUFACTURING COMPANY
- METALLAMICS, INC.
- RAPID TECHNOLOGIES, INC.
- VALLEY-TODECO, INC.

MANUFACTURERS OF NICKEL-ALUMINIDES

- AMETEK SPECIALTY METAL PRODUCTS DIVISION
- THE BIMAC CORPORATION
- CAST MASTERS
- MANUFACTURING SCIENCES CORPORATION
- PCC AIRFOILS
- SANDUSKY INTERNATIONAL
- ALLOY ENGINEERING & CASTING COMPANY
- CANNON MUSKEGON CORPORATION
- ALLEGHENY LUDLUM CORPORATION
- TEXAS INSTRUMENTS
- XFORM INCORPORATED

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OAK RIDGE
NATIONAL
LABORATORY

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DATA PACKAGE ON Ni_3Al- AND NiAl-BASED ALLOYS DEVELOPED AT ORNL

Compiled by

VINOD K. SIKKA

January 20, 1993

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MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY
VKS020194-707

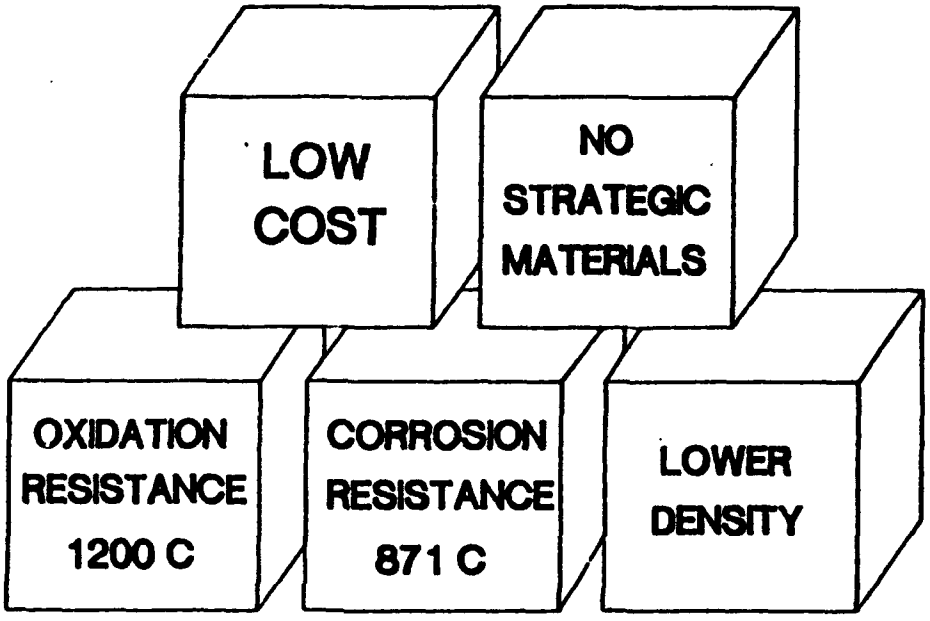
5.56

6. Technology and Applications of Fe_3Al Based Materials

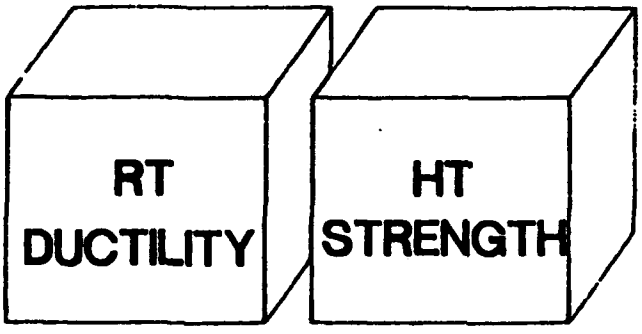
V. Sikka
Oak Ridge National Laboratory, USA

Fe_3Al

ADVANTAGES



DISADVANTAGES



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TECHNOLOGY AND APPLICATIONS OF Fe_3Al-BASED MATERIALS*

Vinod K. Sikka
Metals and Ceramics Division
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P.O. Box 2008
Oak Ridge, Tennessee 37831-6083

Presentation at
Defence Metallurgical Research Laboratory
Hyderabad, India

February 6, 1994

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

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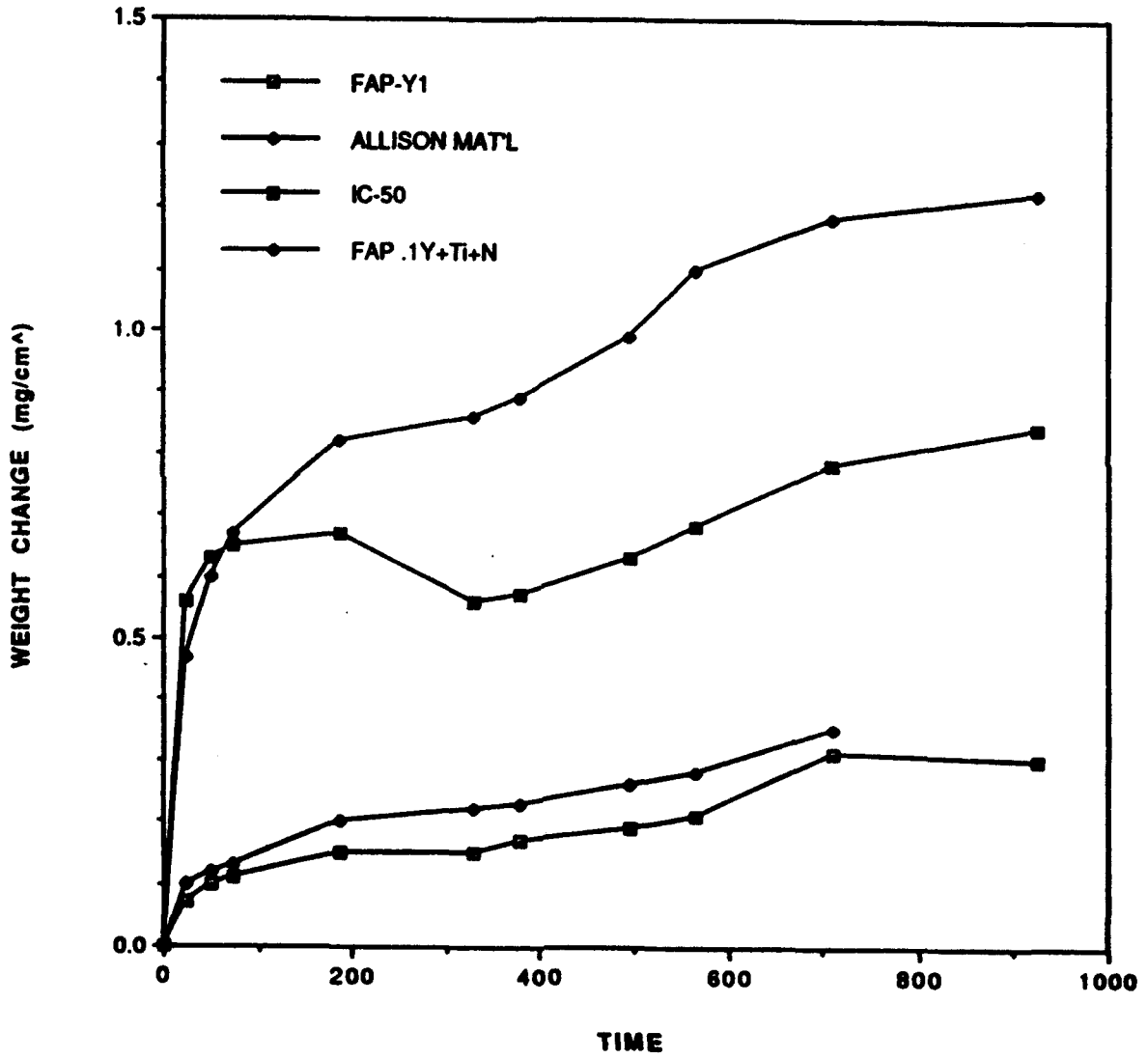
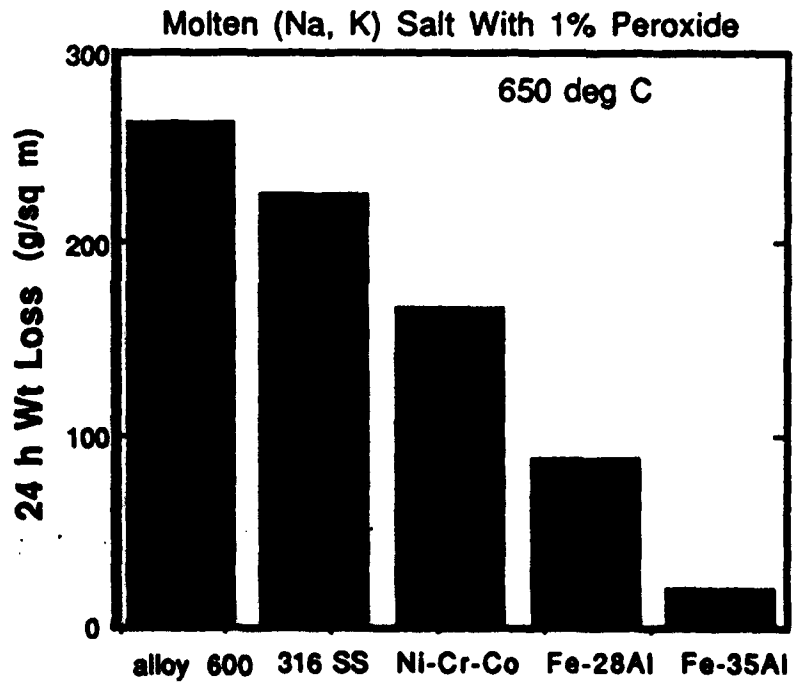
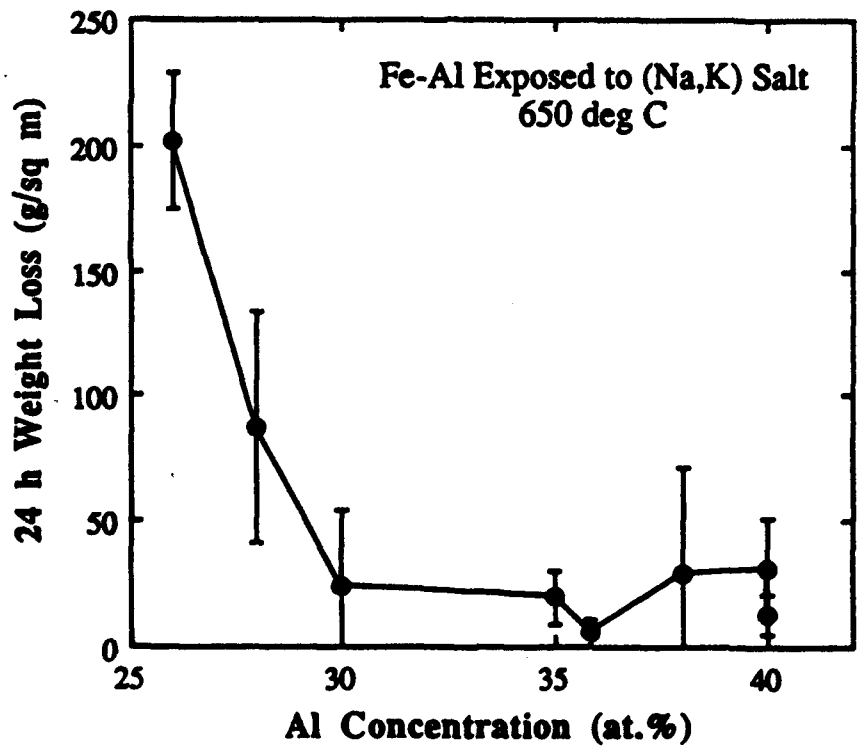
OXIDATION @ 946°C



