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SPRING COLLEGE IN MATERIALS SCIENCE
ON
"METALLIC MATERIALS"
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ORDERED INTERMETALLICS AND NICKEL-BASE SUPERALLOYS

(Part I)

C.T. LIU
Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6117
U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

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C. T. LIU
METALS AND CERAMICS DIVISION
OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE 37831-6117

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OUTLINE

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   (C) GENERAL MECHANICAL BEHAVIOR OF ORDERED INTERMETALLICS
   (D) RECENT DEVELOPMENT IN DUCTILE ORDERED INTERMETALLIC ALLOYS

II. NICKEL-BASE SUPERALLOYS
   (A) HISTORICAL DEVELOPMENT OF NICKEL-BASE SUPERALLOYS
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THE STRUCTURE OF INTERMETALLIC PHASES

1. DEFINITION: AN INTERMETALLIC COMPOUND IS A PHASE WHICH CRYSTALLIZES WITH A STRUCTURE DIFFERENT FROM THOSE OF ITS COMPONENTS.
   AB, AB_2, AB_3, AB_5, AB_7, A_3B_5 ...
2. ATOMIC BONDING: METALLIC, COVALENT, IONIC, OR COMBINATIONS AMONG THESE THREE.
3. THREE GROUPS OF INTERMETALLIC COMPOUNDS:
   (A) ELECTROCHEMICAL COMPOUNDS (VALENCE COMPOUNDS)
   (B) ELECTRON COMPOUNDS (HUME-ROTHERY PHASES)
   (C) SIZE-FACTOR COMPOUNDS.

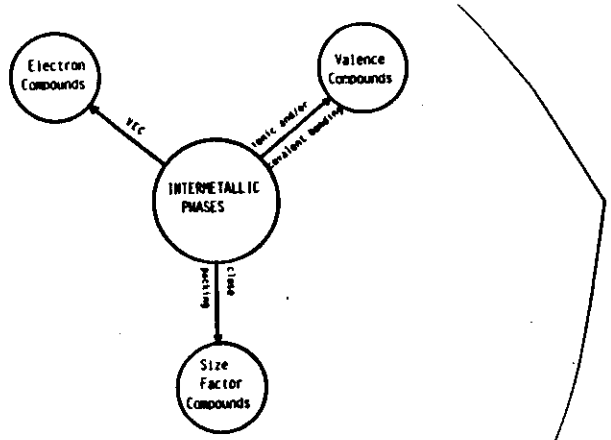


Fig. 4. Simple representation of the three main categories of intermetallic compounds.

ELECTROCHEMICAL COMPOUNDS (VALENCE COMPOUNDS)

*THE COMPOUNDS ARE FORMED WHEN ONE ELEMENT IS STRONGLY ELECTROPOSITIVE AND THE OTHER IS STRONGLY ELECTRONEGATIVE.

*ALL ATOMS IN THE COMPOUNDS EITHER ACCEPT OR PROVIDE VALENCE ELECTRONS TO OBTAIN A STABLE OCTET CONFIGURATION, I.E. ALL S&P ORBITALS ARE COMPLETELY FILLED OR COMPLETELY EMPTY.

- ELECTRONS ARE DONATED TO ONE KIND OF ATOMS BY THE OTHER ONE: IONIC INTERACTION
- ELECTRONS ARE SHARED BETWEEN THE ATOMS: COVALENT INTERACTION.

*EXAMPLES: Mg_3Sb_2, Mg_2Si, ZrS, Zn_3P_2.

*IN GENERAL, THE RANGE OF SOLUBILITY IN THEM IS SMALL.

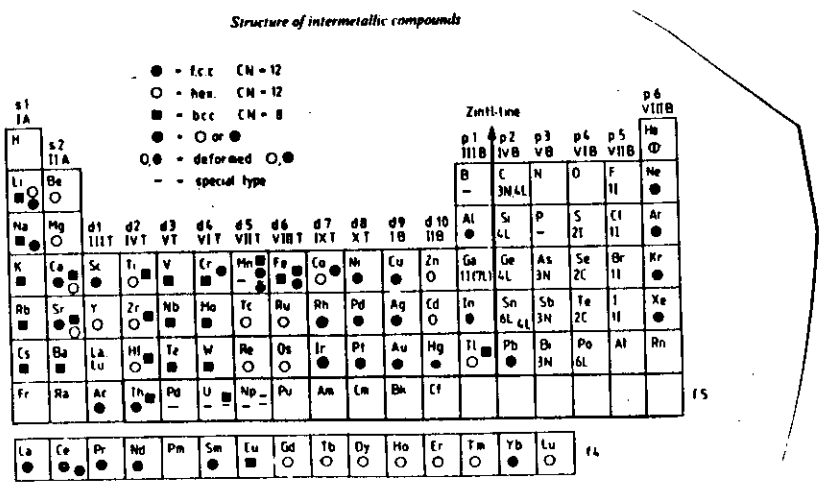


Fig. 2. Structure of the elements. The modifications stable at room temperature are symbolized at the left side of each partition. (After LAVES [1956].)

ELECTRON COMPOUNDS (HUME-ROTHERY PHASES)

*A LARGE NUMBER OF COMPOUNDS – ELECTRON COMPOUNDS – CRYSTALLIZES WITH THE SAME CRYSTAL STRUCTURE WHEN THEY POSSESS THE SAME AVERAGE NUMBER OF VALENCE ELECTRONS PER ATOM [VALENCE ELECTRON CONCENTRATION (VEC)].

*METALLIC BONDS

Table 2
The valence electron concentration calculation scheme.

Element		Valence
Transition elements with nonfilled d-shells		0
Cu, Ag, Au	(d-electrons)	1
Mg	(s-electrons)	2
Zn, Cd, Hg	(d-electrons)	2
Sn, Si, Ge	(p-electrons)	4
Sb	(p-electrons)	5

Table 3
Some representatives of Hume-Rothery phases.

VEC = 3/2			VEC = 21/13	VEC = 7/4
Body-centred cubic structure	Complex cubic "β-manganese" structure	Close-packed hexagonal structure	"γ-brass" structure[c]	Close-packed hexagonal structure
CuBe	Cu_5Si	Cu_3Ga	Cu_5Zn_8	$CuZn_3$
CuZn	Ag_5Al	Cu_3Ge	Cu_5Cd_8	$CuCd_3$
Cu_3Al	Au_5Al	AgZn	Cu_5Hg_8	Cu_3Sn
Cu_3Ga[b]	$CoZn_3$	AgCd	Cu_9Al_4	Cu_3Ge
Cu_3In[a]		Ag_3Al	Cu_9Ga_4	Cu_3Si
Cu_3Si		Ag_3Ga	Cu_9In_4	$AgZn_3$
Cu_3Sn		Ag_3In	$Cu_{31}Si_8$	$AgCd_3$
AgMg		Ag_3Sn	$Cu_{31}Sn_8$	Ag_3Sn
AgZn[b]		Ag_3Sb	Ag_5Zn_8	Ag_3Al_3
AgCd[b]		Au_3In	Ag_5Cd_8	$AuZn_3$
Ag_3Al[b]		Au_3Sn	Ag_5Hg_8	$AuCd_3$
Ag_3In[b]			Ag_9In_4	Au_3Sn
AuMg			Au_5Zn_8	Au_3Al_3
AuZn			Au_5Cd_8	Cu_3Sb & Ag_3Sb[d]
AuCd			Au_9In_4	
FeAl			Mn_5Zn_{21}	
CoAl			Fe_5Zn_{21}	
NiAl			Co_5Zn_{21}	
NiIn			Ni_5Be_{21}	
PdIn			Ni_5Zn_{21}	
XTl[e]			Ni_5Cd_{21}	
			Rh_5Zn_{21}	
			Pd_5Zn_{21}	
			Pt_5Be_{21}	
			Pt_5Zn_{21}	
			$Na_{31}Pb_8$	

SIZE-FACTOR COMPOUNDS

*SIZE-FACTOR COMPOUNDS ARE FORMED, IN WHICH ONE ATOM IS MUCH SMALLER THAN THE OTHER (E.G. 20–30%).

*AN IMPORTANT GROUP OF THE COMPOUNDS ARE THE LAVES PHASES WITH AB_2 COMPOSITIONS. THE DIFFERENCE IN A AND B ATOMS BY ABOUT 22.5%.

*LAVES PHASES: $MgCu_2$, $MgNi_2$, $MgZn_2$, $AgBe_2$, $TiFe_2$,...

*INTERSTITIAL PHASES: HYDRIDES, NITRIDES, CARBIDES, AND BORIDES OF TRANSITION METALS.
: SMALL NON-METALLIC ATOMS TAKE UP INTERSTITIAL POSITIONS BETWEEN THE METALLIC ATOMS.

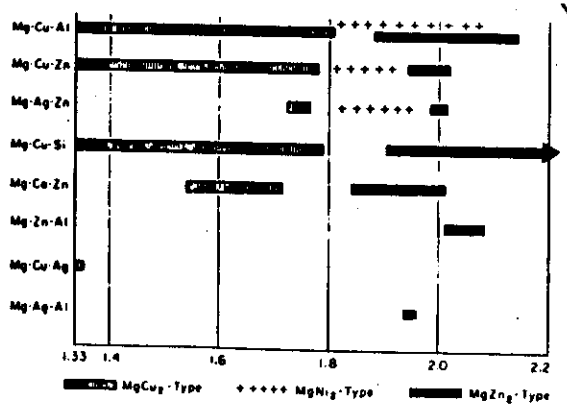


Fig. 22. The ranges of homogeneity in terms of electron concentration of several ternary magnesium alloys which possess the three typical Laves structures (from MASSALSKI [1956] after LAVES and WITTE [1936]).

TABLE 3
Some examples of laves phase intermetallic compounds.

$MgCu_2$ structure-type	$MgZn_2$ structure-type	$MgNi_2$ structure-type
$MgCu_2$	$MgZn_2$	$MgNi_2$
$CuBe_2$	$MnBe_2$	UPt_2
$CeAl_2$	$CaMg_2$	$U(Fe, Ni)_2$
UAl_2	$NbFe_2$	$U(Mn, Ni)_2$
$BiAu_2$	$ZrCr_2$	$CuMg_2Zn_2$
KBi_2	$ZrOs_2$	
$NaAu_2$	$HfMn_2$	
$CeCo_2$	$TiMn_2$	
UMn_2	UNi_2	
$HfCo_2$	KNa_2	
$ZrCr_2$	CoCrTa	
$TaCr_2$	CoTaTi	
$TiCr_2$		
$ZrCo_2$		
CdCuZn		
CuTaV		
MgNiZn		

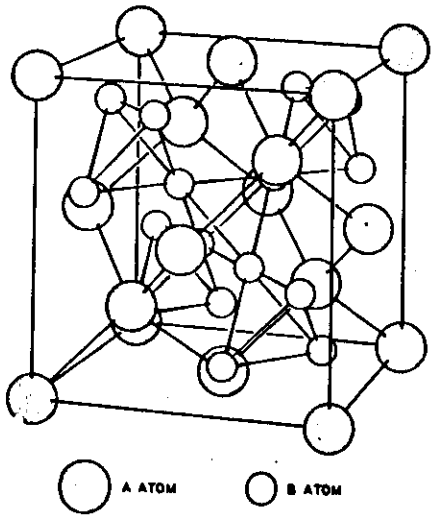


Fig. 4. The $MgCu_2$ structure (AB_2).

STRUCTURAL FEATURES OF ORDERED INTERMETALLICS

*LONG-RANGE ORDERED CRYSTAL STRUCTURES.

*ANTIPHASE BOUNDARIES (APB) AND DOMAIN STRUCTURES.

*SUPERLATTICE DISLOCATIONS.

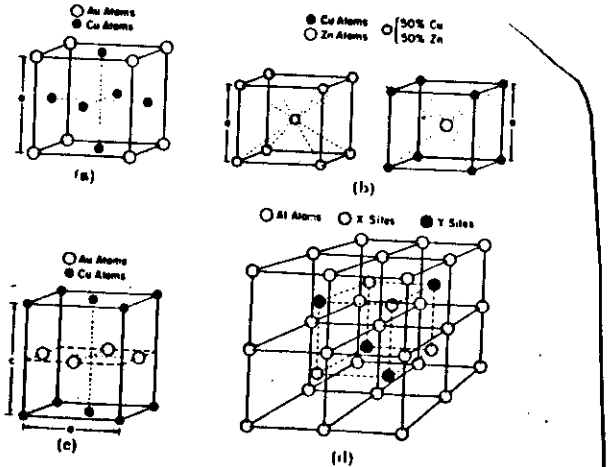
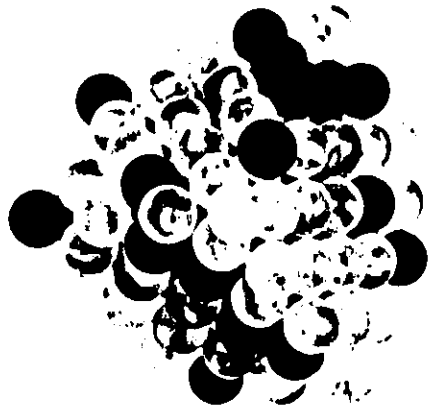


Fig. 34. Various types of ordered superlattices: (a) ordered cubic superlattice Cu_3Au; (b) disordered and ordered structures of β brass; (c) the tetragonal superlattice of AuCu; (d) the structure of Fe_3Al and FeAl. Al atoms fill the X sites in Fe_3Al and the X and Y sites in FeAl.