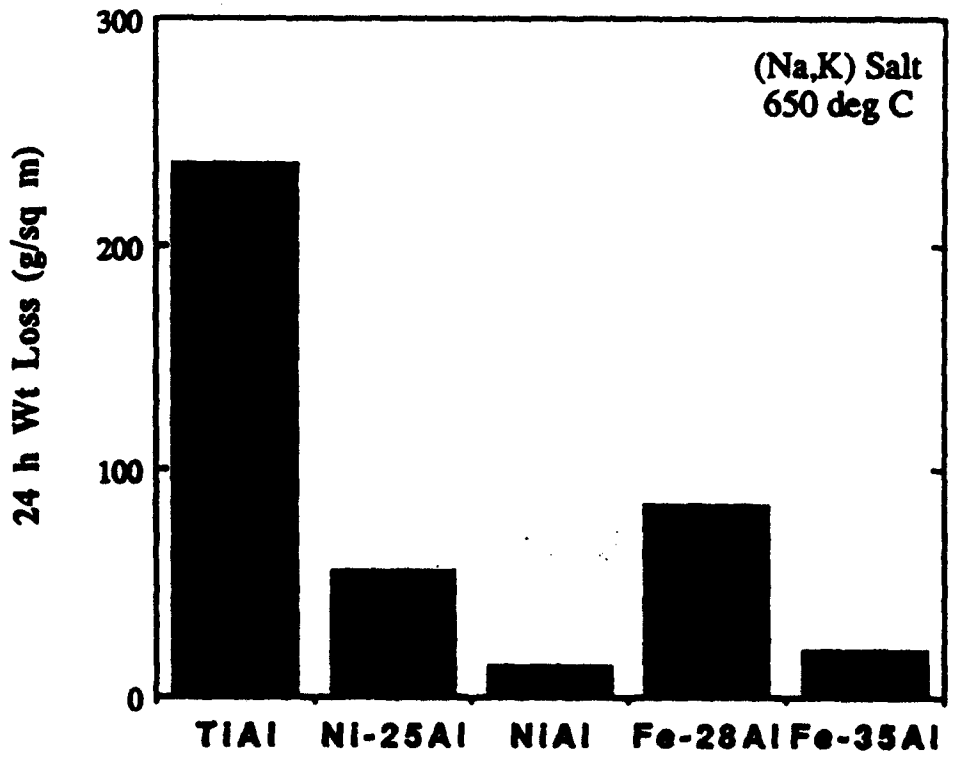
Encouraging Corrosion Results for FeAl in Molten Nitrate Salts Provided a Driving Force for Development of This Type of Aluminide



Fe-35.8Al Chosen As Base Binary Composition Based On Ductility, Corrosion Considerations



Fe-35Al Showed As Good Resistance As Any Of The Aluminides



IRON-ALUMINIDE APPLICATIONS

- AUTOMOTIVE
  - CATALYTIC CONVERTER SUBSTRATE
  - HANGERS FOR EXHAUST SYSTEM
  - REGENERATOR DISKS
  - EXHAUST MANIFOLDS

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IRON-ALUMINIDE APPLICATIONS (CONTINUED)

- ENERGY
  - HEATING ELEMENTS
    - STOVES
    - TOASTERS
    - DRYERS
  - SHIELDS FOR PROTECTING
    - SUPERHEATER TUBES
  - POROUS GAS METAL FILTERS
    - COAL GASIFICATION
  - SUPERHEATER TUBES
    - SULFIDATION ENVIRONMENT

IRON-ALUMINIDE APPLICATIONS (CONTINUED)

- FURNACES
  - WALKING BEAM
  - RETORTS
  - ROLLERS
  - FIXTURES

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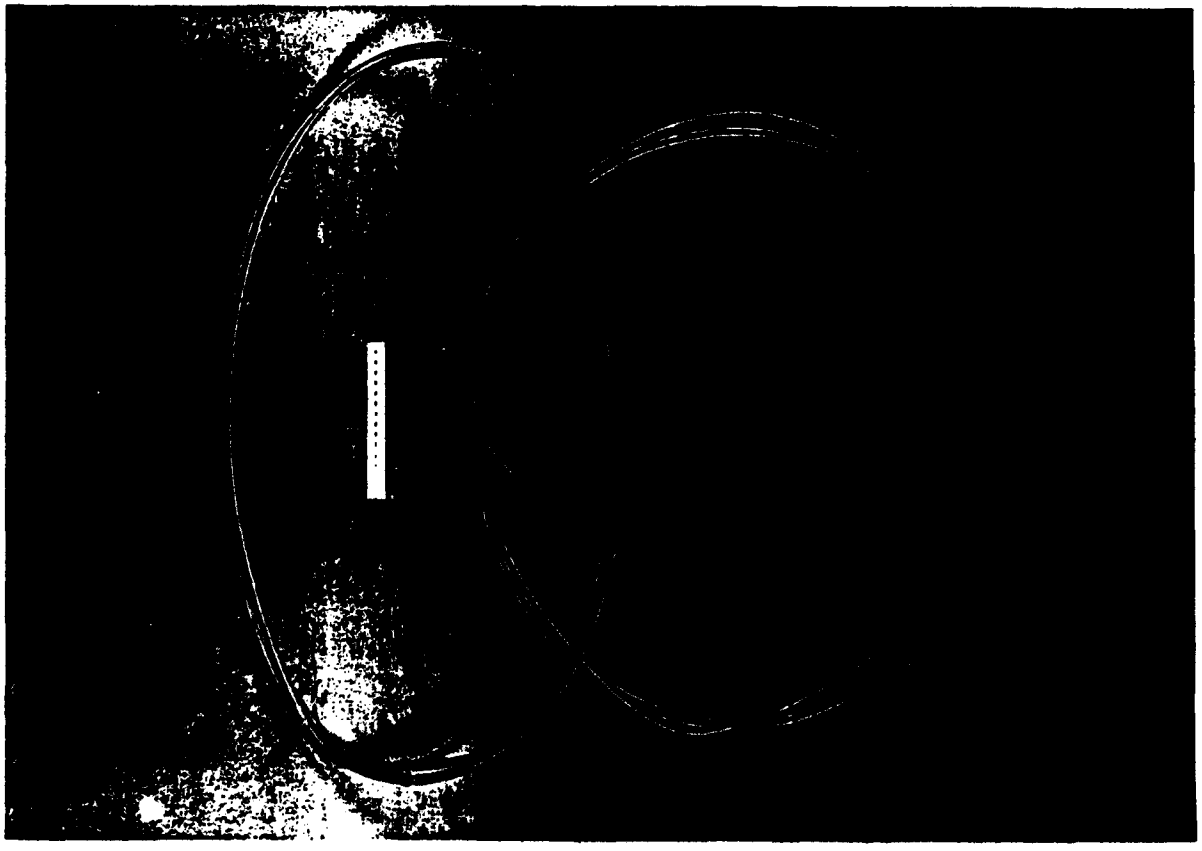
IRON-ALUMINIDE APPLICATIONS (CONTINUED)

- OTHER
  - KNIVES
  - WRAPPING WIRE FOR CERAMIC MOLDS
  - TUBES FOR CS_2 PRODUCTION



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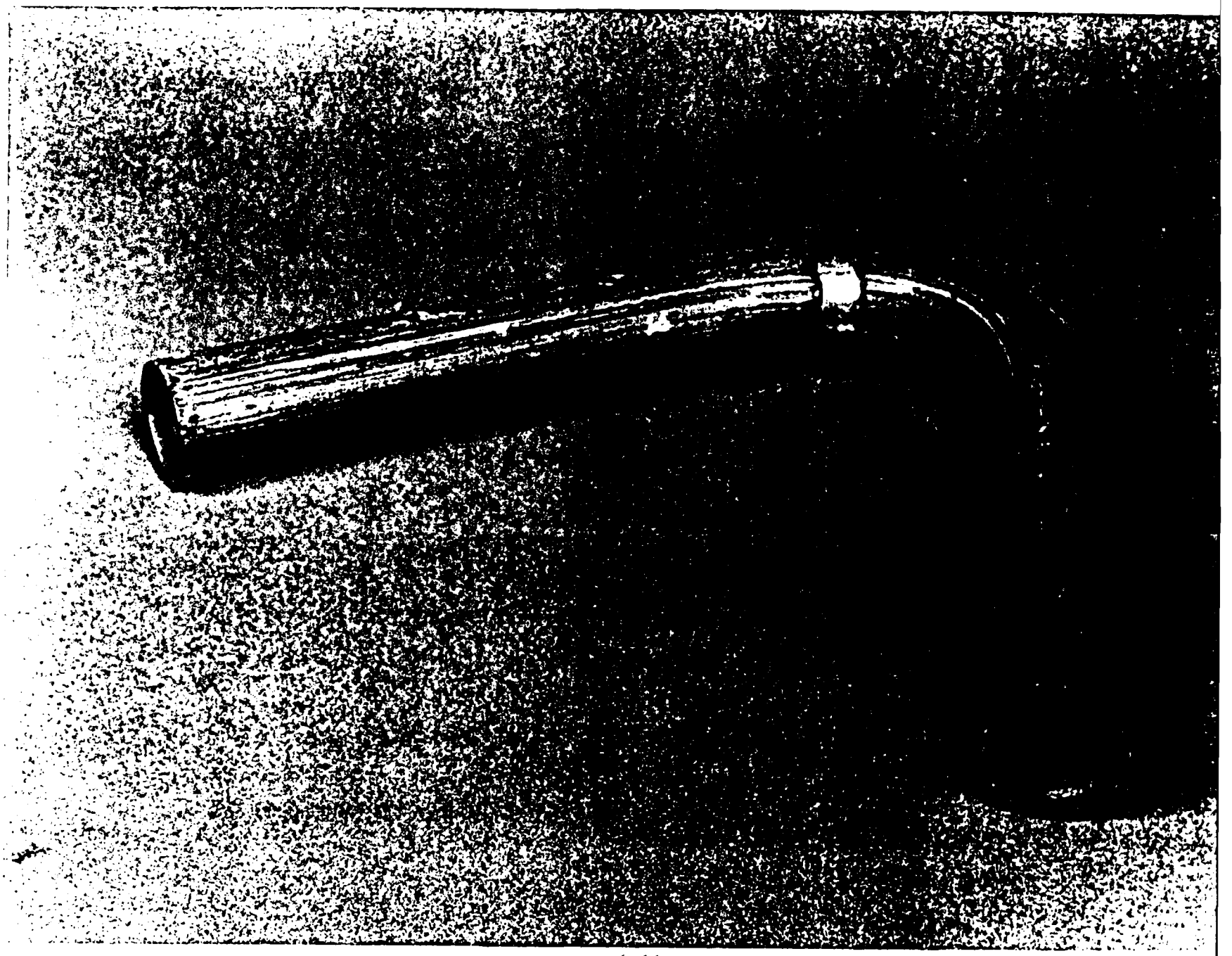