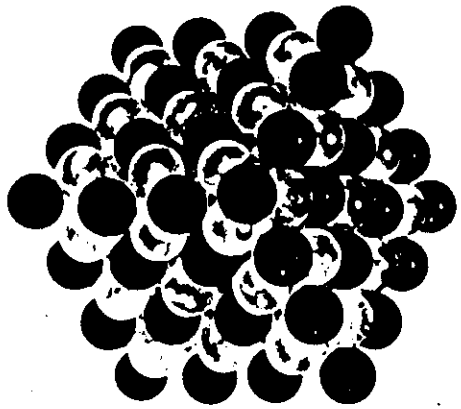
LONG-RANGE ORDERED (LRO) ALLOYS AND INTERMETALLIC COMPOUNDS (IC) ARE DIFFERENT FROM 'CONVENTIONAL' ALLOYS IN ATOMIC ARRANGEMENT

CONVENTIONAL ALLOYS

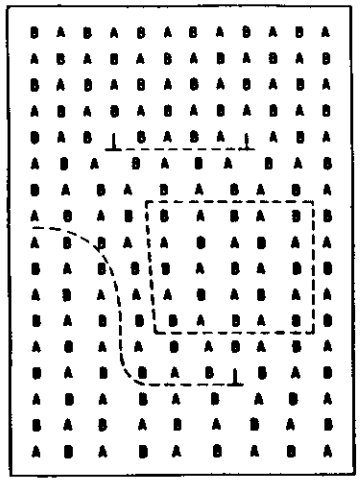


DISORDERED CRYSTAL STRUCTURE

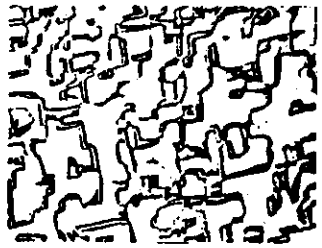
LRO AND IC



ORDERED CRYSTAL STRUCTURE



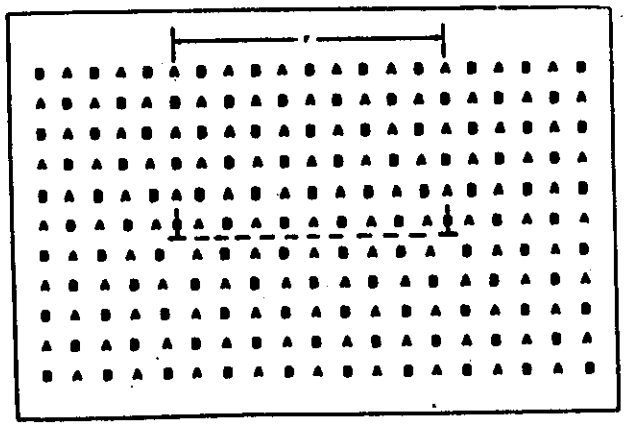
Schematic representation of a superlattice dislocation in an ideal simple cubic lattice, along with two thermally produced antiphase boundaries, one of which terminates on an ordinary dislocation (from Marcinkowski[103]).



(b)

(a)

FIG. 5. Thermally produced antiphase boundaries in (a) Fe_3Al-$L2_1$ Schmatz[106]), (b) Cu_3Au-$L1_2$ structure (from Kear[91]), (c) Mg_3Cd-DO_{19} Blackburn[120]).



GENERAL MECHANICAL BEHAVIOR OF ORDERED INTERMETALLICS

I. GOOD HIGH-TEMPERATURE PROPERTIES.

(1) GOOD CREEP RESISTANCE DUE TO SLOW DIFFUSION IN ORDERED LATTICES.

(2) GOOD HIGH-TEMPERATURE STRENGTH: INCREASE IN YIELD STRENGTH WITH INCREASING TEMPERATURE (ANOMALOUS TEMPERATURE DEPENDENCE OF YIELD STRENGTH).

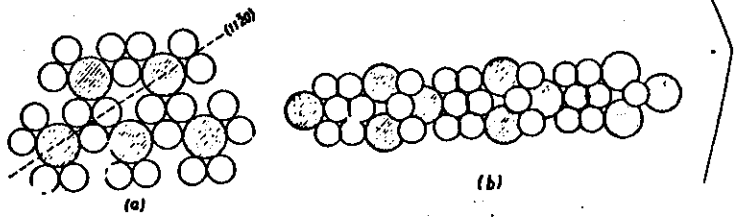
II. LOW DUCTILITY AND BRITTLE FRACTURE.

(A) LACK OF SUFFICIENT DEFORMATION MODES.

(B) BRITTLE GRAIN BOUNDARIES.

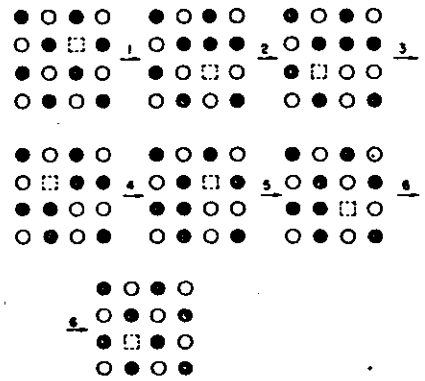
(C) LOW MOBILITY OF DISLOCATIONS.

(D) HIGH LOCALIZED STRESS CONCENTRATION: PLANAR SLIP.



(a) (b)

VACANCIES IN ORDERED LATTICE ARE "TRAPPED" IN THEIR ORIGINAL SITES



- SLOW DIFFUSION
- CREEP RESISTANCE
- SWELLING RESISTANCE

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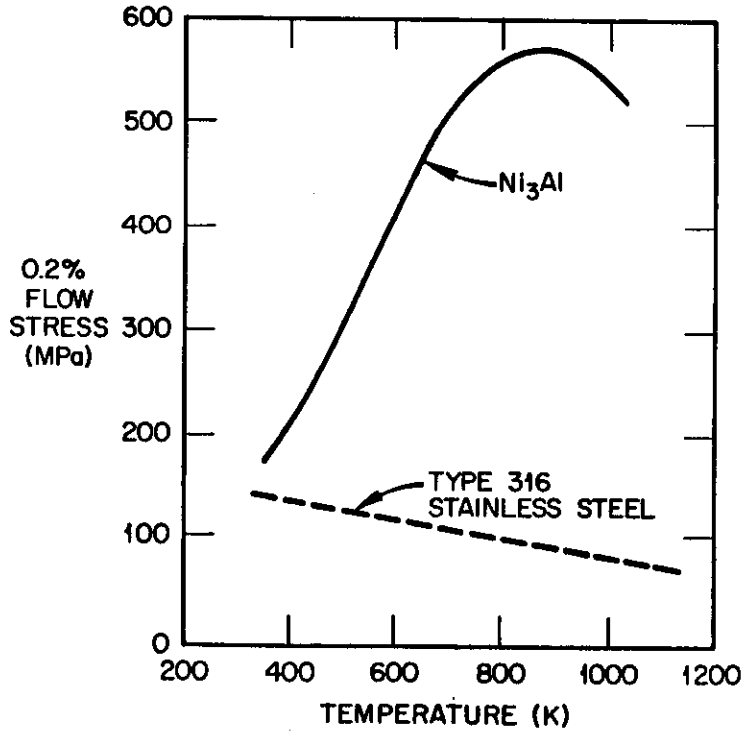
THE YIELD STRENGTH OF Ni_3Al INCREASES WITH TEMPERATURE AND REACHES A MAXIMUM AROUND 830 K



- BECAUSE OF THE INCREASE IN YIELD STRENGTH WITH TEMPERATURE, Ni_3Al IS MUCH STRONGER THAN TYPE 316 STAINLESS STEEL AT ELEVATED TEMPERATURES.

Cross-slip of a Superlattic Dislocation from the (111) Slip Plane Into (100) (from Kear)

RECENT DEVELOPMENT IN ORDERED INTERMETALLIC ALLOYS

ORDERED INTERMETALLICS BASED ON ALUMINIDES AND SILICIDES OFFER POTENTIAL ADVANTAGES FOR HIGH-TEMPERATURE STRUCTURAL USE

- GOOD HIGH-TEMPERATURE STRENGTH
- SLOW KINETIC PROCESSES
- RESISTANCE TO OXIDATION AND CORROSION
- HIGH MELTING POINT
- LOW MATERIAL DENSITY

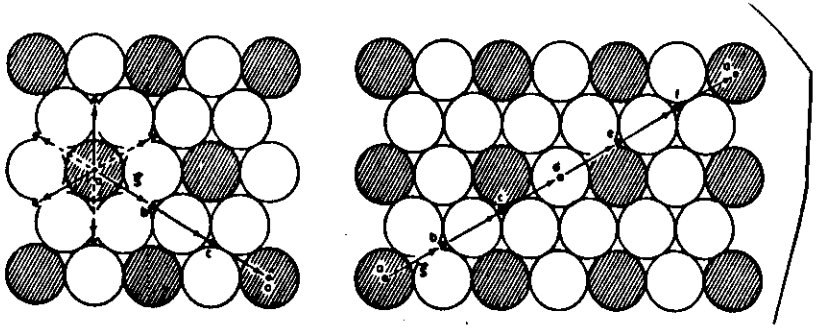
MOST ORDERED INTERMETALLICS EXHIBIT BRITTLE FRACTURE AND LOW DUCTILITY

- THE BRITTLENESS IS PRIMARILY CAUSED BY
  - LACK OF SUFFICIENT DEFORMATION MODES
  - GRAIN BOUNDARY WEAKNESS
  - LOW MOBILITY OF SUPERLATTICE DISLOCATIONS
  - DIFFICULTY IN CROSS SLIP (PLANAR SLIP)
- THE BRITTLENESS HAD LIMITED THE USE OF INTERMETALLICS AS ENGINEERING MATERIALS

DESIGN OF DUCTILE ORDERED INTERMETALLIC THROUGH CONTROL OF ORDERED CRYSTAL STRUCTURE IN AB_3 ALLOY SYSTEMS

I. STRUCTURAL FEATURES OF AB_3 ORDERED PHASES

- IN RECENT YEARS CLOSE-PACKED ORDERED STRUCTURES WITH AB_3 COMPOSITION HAVE BEEN OBSERVED IN MANY BINARY AND PSEUDOBINARY ALLOY SYSTEMS.
- ALL THESE STRUCTURES ARE BUILT UP FROM CLOSE-PACKED ORDERED AB_3 LAYERS BUT DIFFER IN STACKING SEQUENCE.
- TWO BASIC STRUCTURES OF ORDERED LAYERS.

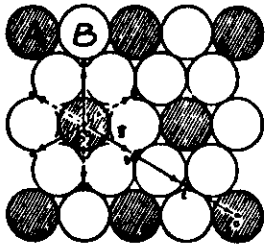


a.
$AuCu_3$-type "T-mesh" with "triangular ordering"

b.
$TiAl_3$-type "R mesh" with "rectangular ordering"

II. CHARACTERIZATION OF CLOSE-PACKED ORDERED CRYSTAL STRUCTURES IN AB_3 ALLOY SYSTEM

1. Basic Structure – Close-packed ordered layer



2. Ordered Crystal Structure

	Stacking Sequence	Hexagonality
Simple Hexagonal Ordered Structure	abababab...(hhhh...)	100%
Simple Cubic Ordered Structure	abcabcabc..,(cccc...)	0%
Transition Ordered Structure	abcbcacab...(hchhchhch...)	66.7%

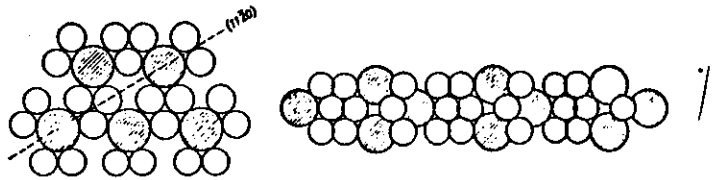
III. FACTORS CONTROLLING THE RELATIVE STABILITY OF THE VARIOUS ORDERED STRUCTURE

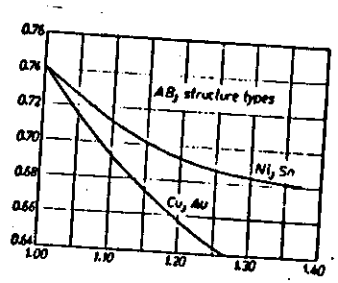
AB_3 $A(B,C)_3$

1. ATOMIC SIZE EFFECT (VAN VUCHT's RULE)

- AS R_A/R_B INCREASES IN AB_3 ALLOYS, THE STACKING SEQUENCE CHANGES FROM PURELY CUBIC THROUGH DIFFERENT ORDERED MIXTURE OF CUBIC TO HEXAGONAL LAYERS TO PURELY HEXAGONAL

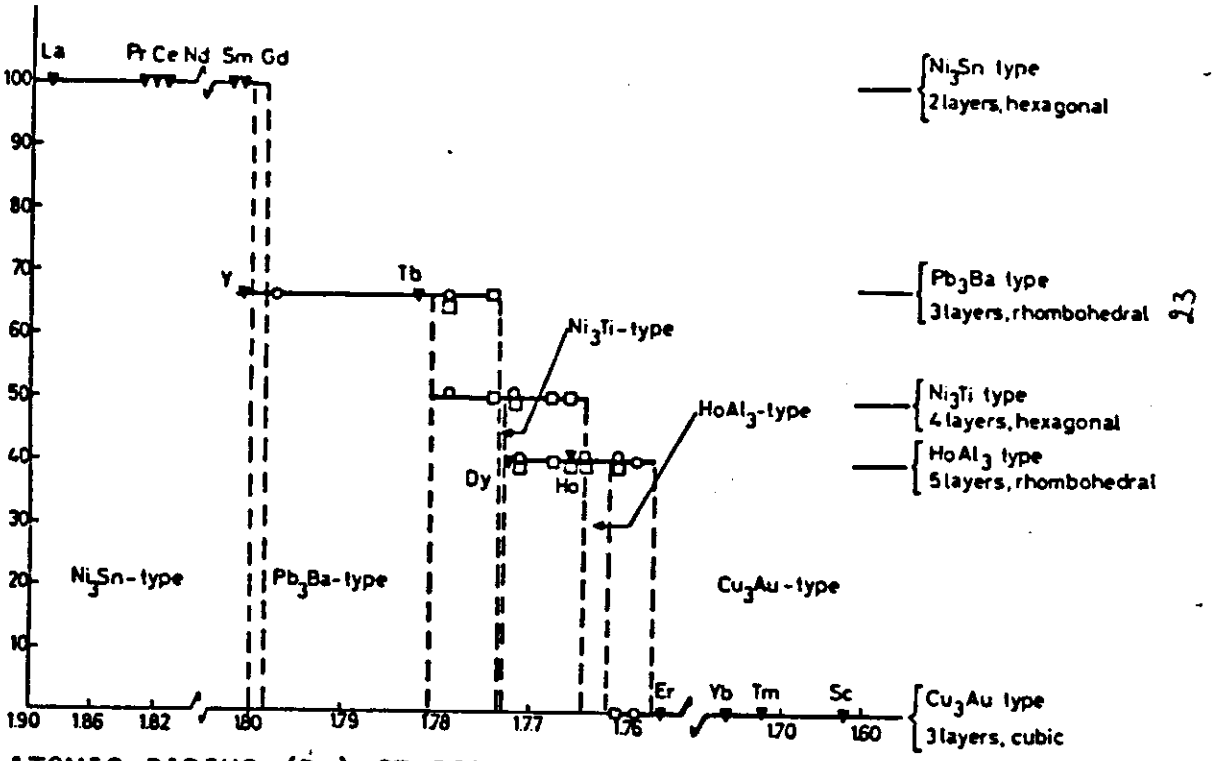
- CLUSTERING OF SMALLER ATOMS IN THE LAYER LOWERS THE SYMMETRY OF SPACE GROUP FROM CUBIC TO HEXAGONAL, BUT ADMITS A BETTER PACKING WHEN THE LARGER A ATOMS OF BOTH ADJOINING LAYERS PROFIT FROM THE OPEN SPACES.





PCT OF HEXAGONAL STACKING DECREASES WITH THE DECREASE IN THE ATOMIC SIZE OF RARE-EARTH ELEMENTS (R_A) IN TRIALUMINIDES

▼ RAl_3 ; ○ $(Y,Er)Al_3$; □ $(Gd,Er)Al_3$;



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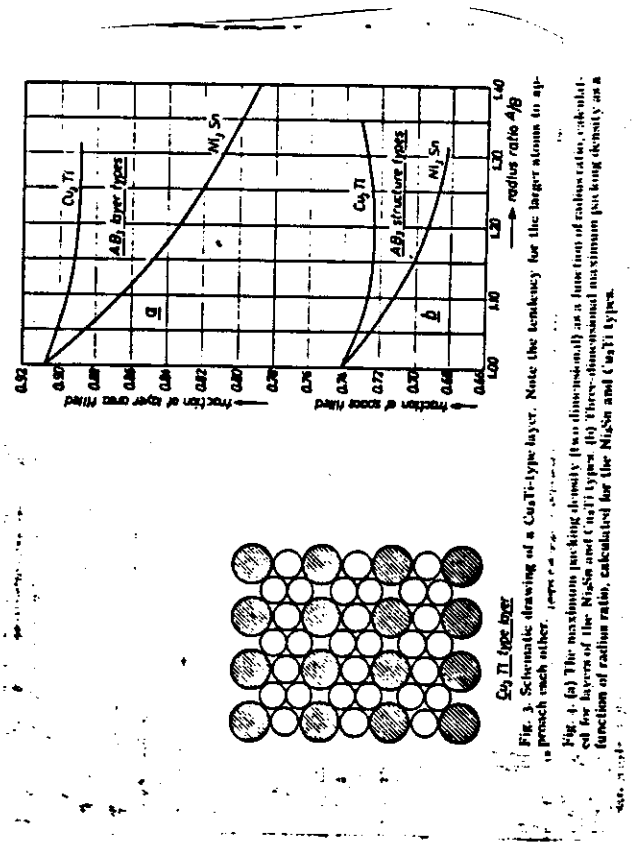

Fig. 3. Schematic drawing of a Cu_2Ti-type layer. Note the tendency for the larger atoms to approach each other.

Fig. 4. (a) The maximum packing density (two-dimensional) as a function of radius ratio, calculated for layers of the Ni_2Si and Cu_2Ti types. (b) Three-dimensional maximum packing density as a function of radius ratio, calculated for the Ni_2Si and Cu_2Ti types.

Co_2Ti type layer

$A(B,C)_3$

AB_3

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2. ELECTRON CONCENTRATION EFFECT (PAUL BECK'S RULE)

- ELECTRON CONCENTRATION INFLUENCE ON STRUCTURE HAS BEEN ATTRIBUTED TO THE FILLING OF BRILLOUIN ZONES.

- e/a IS DEFINED AS NUMBER OF ELECTRONS OUTSIDE THE INERT GAS SHELLS.

ELEMENT V	e/a 5
Mn	7
Fe	8
Co	9
Ni	10

- AS e/a DECREASES, THE STACKING SEQUENCE CHANGES FROM PURE HEXAGONAL THROUGH DIFFERENT ORDERED MIXTURE OF HEXAGONAL TO CUBIC LAYERS TO PURELY CUBIC.

	VNi_3	VCo_3	VFe_3
STRUCTURE	ORDERED TETRAGONAL	ORDERED HEXAGONAL	DISORDERED bcc
ORDERED LAYER	R-TYPE	T-TYPE	
e/a	8.75	8.00	7.25

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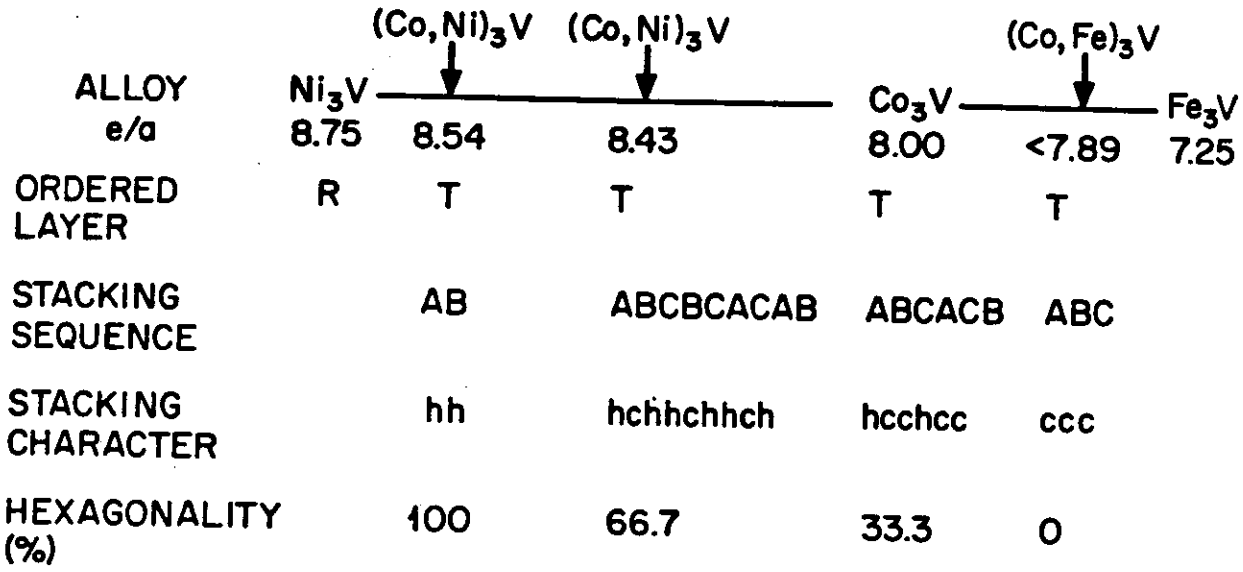