THE COMMERCIALIZATION OF IRON ALUMINIDES HAVE BEEN UNSUCCESSFUL IN THE PAST BECAUSE OF THE FOLLOWING REASONS:

- LOW ROOM-TEMPERATURE DUCTILITY
- RAPID DROP IN STRENGTH OVER 600°C

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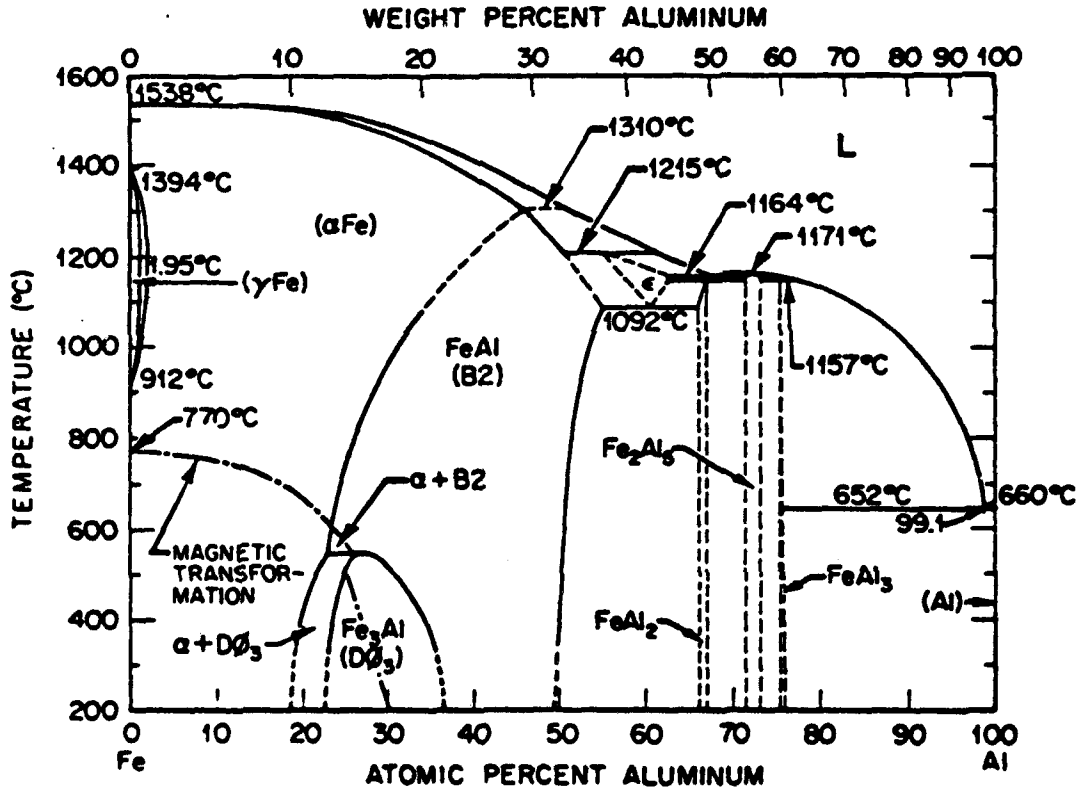
IRON-ALUMINUM PHASE DIAGRAM

ORNL-DWG 93-6472



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MAJOR DEVELOPMENT IN Fe_3Al-BASED ALLOY COMPOSITIONS HAVE RESULTED FROM THE RECOGNITION THAT THE ENVIRONMENTAL EFFECTS ARE THE PRIMARY CAUSE FOR THEIR POOR ROOM-TEMPERATURE DUCTILITY.

- THE ENVIRONMENTAL EMBRITTLEMENT INVOLVES THE FOLLOWING CHEMICAL REACTION:

$$2\,Al + 3H_2O \rightarrow Al_2O_3 + 6\,H\ .$$

- THE EMBRITTLING EFFECT OF ABOVE REACTION CAN BE MINIMIZED THROUGH:
  - STOPPING THE GENERATION OF HYDROGEN
  - REDUCING ITS EMBRITTLEMENT EFFECT

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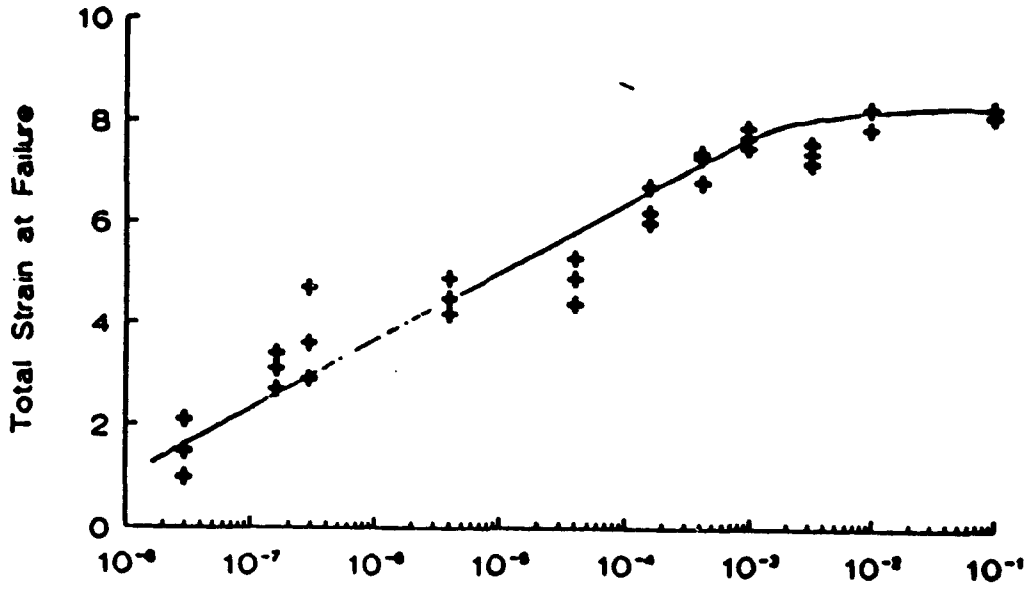
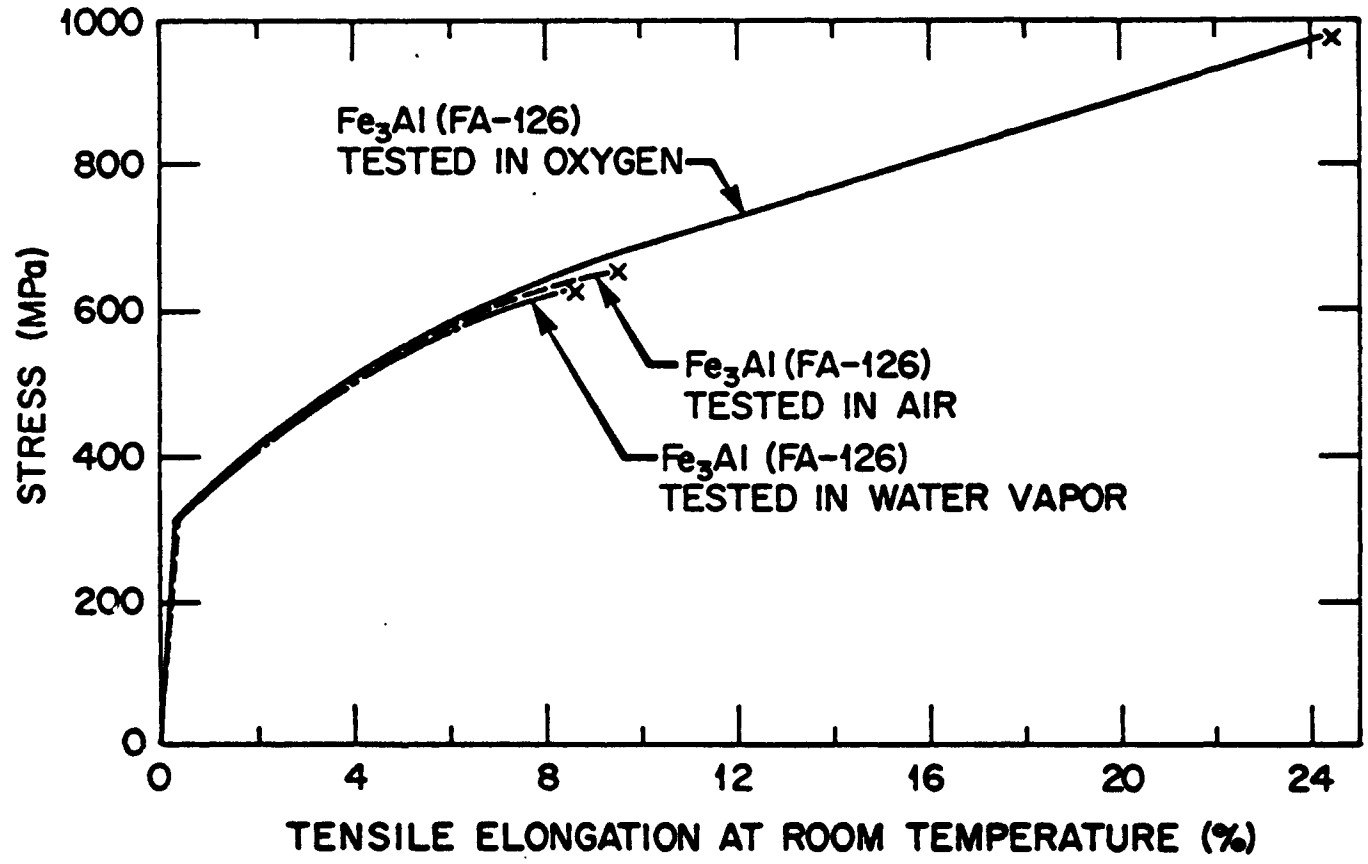


Figure 9. Influence of strain rate on ductility of Fe-24a%Al tested in air (Scott et al, 1992).

WATER VAPOR HAS A STRONG EFFECT ON THE ROOM-TEMPERATURE DUCTILITY OF Fe_3Al ALLOY

ORNL-DWG 89-14389A



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CONTROL OF HYDROGEN EMBRITTLEMENT THROUGH THE TEST ENVIRONMENT

Effect of Test Environment on Room-Temperature (RT) Tensile Properties of Binary Fe_3Al (28% Al)[a]

Test Environment	Elongation (%)	Strength (MPa)	
		0.2% Yield	Ultimate Tensile
Air	3.7	279	514
Vacuum (10^{-4} Pa)	12.4	316	813
Oxygen[b]	11.7	298	888
H_2O vapor[c]	2.1	322	439

[a]Specimens were annealed at 850°C for 1 h followed by a five-day treatment at 500°C to stabilize $D0_3$ at RT. All of the tests were at a strain rate of 3.3×10^{-3} s^{-1}.

[b]Chamber was evacuated to 10^{-4} Pa, then oxygen was leaked in to a partial pressure of 6.7×10^4 Pa.

[c]Air saturated with water vapor was leaked into the vacuum chamber.