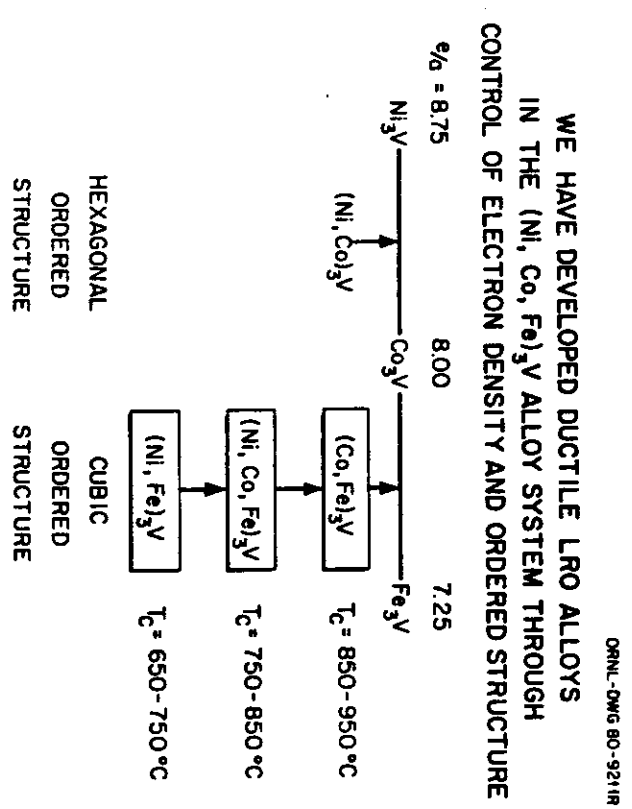

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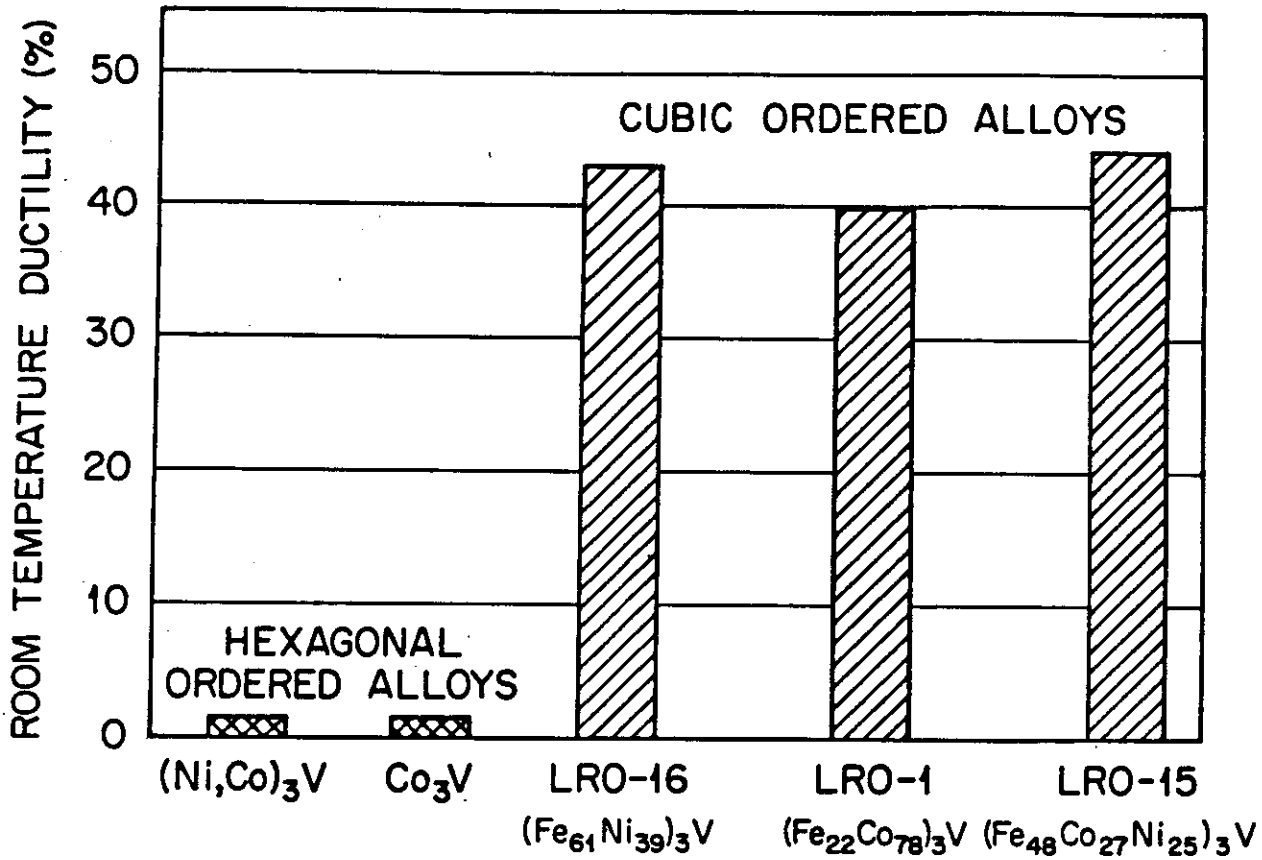

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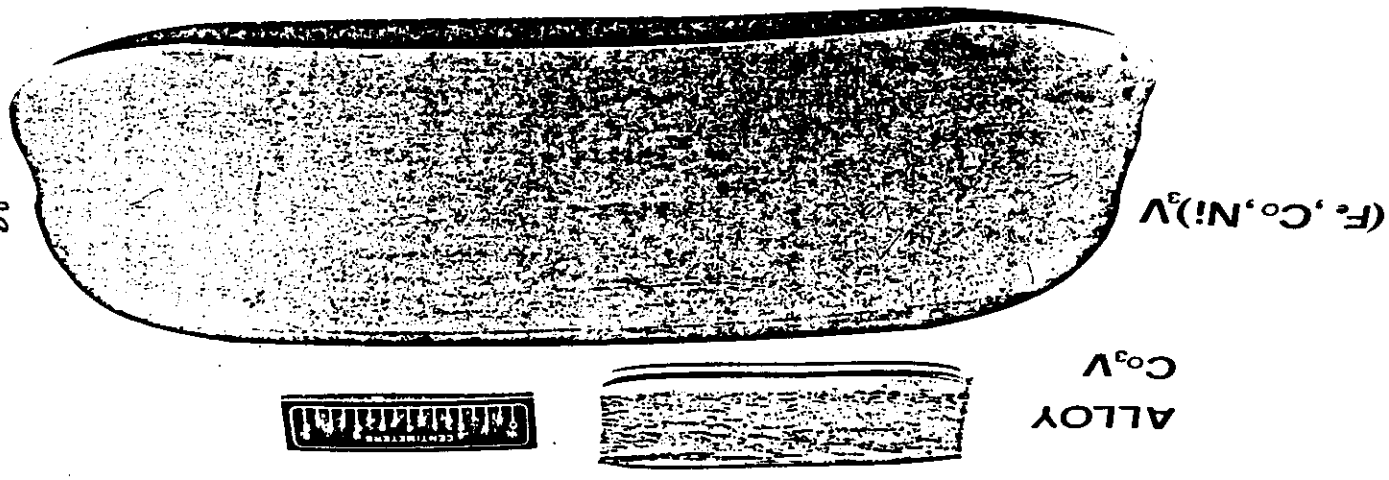

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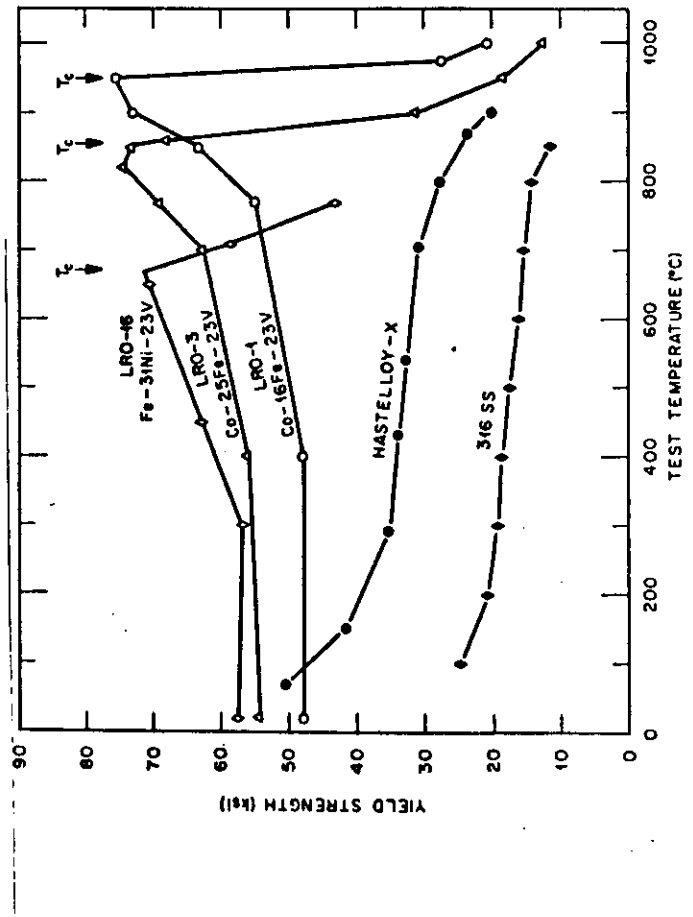
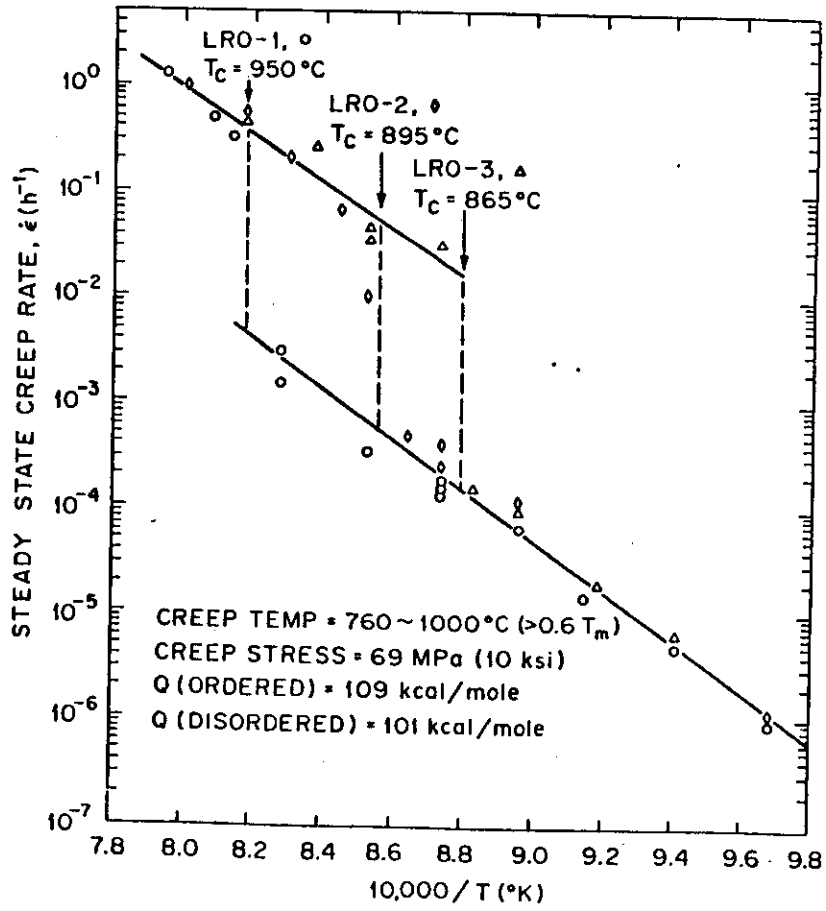
LRO ALLOYS SHOW UNUSUAL MECHANICAL PROPERTIES-THEIR STRENGTH INCREASES RATHER THAN DECREASES WITH TEST TEMPERATURE



LRO ALLOYS SHOW A DISCONTINUOUS CHANGE IN CREEP RATE ($\dot{\epsilon}$) AROUND FORMATION OF LRO LOWERS $\dot{\epsilon}$ BY 2 ORDERS OF MAGNITUDE



GENERAL PROPERTIES OF Ni_3Al

- $L1_2$ ORDERED CRYSTAL STRUCTURE

○: Ni ATOMS ●: Al ATOMS

- INCREASE IN YIELD STRESS WITH INCREASING TEMPERATURE
- EXCELLENT OXIDATION RESISTANCE
- SINGLE CRYSTALS OF Ni_3Al ARE DUCTILE
- POLYCRYSTALLINE Ni_3Al IS EXTREMELY BRITTLE

ORNL PHOTO 3430-83

POLYCRYSTALLINE Ni_3Al SHOWS POOR DUCTILITY AND BRITTLE GRAIN-BOUNDARY FRACTURE

- SINGLE CRYSTALS OF Ni_3Al ARE DUCTILE
- POLYCRYSTALLINE Ni_3Al IS EXTREMELY BRITTLE BECAUSE OF GRAIN-BOUNDARY WEAKNESS

BRITTLE GRAIN BOUNDARY FRACTURE AT ROOM TEMPERATURE

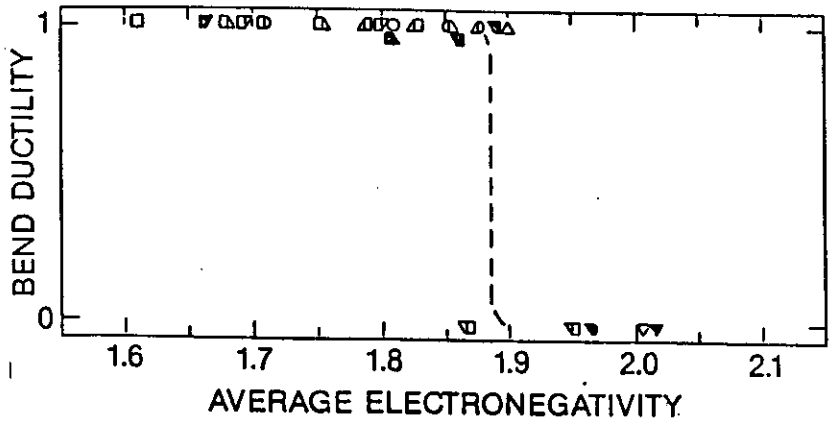
EXTENSIVE CRACKING ALONG GRAIN BOUNDARIES IN Ni_3Al CAST INGOT HOT ROLLED AT 1200°C

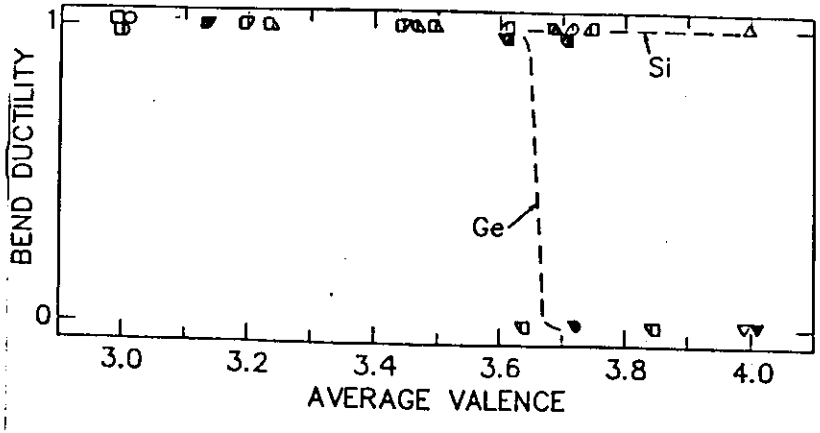
THE GRAIN-BOUNDARY FRACTURE IN Ni_3X CAN BE CORRELATED WITH THE DIFFERENCE IN VALENCY, ELECTRONEGATIVITY AND ATOM SIZE BETWEEN Ni AND X ATOMS

ALLOY	VALENCY[A] DIFFERENCE (ΔZ)	ELECTRONEGATIVITY[B] DIFFERENCE (PAULING'S)	SIZE[C] RATIO $\frac{D_{Ni-X}}{D_{Ni-Ni}}$	FRACTURE BEHAVIOR[D] UNDOPED	B-DOPED
Ni_3Fe	0.2		1.02	D	–
Ni_3Mn	0.9	−0.36	1.01	D	–
Ni_3Al	3.0	−0.30	1.135	B	D
Ni_3Ga	3.0	−0.10	1.083	B	D
Ni_3Si	4.0	−0.01	1.089	B	D
Ni_3Ge	4.0	+0.10	1.132	B	B

(A) TAKASUGI ET AL.
(B) TAUB ET AL.
(C) FARKAS ET AL.
(D) TAUB ET AL.
D = DUCTILE, B = BRITTLE

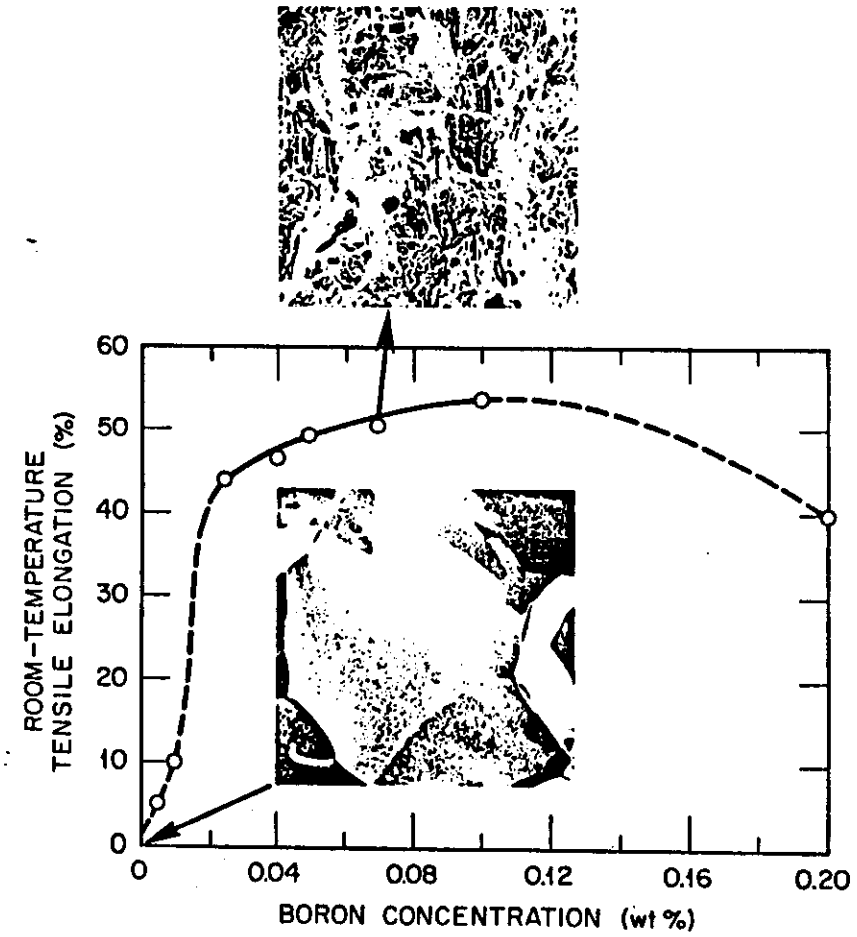
THE AVERAGE ELETRONEGATIVITY APPEARS TO CONTROL THE BEND DUCTILITY OF B-DOPED Ni_3X ALLOYS (WHERE X = Al, Ga, Si, AND/OR Ge)





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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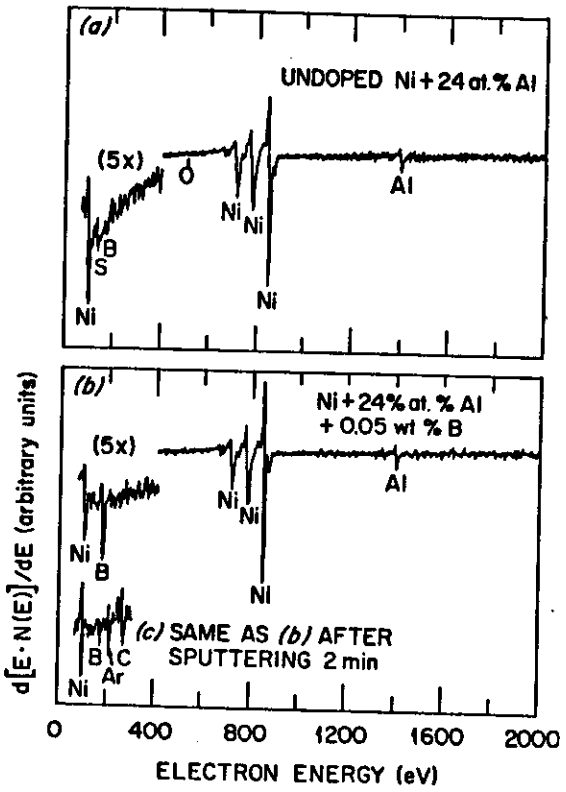
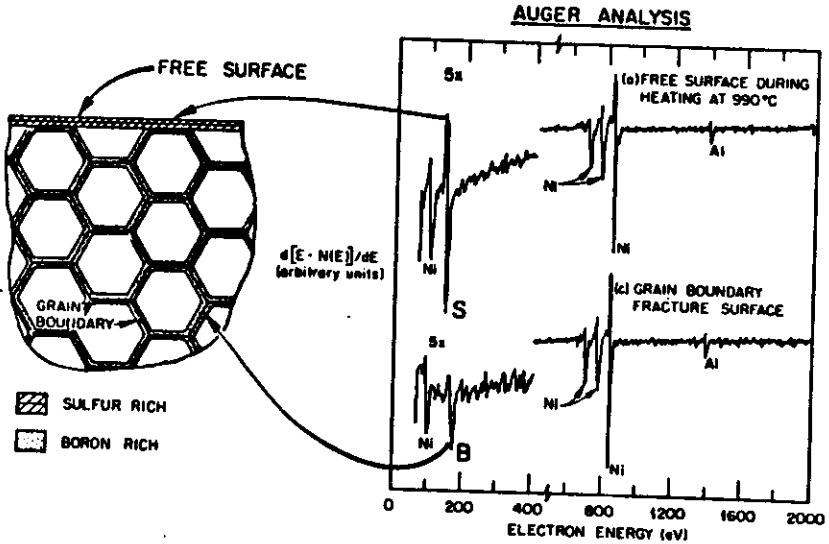
BORON SEGREGATES STRONGLY TO GRAIN BOUNDARIES IN 24 AT. % AL ALLOYS



BORON EXHIBITS AN UNIQUE SEGREGATION BEHAVIOR – STRONG SEGREGATION TO GRAIN BOUNDARIES BUT NOT TO FREE SURFACES



- IN CONTRAST, SULFUR, AN EMBRITTLING ELEMENT, SEGREGATES MUCH MORE STRONGLY TO FREE SURFACES THAN TO GRAIN BOUNDARIES.

EFFECTS OF SOLUTE SEGREGATION ON GRAIN-BOUNDARY COHESIVE ENERGY (ϕ)

(a) NEWLY CREATED FRACTURE SURFACE, γ_s

GRAIN BOUNDARY, γ_b

$$\phi = \gamma_s + \gamma_s - \gamma_b$$

(b) GRAIN BOUNDARY SEGREGATED WITH SOLUTES

$$\phi^* = \gamma_s^* + \gamma_s^* - \gamma_b^*$$

EMBRITTLING ELEMENTS (SUCH AS S)

$$\phi^*(\downarrow) = \gamma_s^*(\downarrow) + \gamma_s^*(\downarrow) - \gamma_b^*(\downarrow)$$

STRENGTHENING ELEMENTS (SUCH AS B)

$$\phi^*(\uparrow) = \gamma_s^*(\uparrow) + \gamma_s^*(\uparrow) - \gamma_b^*(\downarrow)$$

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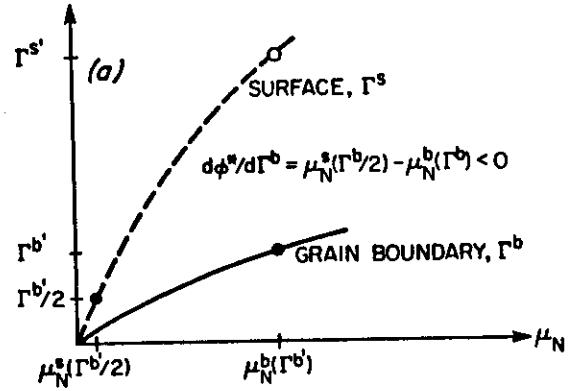
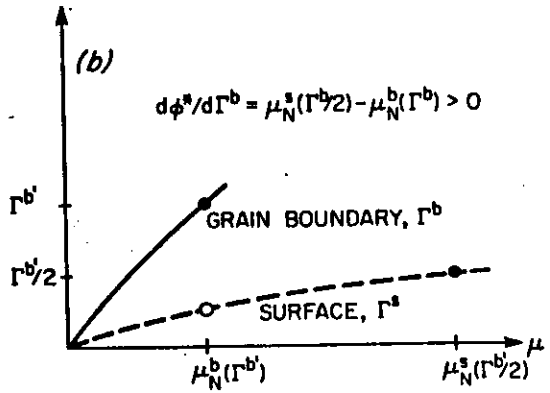
SURFACE SEGREGATION (Γ^s) > GRAIN BOUNDARY SEGREGATION (Γ^b)



SURFACE SEGREGATION (Γ^s) << GRAIN BOUNDARY SEGREGATION (Γ^b)



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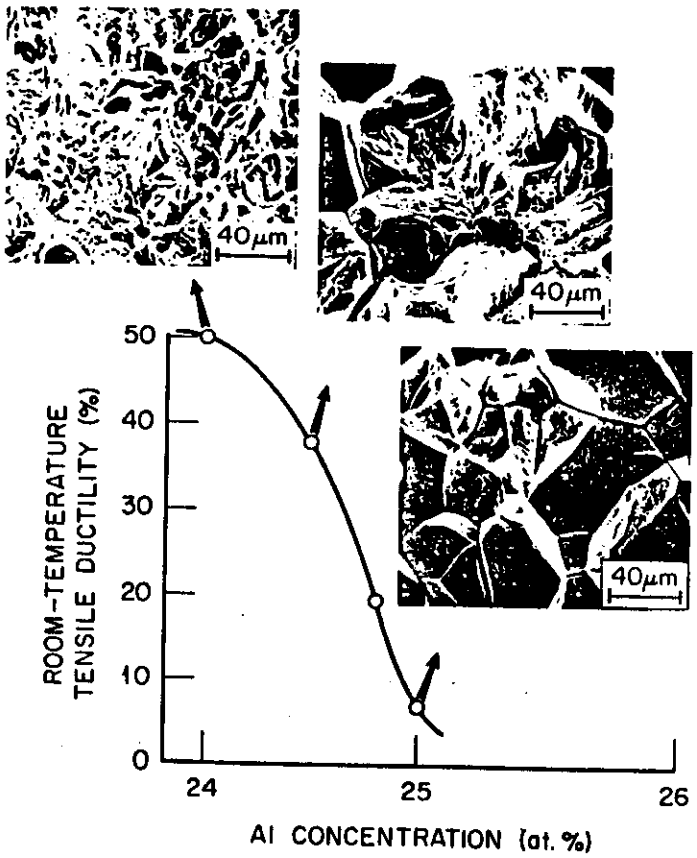
INCREASING Al CONTENT FROM 24 TO 25% SHARPLY DECREASES TENSILE DUCTILITY AND PROMOTES GRAIN-BOUNDARY FRACTURE IN Ni_3Al ALLOYS DOPED WITH 0.2% BORON