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CONTROL OF HYDROGEN EMBRITTLEMENT THROUGH THE PROTECTION OF TEST SPECIMEN SURFACE

Effect of Oil Film on Room-Temperature Tensile Properties of a Ternary Fe-28% Al-2% Cr Alloy

Surface Treatment[a]	Elongation (%)	Strength (MPa)	
		0.2% Yield	Ultimate Tensile
Bare	6.4	537	810
Coated with oil[b]	17.8	519	1018

[a]Tensile tests were conducted in air at a strain rate of $3.3 \times 10\text{-}3\ s^{-1}$.
[b]Mineral oil.

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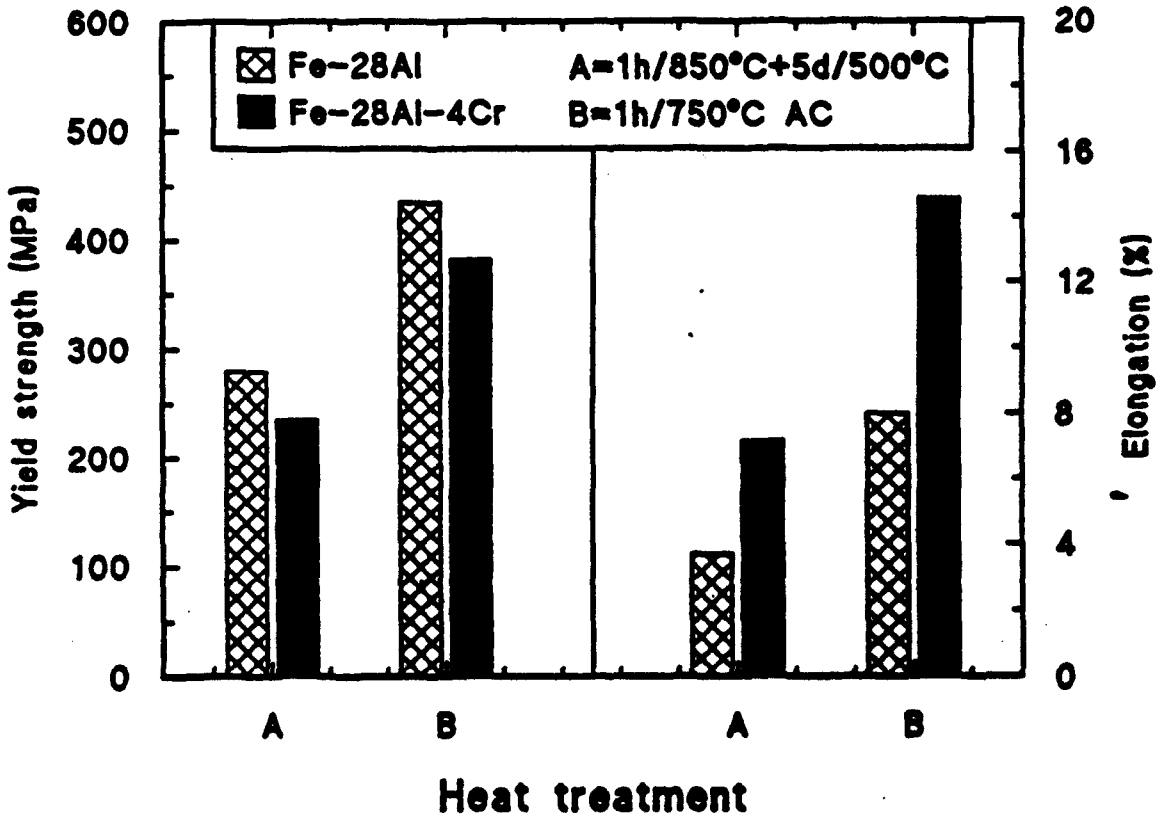
EFFECT OF CHROMIUM ADDITION IN IMPROVING ROOM-TEMPERATURE DUCTILITY OF Fe-28 AT. % Al ALLOY IN DO_3 AND B2 CONDITIONS



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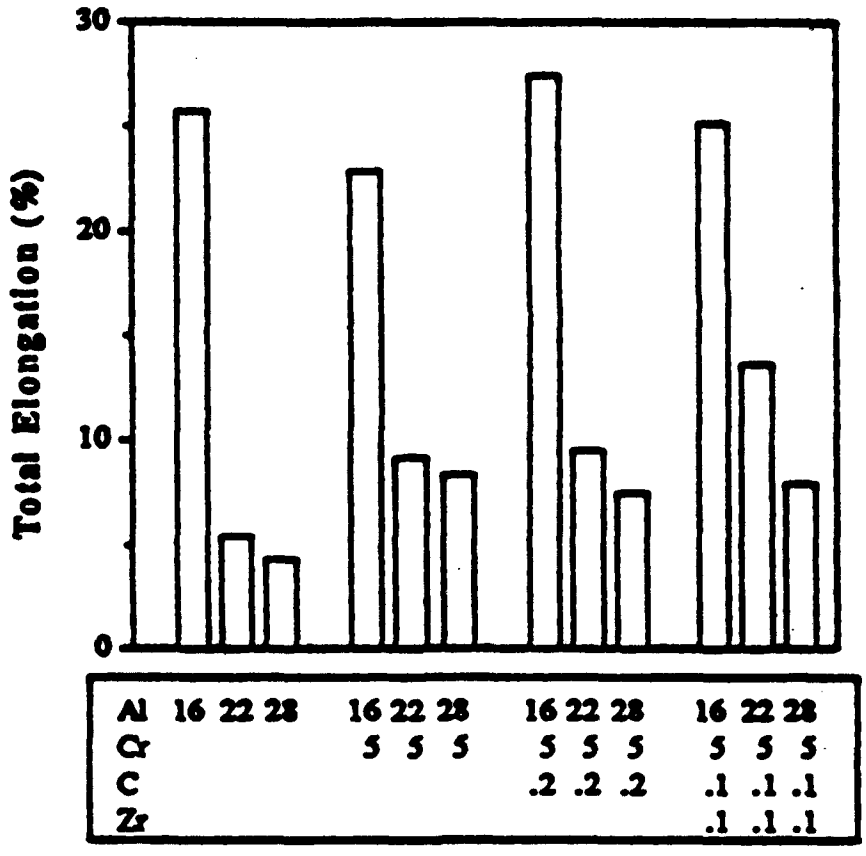
EFFECT OF ADDITIONAL ELEMENTS IN IMPROVING ROOM-TEMPERATURE DUCTILITY OF Fe-Al ALLOYS WITH ALUMINUM IN THE RANGE OF 16 TO 28 AT. %



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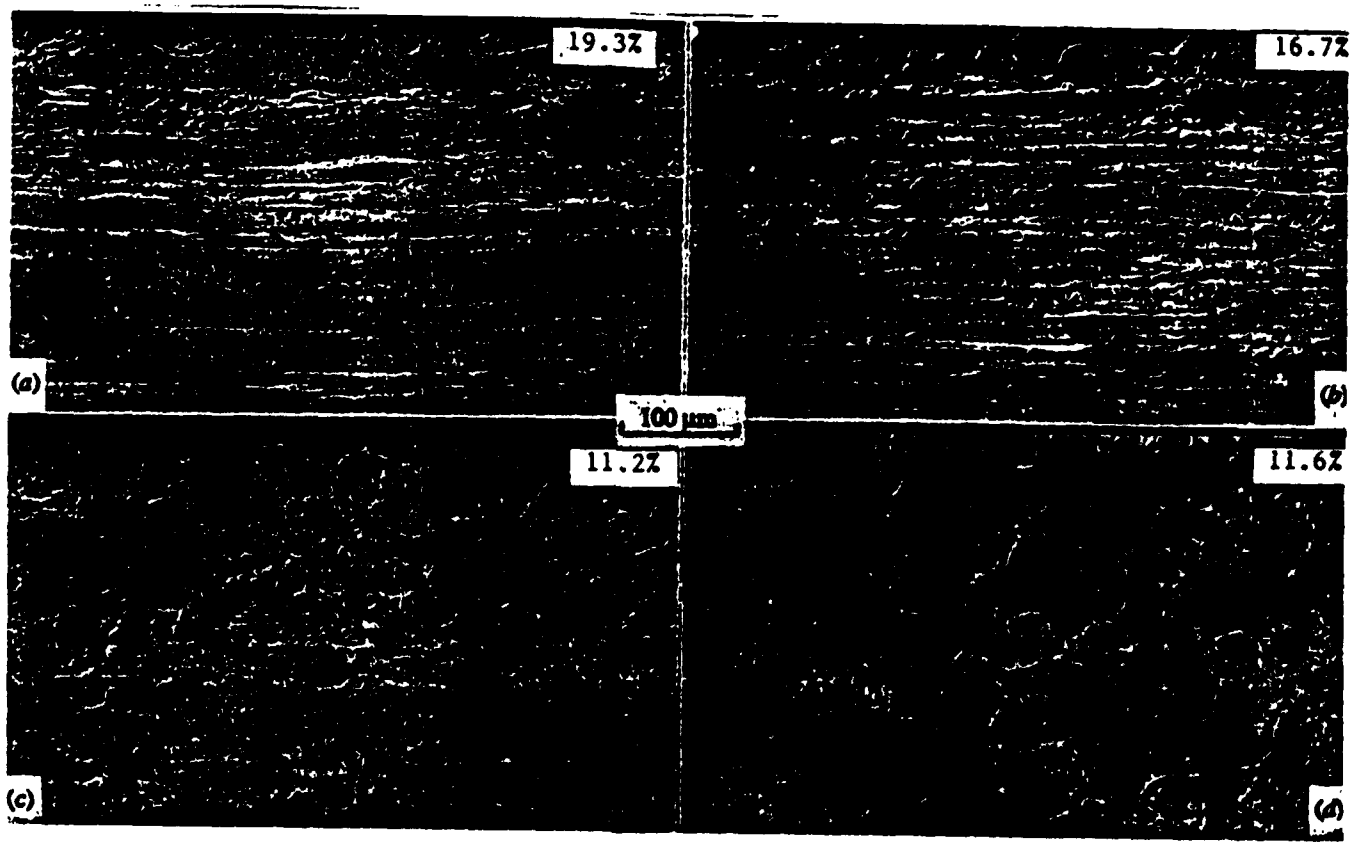
OPTICAL MICROGRAPHS OF THE OIL-QUENCHED, Fe_3Al-BASED ALLOY ANNEALED FOR 1 H AT: (a) 700°C, (b) 750°C, (c) 800°C, AND (d) 900°C.