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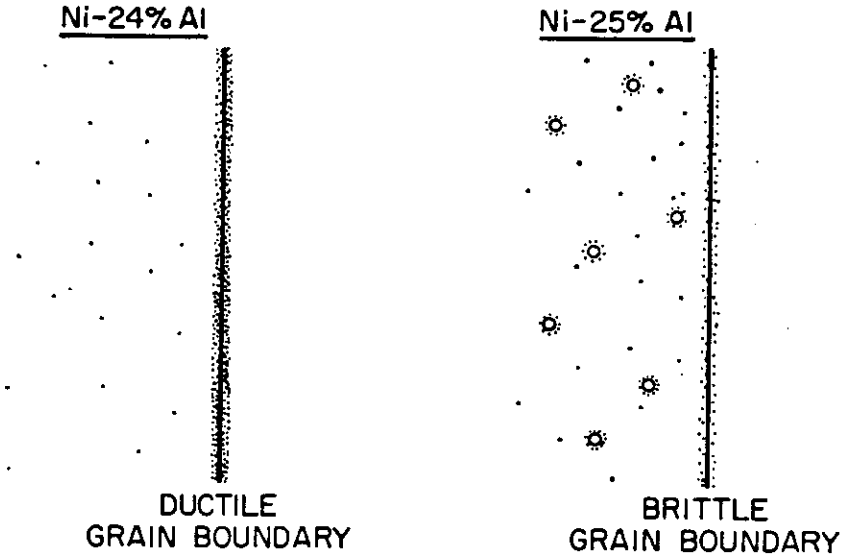
ORNL-DWG 86-7814

THE INTERACTION OF CONSTITUTIONAL VACANCIES WITH BORON IS THOUGHT TO REDUCE BORON ENRICHMENT AT GRAIN BOUNDARIES IN Ni_3Al WITH ≥ 25%Al



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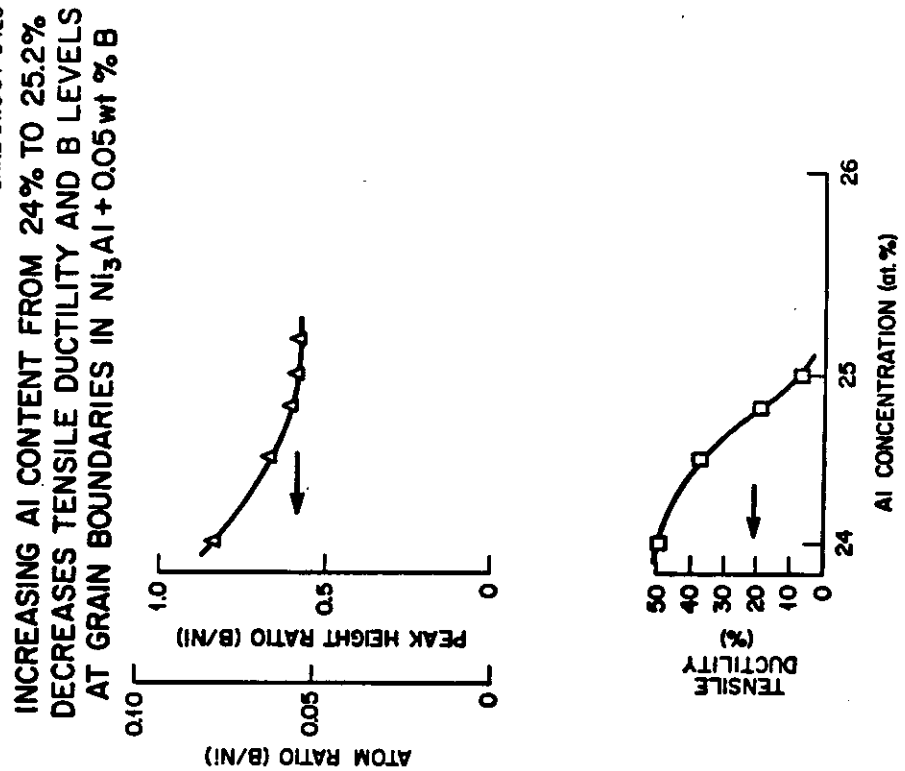
ORNL-DWG 84-8426

INCREASING Al CONTENT FROM 24% TO 25.2% DECREASES TENSILE DUCTILITY AND B LEVELS AT GRAIN BOUNDARIES IN Ni_3Al + 0.05 wt % B



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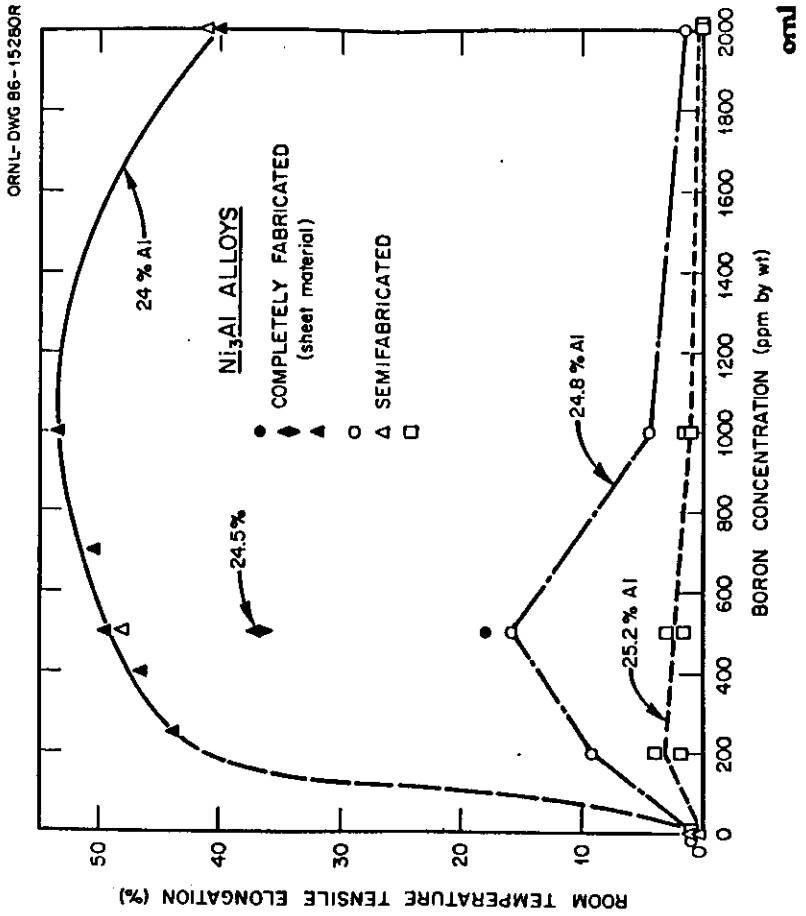
ORNL-DWG 86-15280R
Ni3Al ALLOYS
COMPLETELY FABRICATED
(sheet material)
SEMIFABRICATED
24 % Al
24.5%
24.8 % Al
25.2 % Al
BORON CONCENTRATION (ppm by wt)
ROOM TEMPERATURE TENSILE ELONGATION (%)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
10
20
30
40
50
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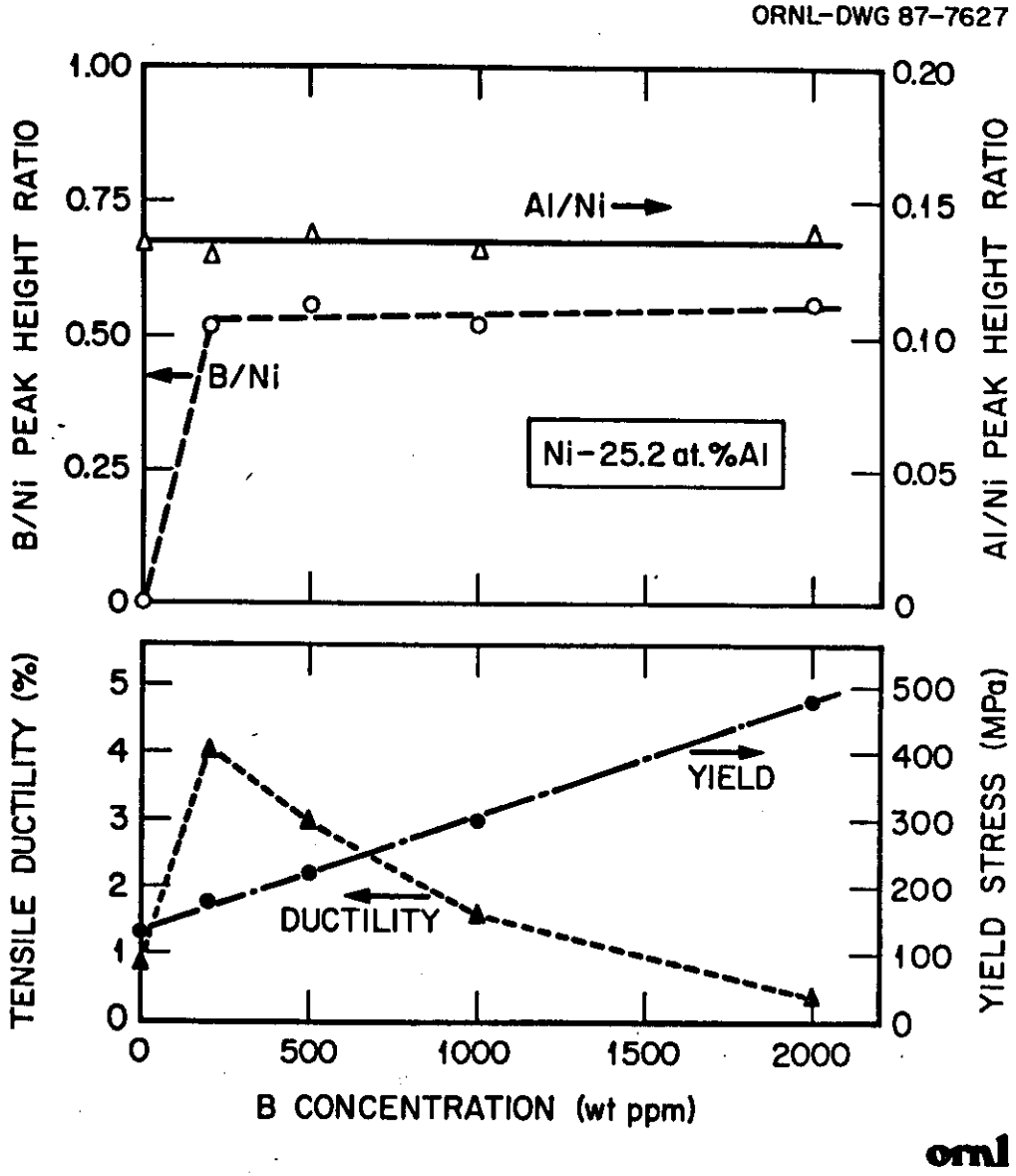
ORNL-DWG 87-7627
B/Ni PEAK HEIGHT RATIO
Al/Ni PEAK HEIGHT RATIO
Al/Ni
B/Ni
Ni-25.2 at.%Al
TENSILE DUCTILITY (%)
YIELD STRESS (MPa)
YIELD
DUCTILITY
B CONCENTRATION (wt ppm)
0
0.25
0.50
0.75
1.00
0.05
0.10
0.15
0.20
1
2
3
4
5
100
200
300
400
500
500
1000
1500
2000
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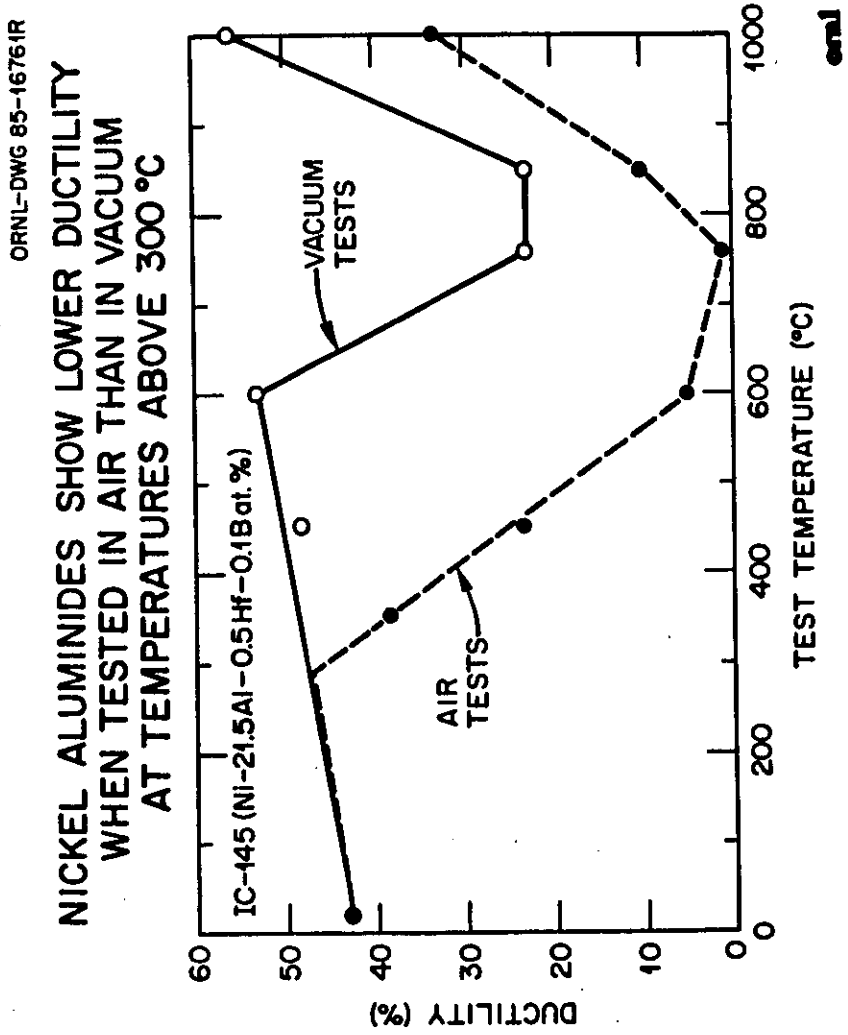
THE ALLOY STOICHIOMETRY EFFECT IS A COMBINATION OF