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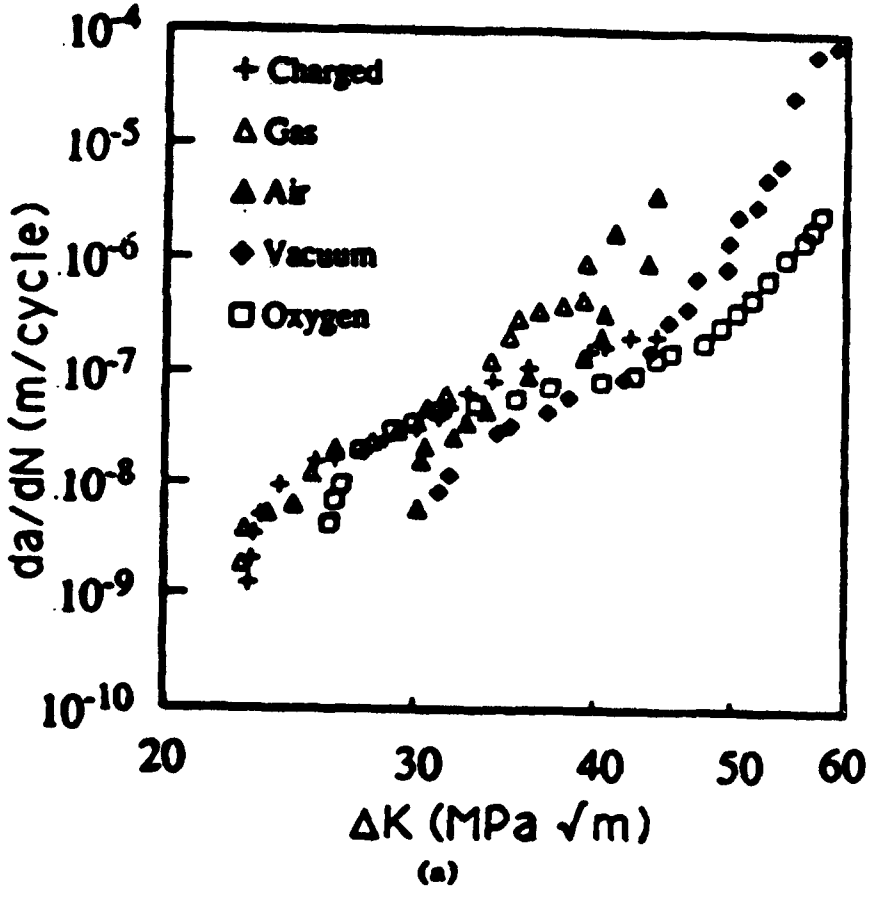
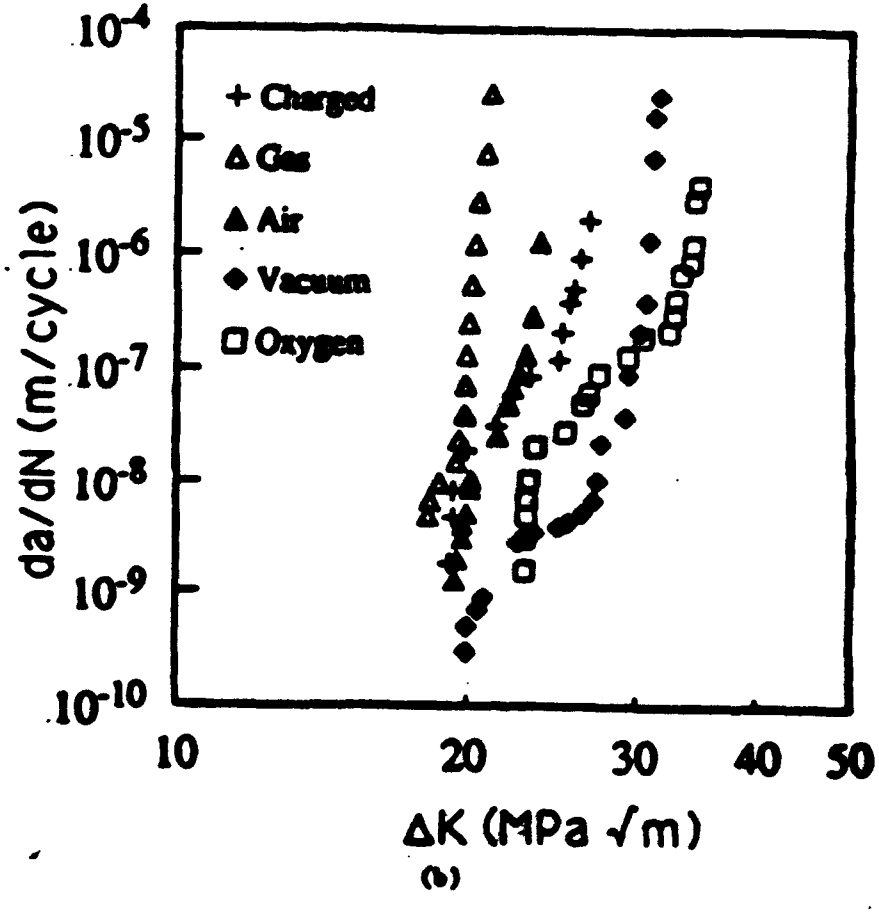
FATIGUE CRACK GROWTH OF Fe_3Al ALLOY FA-129 AT ROOM TEMPERATURE: (a) B2 CONDITION; AND (b) DO_3 CONDITION (CASTAGNA AND STOLOFF, 1992).





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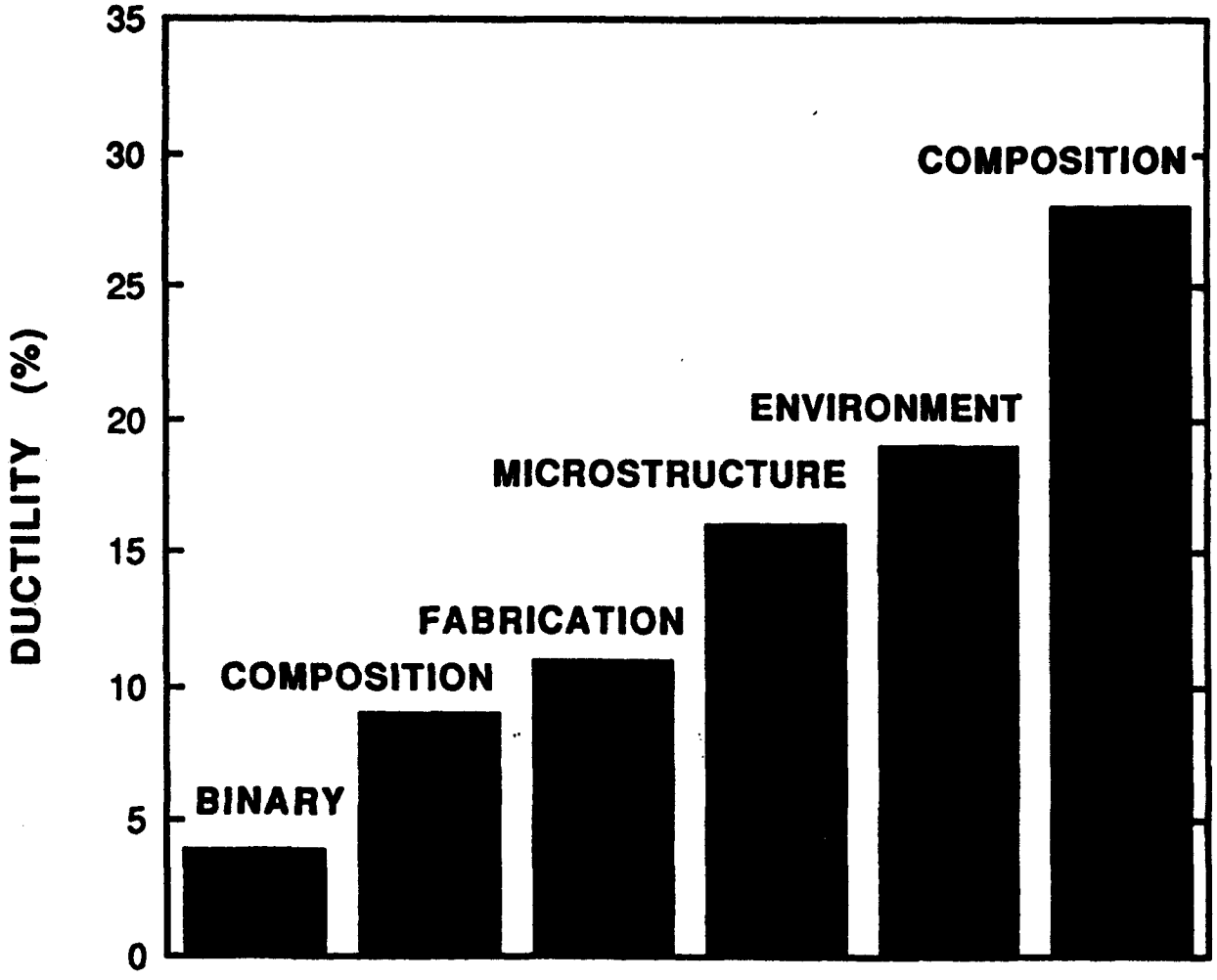
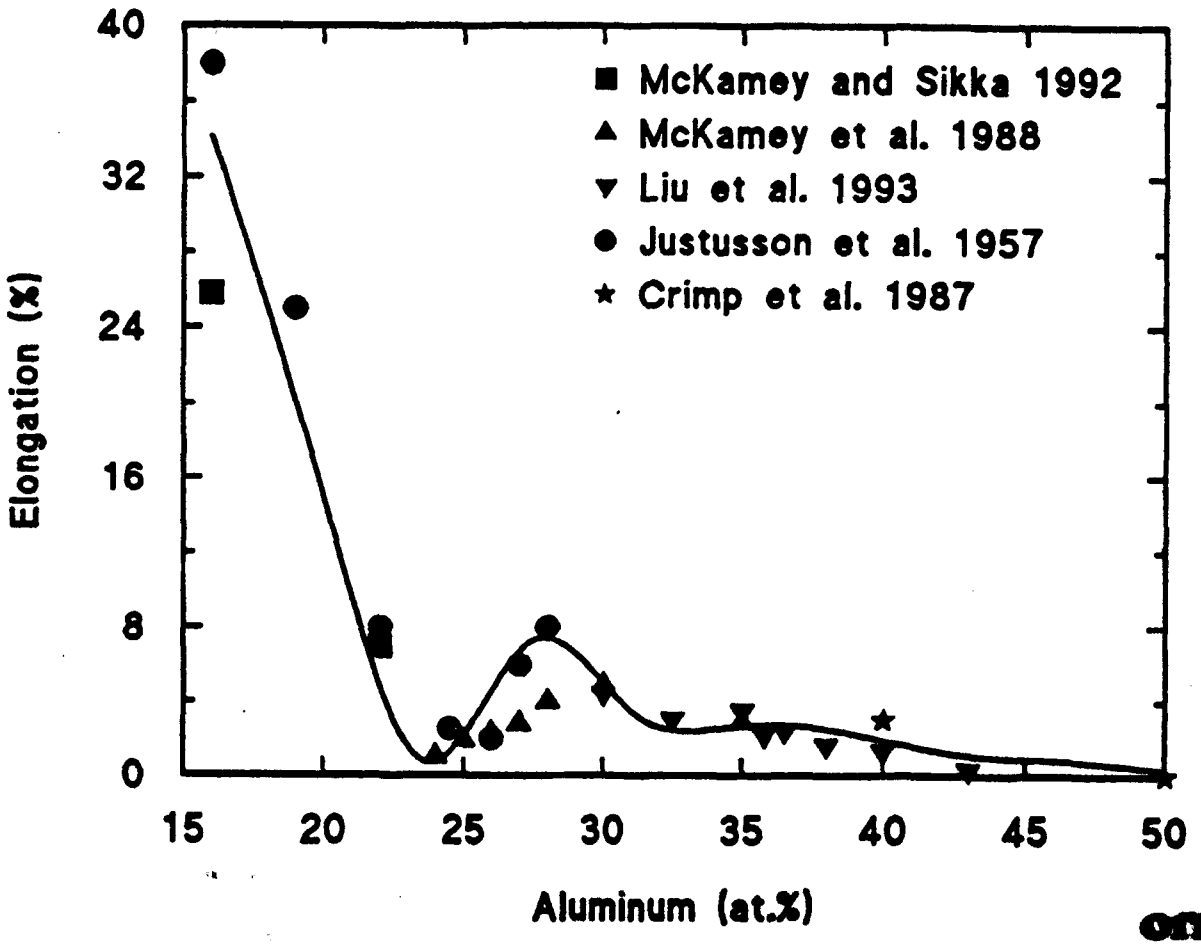
DUCTILITY IMPROVEMENT OF IRON ALUMINIDE