(1) LOWERING BORON SEGREGATION TO GRAIN BOUNDARIES AS THE BULK Al LEVEL INCREASES FROM 24 TO 24.5%

(2) INCREASING THE Al LEVEL AT GRAIN BOUNDARIES AS THE BULK Al INCREASES FROM BELOW TO ABOVE 25%

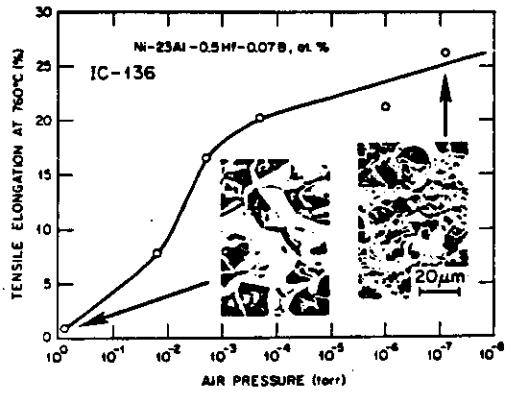
(3) TREMENDOUS HARDENING EFFECT OF BORON IN >25% Al ALLOYS

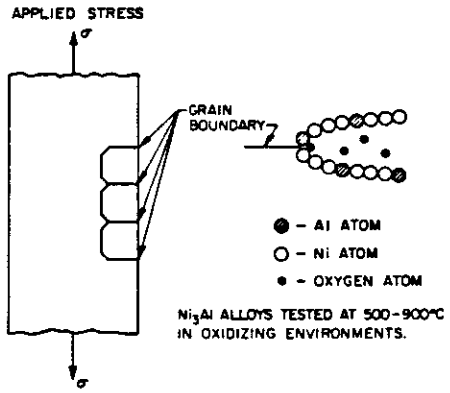


MECHANISM OF DYNAMIC EMBRITTLEMENT IN Ni_3Al ALLOYS

TECHNICAL ACCOMPLISHMENT:

- SMALL PARTIAL PRESSURES OF OXYGEN IN TEST ENVIRONMENTS WERE FOUND TO BE THE CAUSE FOR ELEVATED-TEMPERATURE EMBRITTLEMENT IN Ni_3Al ALLOYS.
- VACUUM TESTING OF PREOXIDED SPECIMENS FAIL TO SHOW ANY EMBRITTLEMENT, INDICATING A DYNAMIC PHENOMENON INVOLVING HIGH LOCALIZED STRESSES, ELEVATED TEMPERATURE, AND GASEOUS OXYGEN.





SIGNIFICANCE:

- THE DYNAMIC EMBRITTLEMENT COULD RESTRICT THE APPLICATION OF Ni_3Al IN OXIDIZING ENVIRONMENTS.
- IDENTFICATION OF THE MECHANISM RESPONSIBLE FOR THE EMBRITTLEMENT SUGGESTS METALLURGICAL SOLUTIONS TO THE PROBLEM, SUCH AS CONTROL OF GRAIN-ORIENTED AND ALLOY ADDITIONS.

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THE EMBRITTLEMENT AT 300-900°C IS DUE TO A DYNAMIC EFFECT

- PREOXIDATION DOES NOT EMBRITTLE THE ALUMINIDE SAMPLES TESTED IN VACUUM AT ELEVATED TEMPERATURES.
- ALLOY SAMPLES FRACTURED BRITTELY AT 600 AND 760°C REMAIN DUCTILE AND SHOW DUCTILE FAILURE WHEN BEND-TESTED AT ROOM TEMPERATURE.
- ALLOY SAMPLES LOST ELEVATED-TEMPERATURE DUCTILITY ALMOST INSTANTANEOUSLY WHEN OXYGEN WAS INTRODUCED TO VACUUM SYSTEMS.
- THE DUCTILITY DEPENDS STRONGLY ON PARTIAL PRESSURE OF O_2 AT ELEVATED TEMPERATURES.

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EFFECTIVE SOLUTIONS TO THE DYNAMIC EMBRITTLEMENT PROBLEM

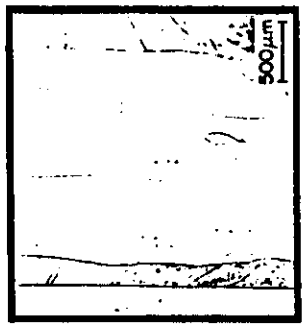
- CONTROL OF GRAIN SHAPE
  - REDUCE NORMAL STRESSES ACROSS GRAIN BOUNDARIES.
- ADDITION OF MODERATE AMOUNTS OF Cr (6–10%)
  - CHROMIUM ADDITIONS PROMOTE A RAPID FORMATION OF PROTECTIVE Cr OXIDE FILMS THAT SHUT OFF GASEOUS OXYGEN FROM GRAIN BOUNDARIES AND BASE METALS.

ORNL-DWG 87-9025

ELIMINATION OF ENVIRONMENTAL EMBRITTLEMENT IN Ni_3Al ALLOYS BY CONTROL OF GRAIN SHAPE

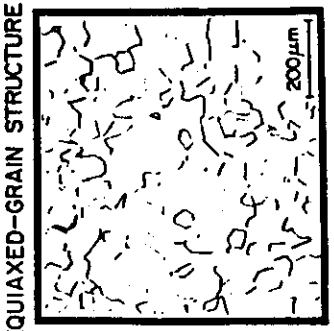
TECHNICAL ACCOMPLISHMENT:

- SMALL PARTIAL PRESSURES OF OXYGEN IN TEST ENVIRONMENTS CAUSE DYNAMIC EMBRITTLEMENT IN Ni_3Al ALLOYS AT ELEVATED TEMPERATURES.
- THE EMBRITTLEMENT CAN BE ELIMINATED IN ALLOYS WITH COLUMNAR GRAIN STRUCTURES PRODUCED BY LEVITATION ZONE-REFINE METHODS.



COLUMNAR GRAIN STRUCTURE

ϵ=33%
TRANSGRANULAR FRACTURE



EQUIAXED-GRAIN STRUCTURE

TENSILE TEST AT 600°C IN AIR

ϵ=0.5%
INTERGRANULAR FRACTURE

SIGNIFICANCE:

- THE ENVIRONMENTAL EMBRITTLEMENT IN Ni_3Al ALLOYS CAN BE ALLEVIATED SIMPLY BY CONTROL OF GRAIN SHAPE.
- MOST SIGNIFICANTLY, THIS RESEARCH HAS DEMONSTRATED A NEW DIMENSION IN DESIGN OF METALS AND ALLOYS WITH GRAIN-BOUNDARY PROBLEMS.

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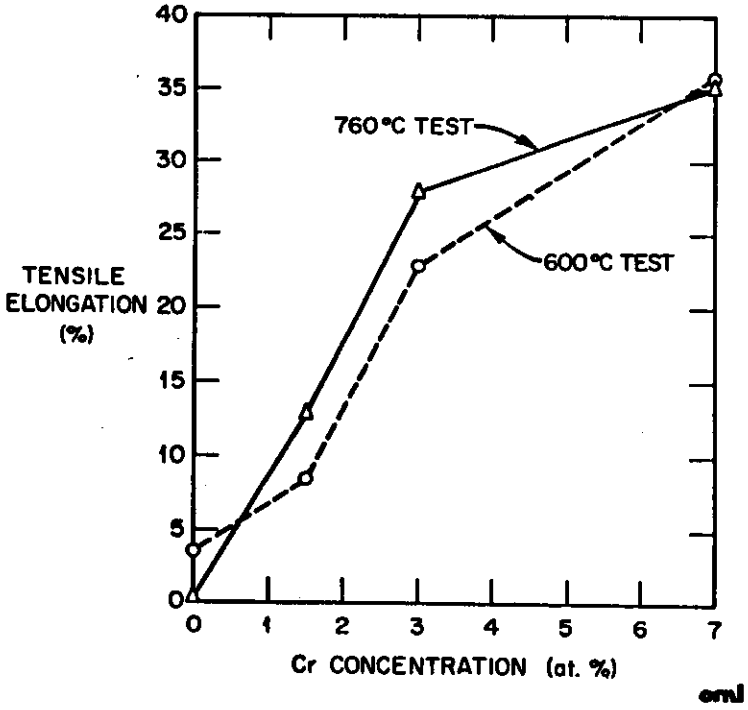
ORNL-DWG 86-10829

CHROMIUM ADDITIONS SUBSTANTIALLY IMPROVE TENSILE DUCTILITY OF Ni-Fe ALUMINIDES (15.5 at.% Fe) AT 600 AND 760 °C IN AIR



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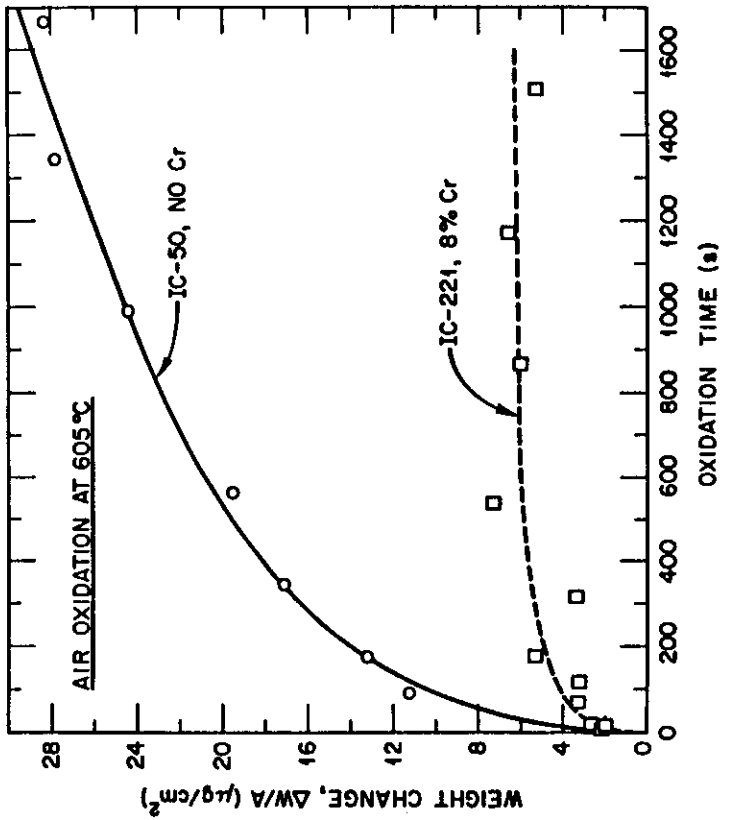
ORNL-DWG 86-7812