EFFECT OF ALUMINUM CONTENT (15 TO 50 AT. %) ON ROOM-TEMPERATURE DUCTILITY OF Fe-Al ALLOYS (ORNL LITERATURE DATA)



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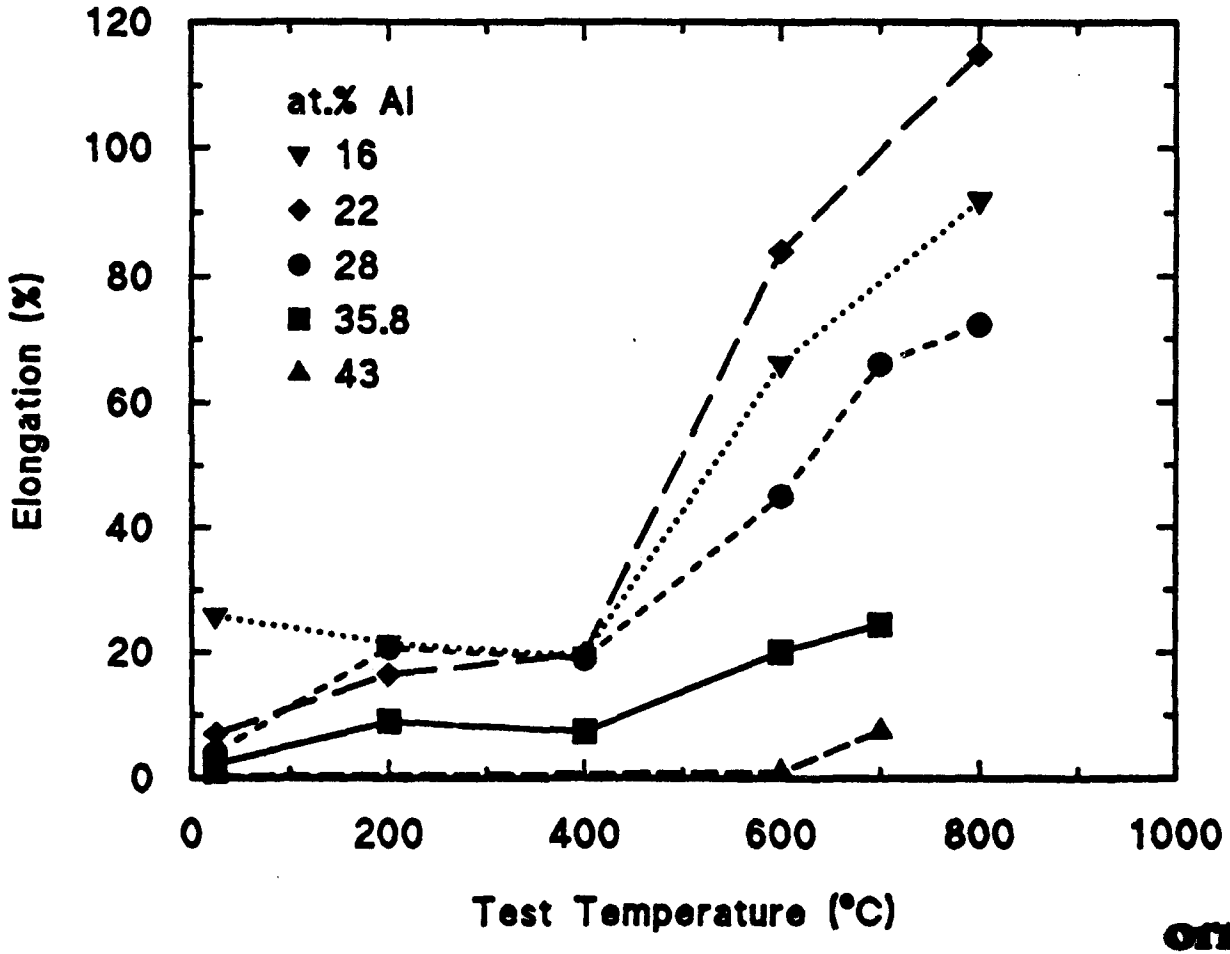
EFFECT OF ALUMINUM CONTENT (15 TO 50 AT. %) ON DUCTILITY AS A FUNCTION OF Fe-Al ALLOYS



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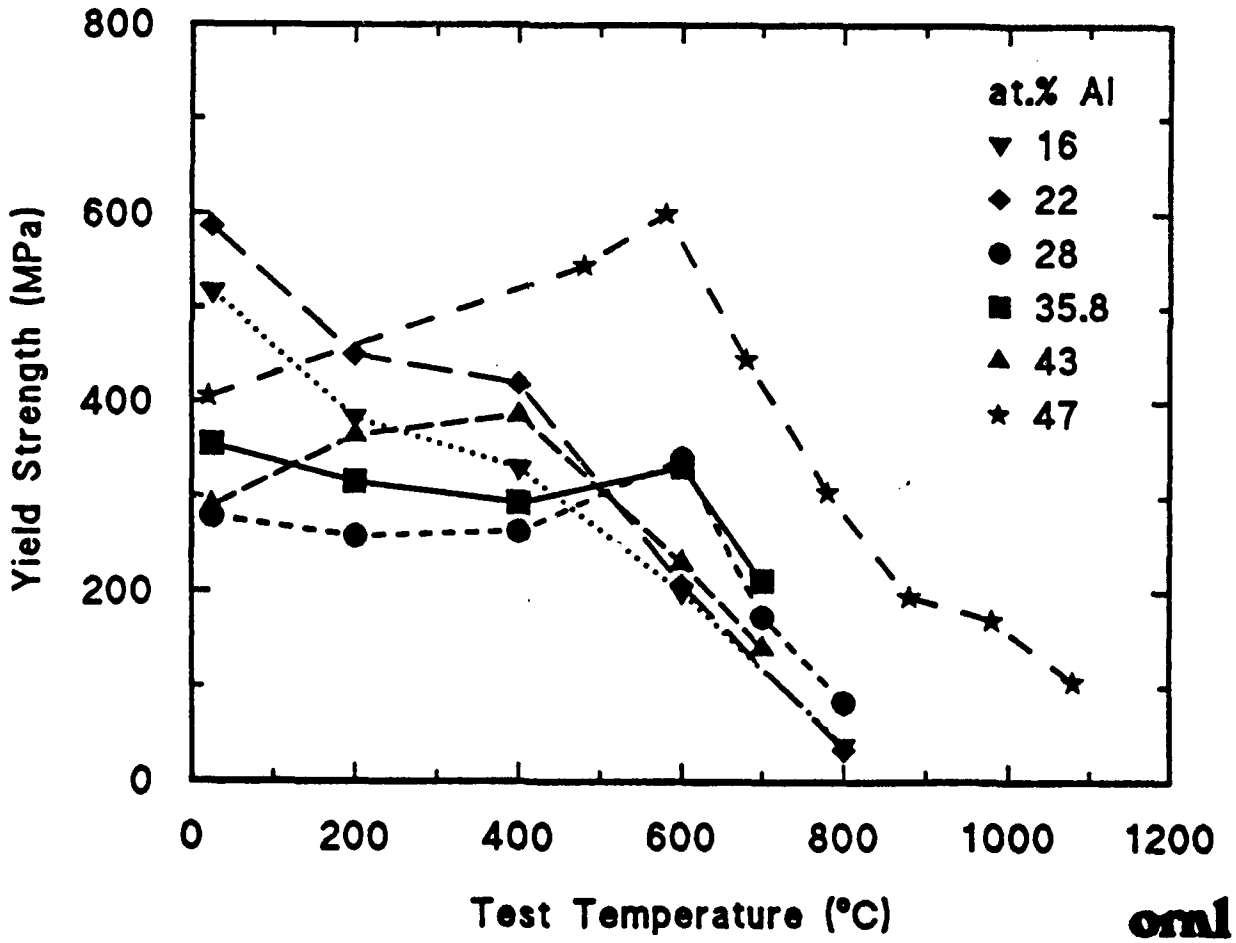
EFFECT OF ALUMINUM CONTENT (15 TO 50 AT. %) ON YIELD STRENGTH AS A FUNCTION OF TEMPERATURE OF Fe-Al ALLOYS



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RECOVERY OF VARIOUS ELEMENTS DURING AIR-INDUCTION MELTING OF 7-kg IRON-ALUMINIDE HEATS

Element	Alloy 1		Alloy 2		Alloy 3		Alloy 4	
	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)
C	--	--	--	--	0.04	250.00[a]	--	--
Cr	2.157	98.75	5.46	91.03	5.46	95.24	2.194	95.72
Mo	0.995	100.00	--	--	--	--	--	--
Nb	1.542	100.00	--	--	0.21	100.00	--	--
Al	15.672	98.86	15.88	96.73	15.88	97.54	15.932	96.67
B	0.011	81.82	0.01	80.00	--	--	0.011	27.27
Zr	0.189	100.00	0.19	100.00	--	--	--	--
Fe	*b*	--	*b*	--	*b*	--	*b*	--

[a]Recovery of greater than 100% indicates pickup of carbon from external sources. For example, a graphite rod was used for stirring the liquid metal, and a small fraction of the graphite was probably dissolved in the metal.

[b]Balance (100 minus total of all other elements).

MELTING REQUIREMENTS
(Continued)

- THE HIGH CONTENT OF Fe_3Al ALLOYS PROVIDES EXCELLENT PROTECTION OF THE MELT THROUGH THE FORMATION OF THIN CONTINUOUS OXIDE SCALE.
- TYPICAL OXYGEN AND NITROGEN LEVELS IN MELTS PREPARED BY DIFFERENT METHODS ARE VERY SMALL.