CHROMIUM ADDITIONS PROMOTE A RAPID FORMATION OF PROTECTIVE OXIDE FILMS ON SURFACES OF Ni_3Al ALLOYS



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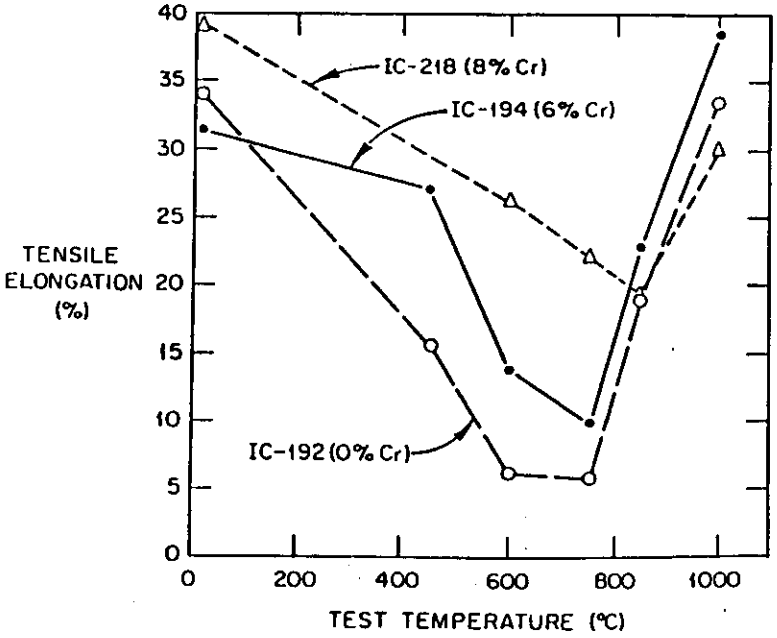
ORNL-DWG 86-7816

ALLOYING WITH 8 at. % Cr SUBSTANTIALLY REDUCES DYNAMIC EMBRITTLEMENT IN OXIDIZING ENVIRONMENTS



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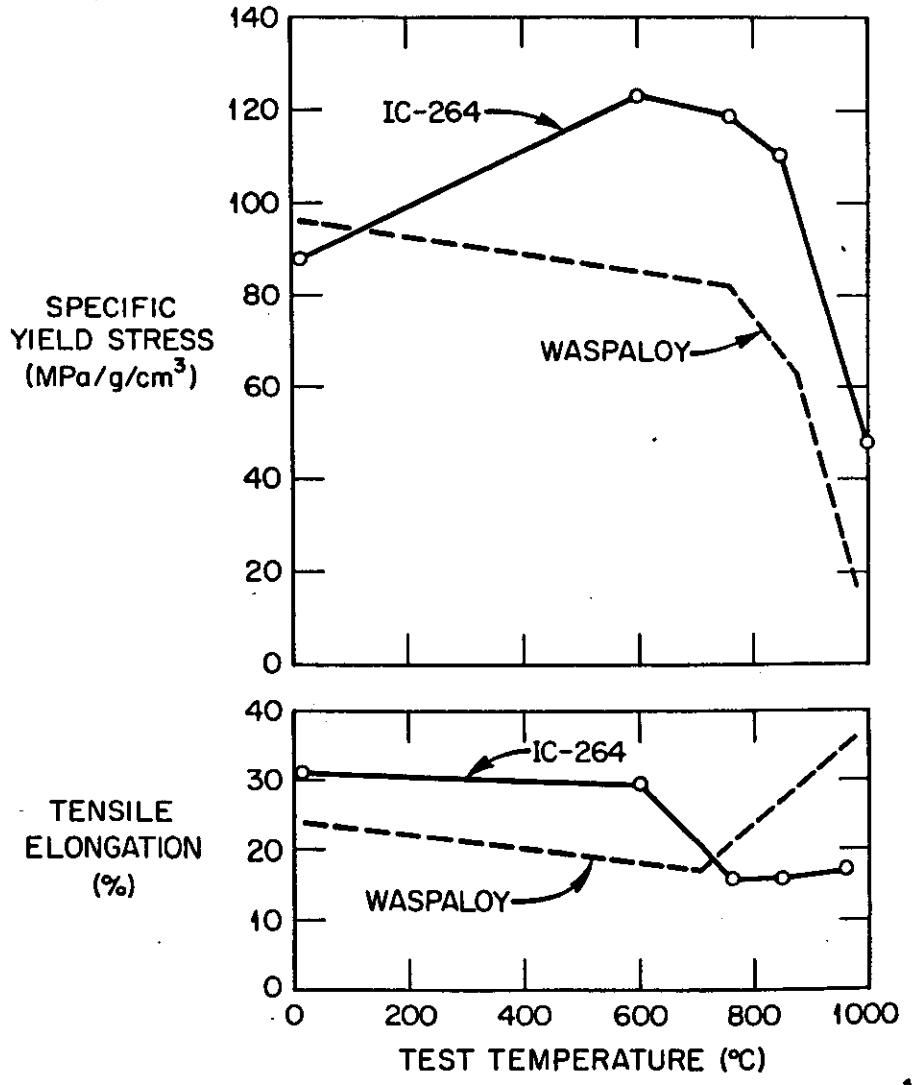
ORNL-DWG 86-10649

NICKEL ALUMINIDE (IC-264) HAS SUPERIOR TENSILE PROPERTIES AT ELEVATED TEMPERATURES



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EFFECT OF COLD WORK (20-22%) ON TENSILE PROPERTIES OF Ni_3Al ALLOYS

ALLOY (AT. %)	TEST TEMPERATURE (C°)	STRENGTH (KSI)		DUCTILITY (%)
		YIELD	TENSILE	
Ni_3Al + 13 Fe	RT	231	249	4.0
Ni_3Al + 1 Hf	RT	221	254	2.0
Ni_3Al + 1 Hf	600	166	212	12.0
Ni_3Al + 1 Hf	760	143	163	8.7

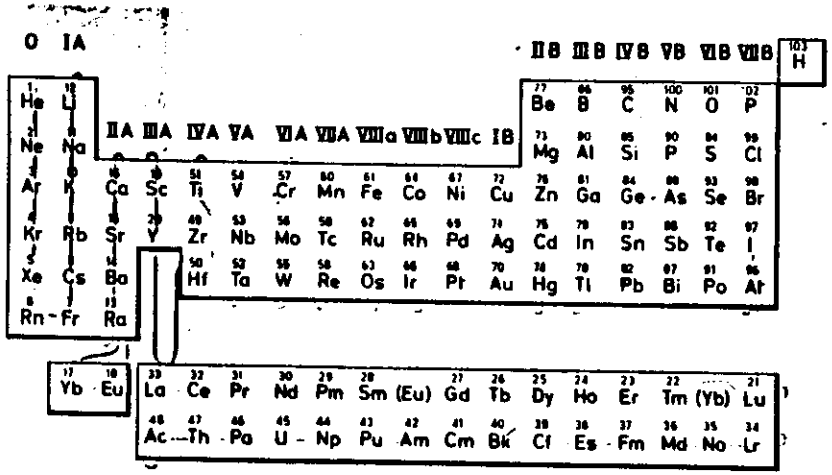
RECENT DEVELOPMENT OF ORDERED INTERMETALLIC ALLOYS HAS FOCUSED ON ALUMINIDES AND SILICIDES

ALLOY	T_M (C°)	DENSITY (G/CM^3)	CRYSTAL STRUCTURE
Ni_3Al	1400	7.5	$L1_2$
NiAl	1640	5.9	B2
FeAl	1250/1400	5.6	B2
Fe_3Al	1540	6.7	DO_3
Ti_3	1600	4.2	DO_{19}
TiAl	1460	3.9	$L1_0$
$TiAl_3$	1350	3.2	DO_{22}
Ni_3Si	1143	7.3	$L1_2$
$MoSi_2$	2020	5.0	$C11_B$
Ti_5Si_3	2130	3.7	D8 8

STRUCTURAL MAPS DEVELOPED BY

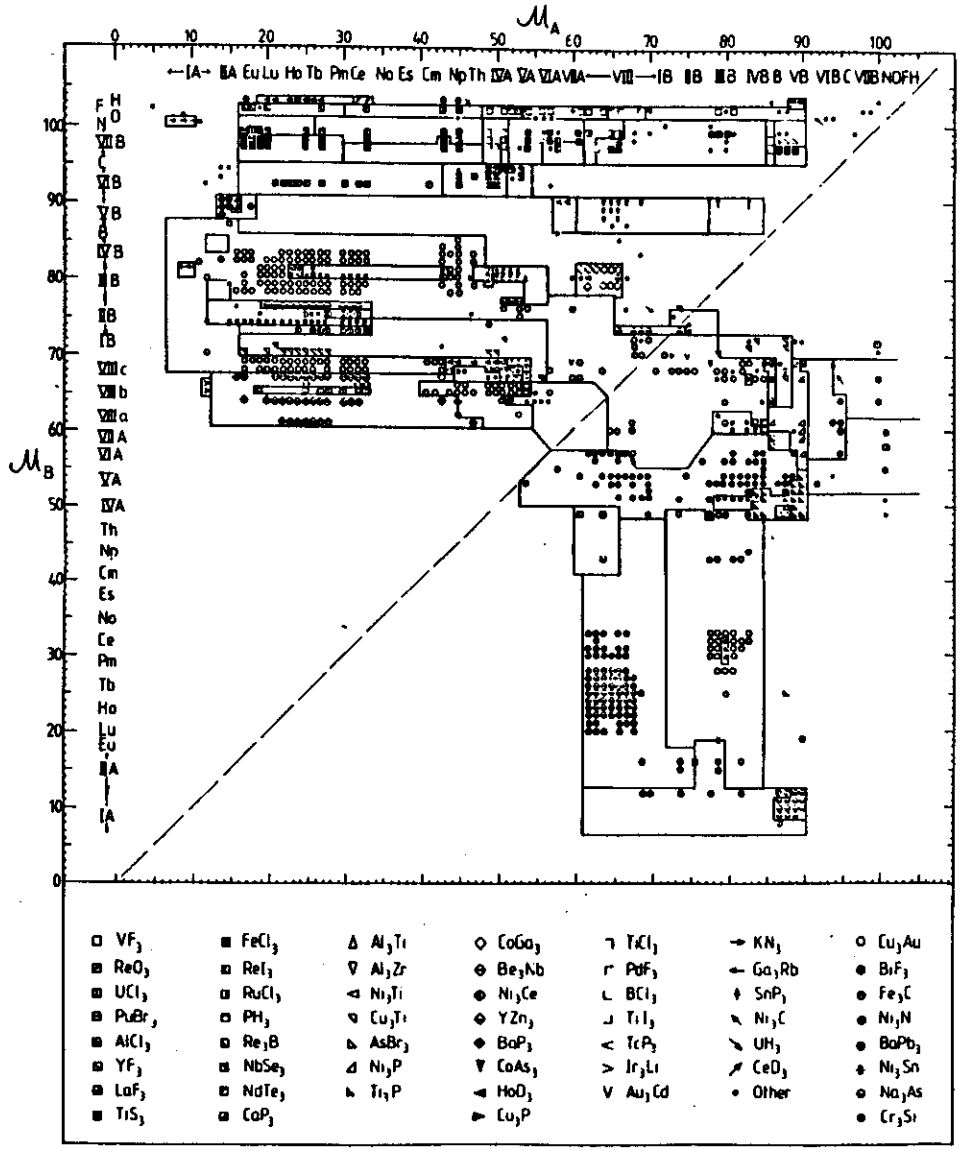
PROF. DAVE PETTIFOR

- PETTIFOR HAS ATTEMPTED TO USE ONE NUMBER, MENDELEEV NUMBER, TO REPRESENT ALL EFFECTS FROM ATOM SIZE, ELECTRONEGATIVITY AND VALENCE ELECTRON
- THE STRING RUNNING THROUGH A MODIFIED PERIODIC TABLE PUTS ALL THE ELEMENTS IN SEQUENTIAL ORDER, GIVEN BY THE MENDELEEV NUMBER



The string running through this modified periodic table puts all the elements in sequential order, given by the Mendeleev number

THE AB_3 MAP



SUMMARY

1. SIGNIFICANT PROGRESS HAS BEEN MADE IN IMPROVING THE DUCTILITY AND FRACTURE BEHAVIOR OF ORDERED INTERMETALLIC ALLOYS.

2. BORON IS EFFECTIVE IN SUPPRESSING BRITTLE GRAIN-BOUNDARY FRACTURE AND INCREASING THE DUCTILITY OF Ni_3X ALLOYS (X = Al, Si AND Ga) WITH HYPO-STOICHIOMETRIC COMPOSITIONS.

3. DUCTILITY IN Ni_3V-Co_3V-Fe_3V ALLOYS CAN BE DRAMATICALLY IMPROVED BY CONTROL OF ELECTRON CONCENTRATION AND ORDERED CRYSTAL STRUCTURES.

4. ALUMINIDES HAVE POTENTIAL TO BE DEVELOPED AS NEW HIGH-TEMPERATURE STRUCTURAL MATERIALS.