Effect of Melting Practice on Range of Oxygen and Nitrogen Content Observed in Fe_3Al-Based Alloys

Melting Practice	Weight Percent	
	Oxygen	Nitrogen
Air Induction	0.0017 to 0.0040	0.0005 to 0.008
Vacuum Induction	<0.0007 to 0.0020	0.0001 to 0.0010
Vacuum-Arc Remelting	0.0010	0.0003
Electroslag Remelting	<0.0010 to 0.0014	0.0002

GROSS POROSITY OBSERVED IN A 230-kg AIR-MELTED INGOT OF IRON ALUMINIDE

VKS013194-684

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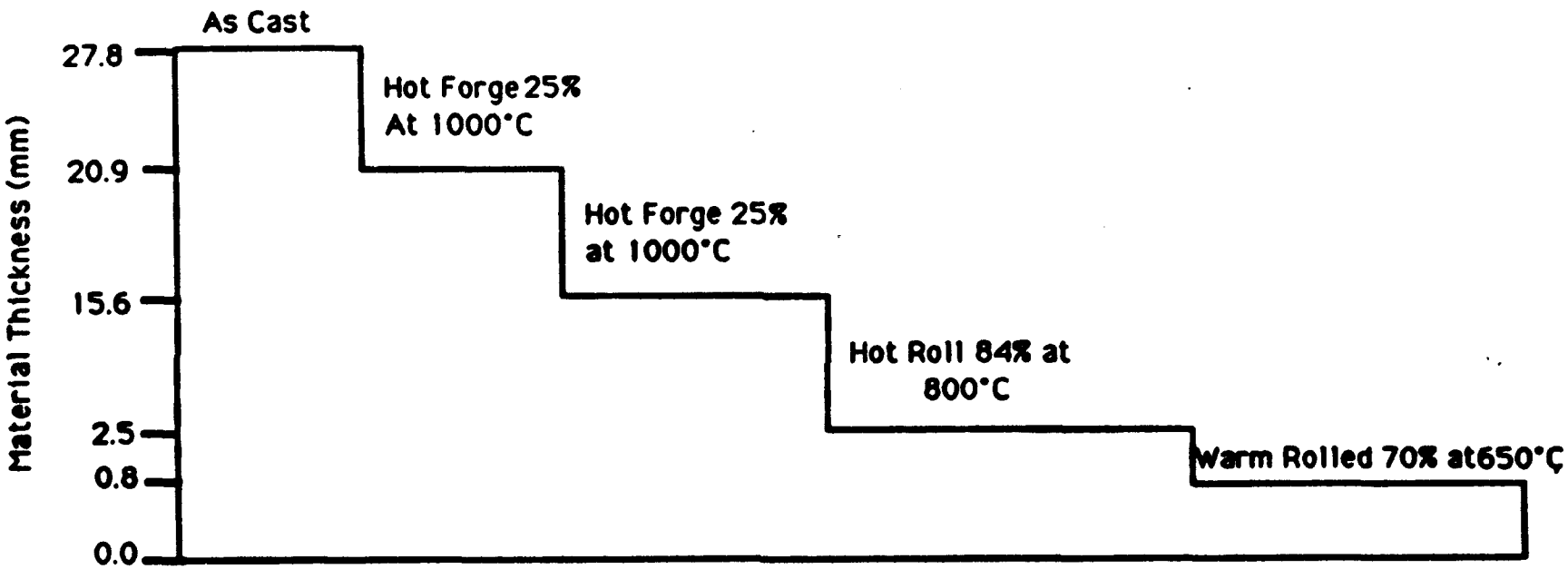
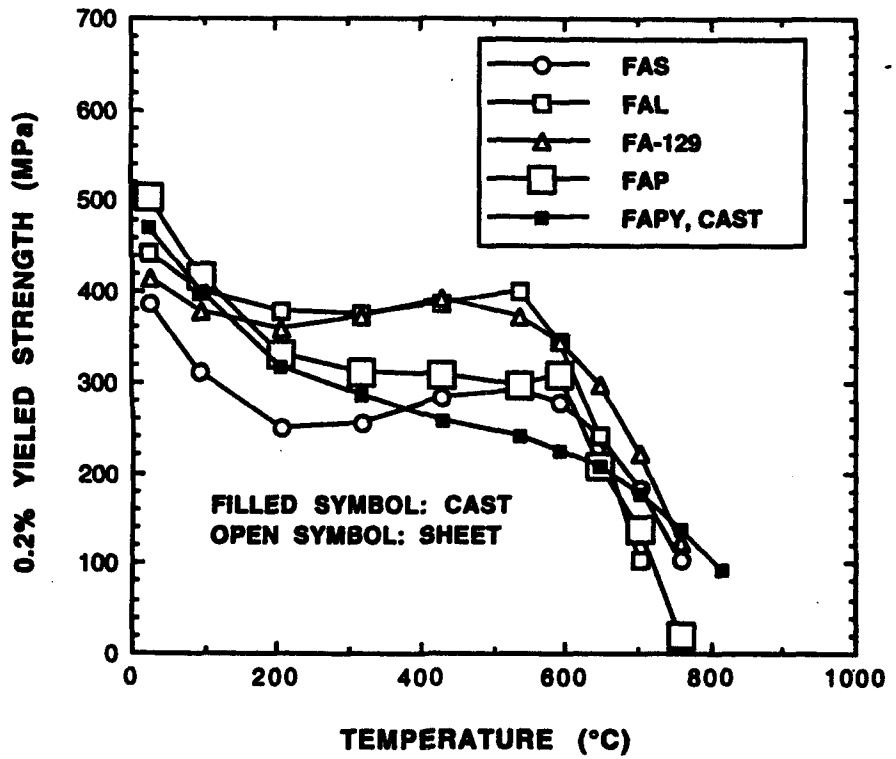


Fig. 4. Fabrication diagram for FA-129 alloy.

MECHANICAL PROPERTIES

- YIELD STRENGTH PLOTS FOR ORNL-DEVELOPED ALLOYS



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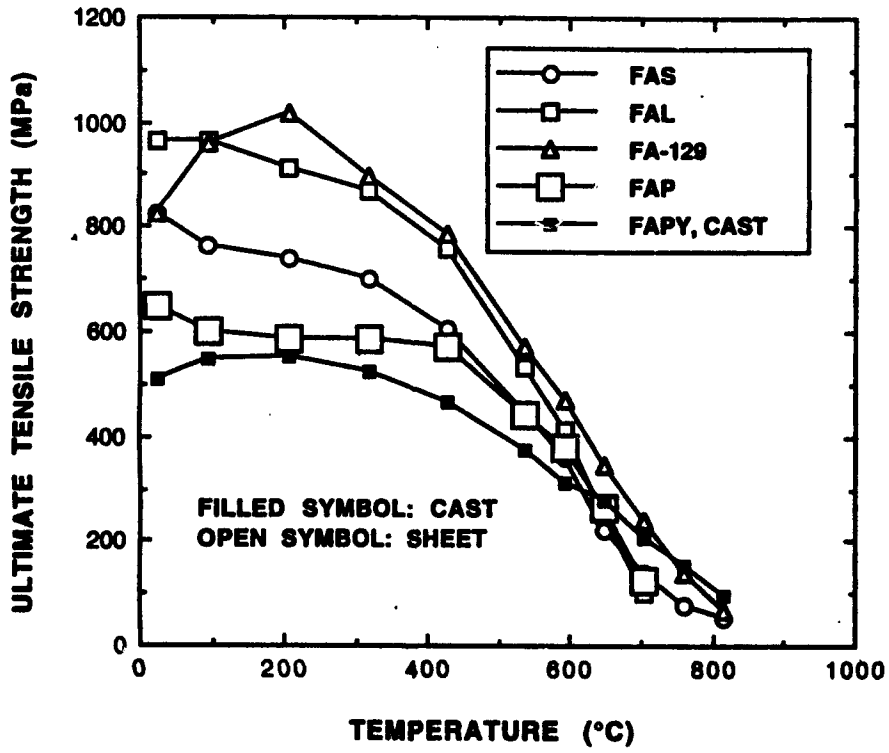
MECHANICAL PROPERTIES
(Continued)

- ULTIMATE TENSILE STRENGTH PLOTS FOR ORNL-DEVELOPED ALLOYS



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COMPOSITION OF LOW-ALUMINUM CONTENT IRON-ALUMINUM ALLOY FAPY IS COMPARED WITH DUCTILE Fe_3Al COMPOSITIONS.

ELEMENT	ALLOY							
	FAS[a]		FAL[b]		FA-129[c]		FAPY[d]	
	WT %	AT %	WT %	AT%	WT %	AT %	WT %	AT %
Al	15.9	28.08	15.9	28.03	15.9	28.08	8.46	16.12
Cr	2.20	2.02	5.5	5.03	5.5	5.04	5.50	5.44
B	0.01	.04	0.01	.04	--	--	--	--
Zr	--	--	0.15	.08	--	--	0.20	.11
Nb	--	--	--	--	1.0	.51	--	--
C	--	--	--	--	0.05	.20	0.03	.13
Mo	--	--	--	--	--	--	2.00	1.07
Y	--	--	--	--	--	--	0.10	.06
Fe	Balance	69.86	Balance	66.81	Balance	66.17	Balance	77.07

[a]Sulfidation-resistant alloy
[b]High room-temperature tensile ductility
[c]High-temperature strength with good room-temperature ductility
[d]Very high room-temperature ductility

VKS050693-333

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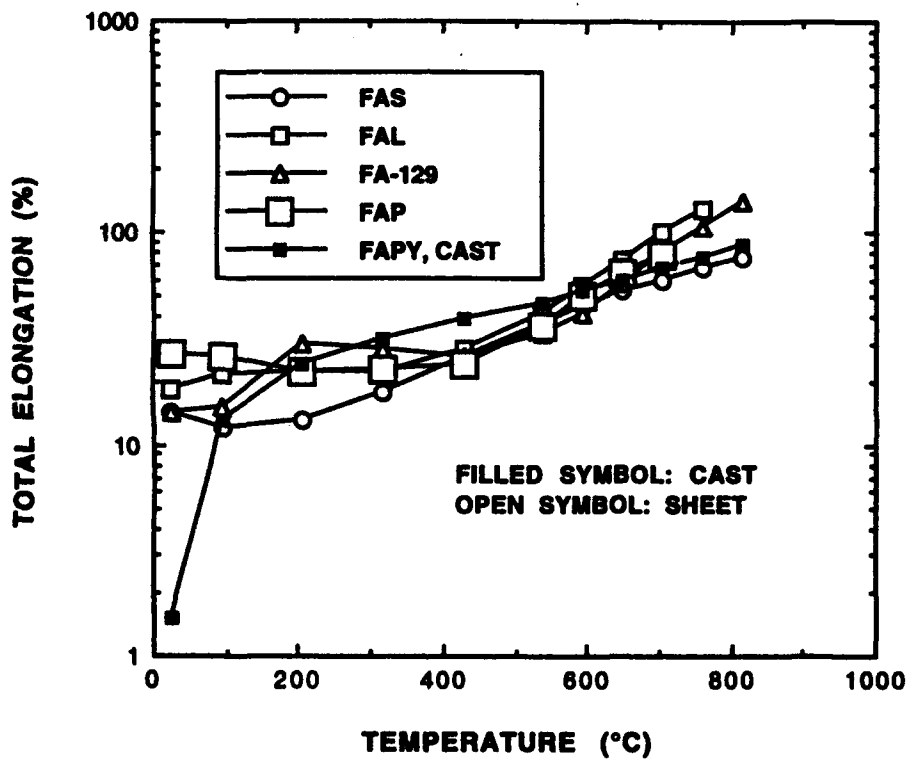
MECHANICAL PROPERTIES
(Continued)

- TOTAL ELOGATION PLOTS FOR ORNL-DEVELOPED ALLOYS

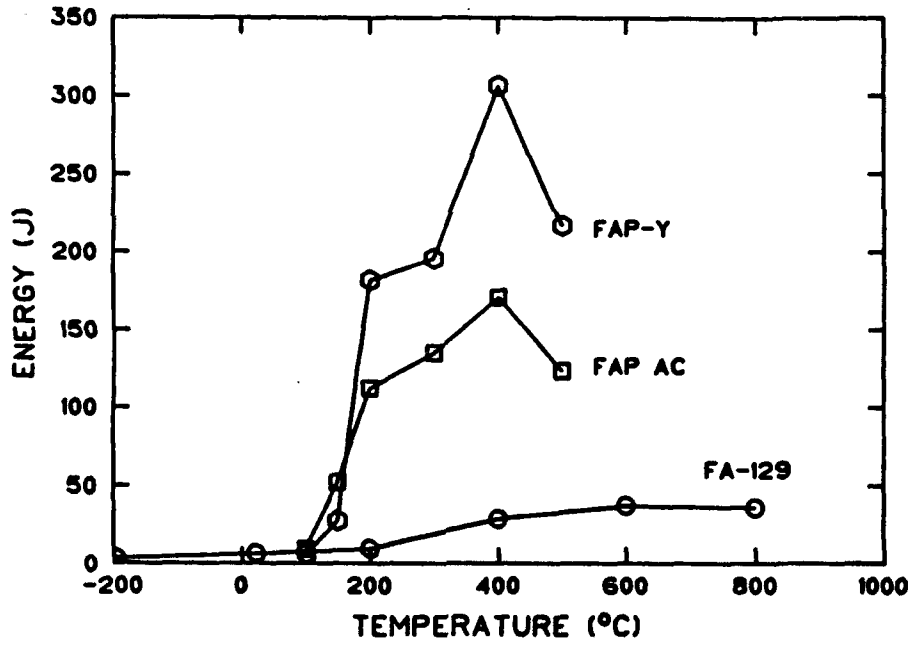


VKS092293-522

ornl

MECHANICAL PROPERTIES
(Continued)

- CHARPY-IMPACT PROPERTIES OF Fe_3Al AND Fe-16 AT. % Al ALLOYS

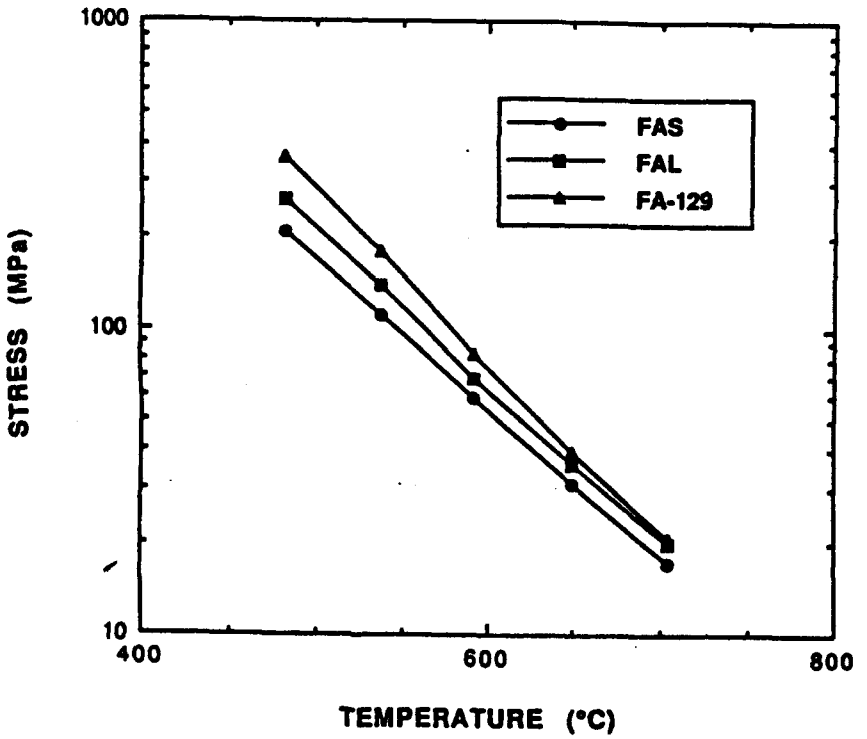


VKS092293-524

ornl

MECHANICAL PROPERTIES
(Continued)

- COMPARISON OF 1000-H CREEP RUPTURE PROPERTIES OF THOSE Fe_3Al-BASED ALLOYS IN THE TEMPERATURE RANGE OF 450 TO 700°C



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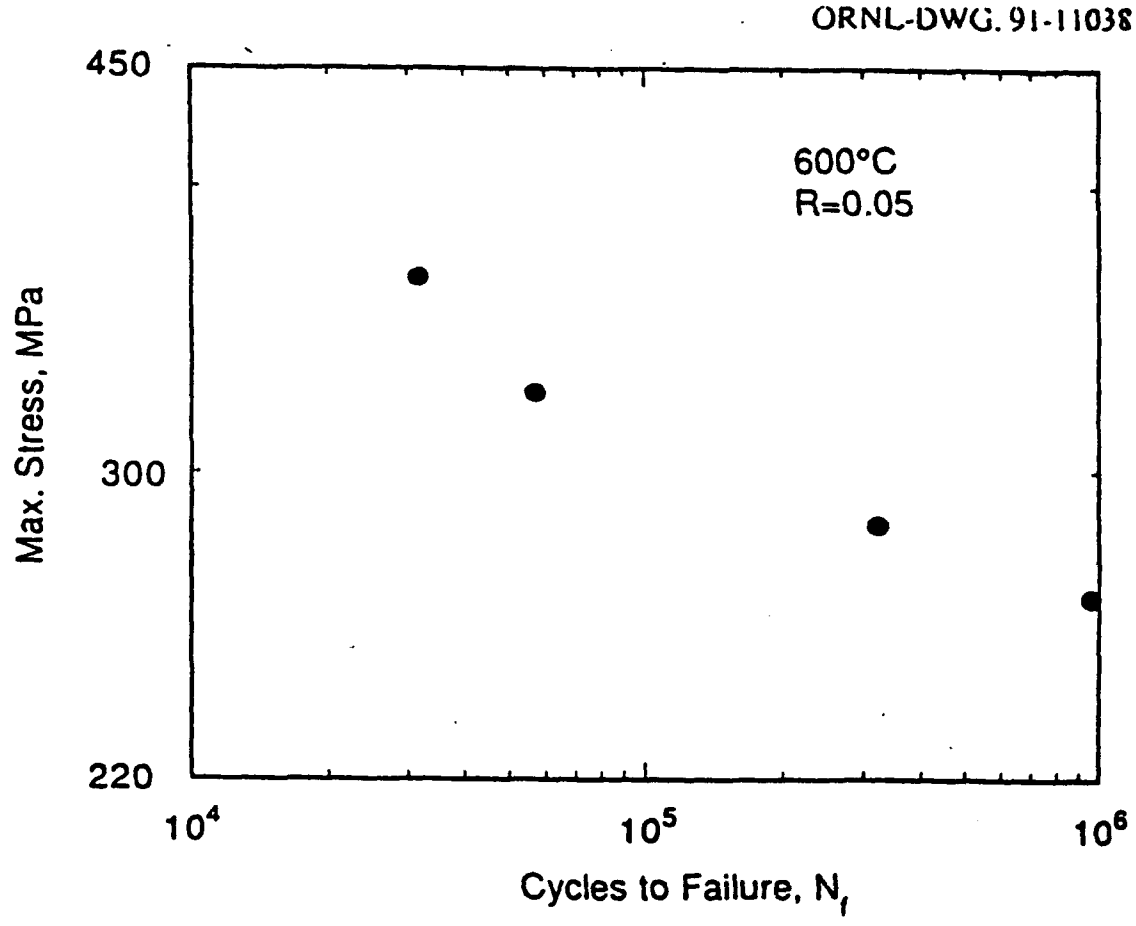
FATIGUE CURVE FOR ALLOY FA-129 AT 600°C



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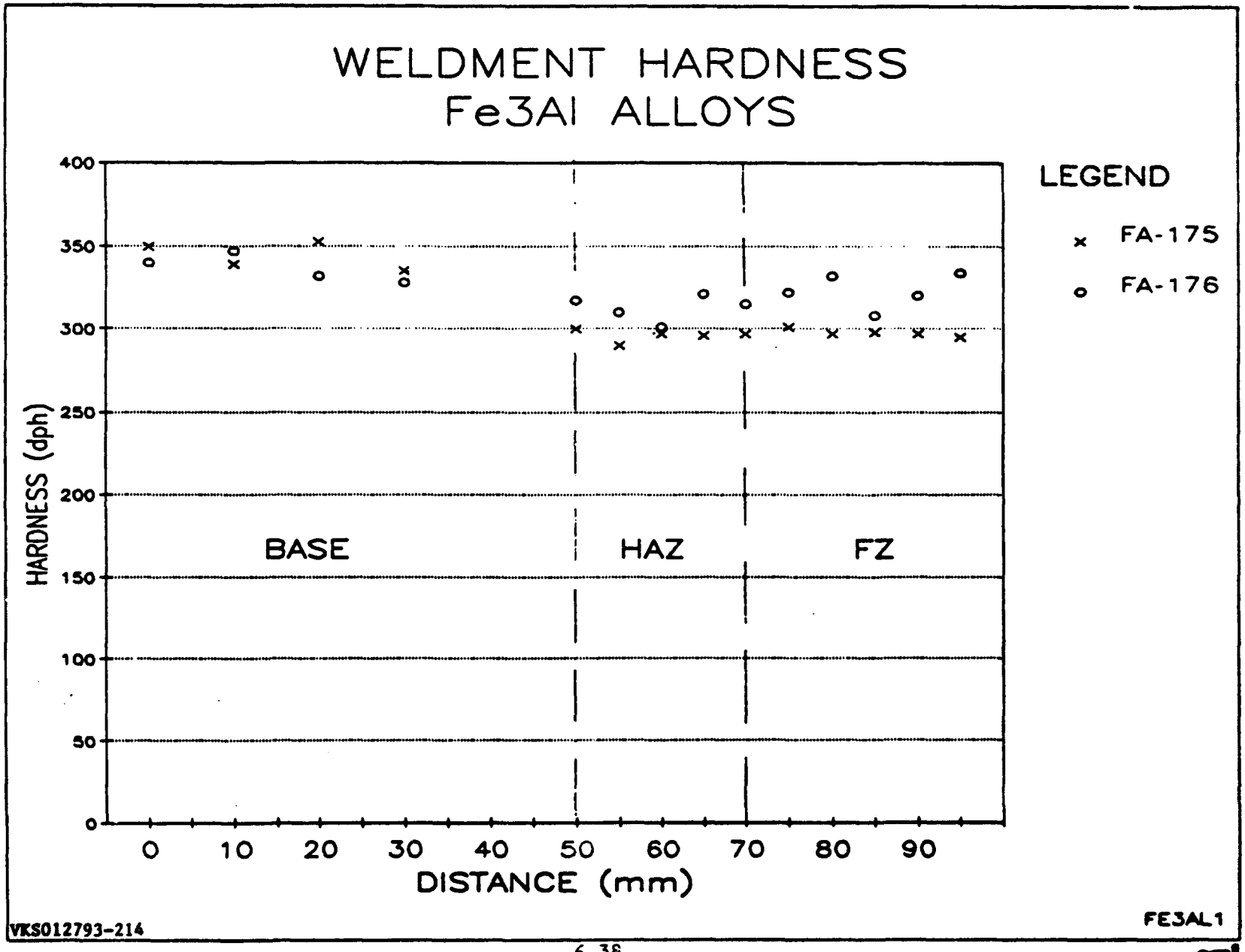
WELDMENT HARDNESS
Fe3Al ALLOYS
HARDNESS (dph)
400
350
300
250
200
150
100
50
0
BASE
HAZ
FZ
0
10
20
30
40
50
60
70
80
90
DISTANCE (mm)
LEGEND
FA-175
FA-176
VKS012793-214
FE3AL1