Final Proceedings of The EOARD/IRC-sponsored International Workshop on Gamma Aluminide Alloy Technology

held from 1 to 3 May 1996
at The IRC in Materials for High Performance Applications
The University of Birmingham

SECTION THREE

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Interdisciplinary Research Centre

in

Materials for High Performance Applications

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SECTION THREE

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Gamma Alloy Technology: Fundamentals and Development

Young-Won Kim
UES-Materials & Processes
Dayton, OH, USA

Fundamentals
Processing
Microstructural Evolution
Structure/Property Relationships
Designing Microstructures
Component-Specific Alloy Design
Forming and Application
Summary and Future Direction

(April 1996)

√

Fundamentals

Phase Relations and Transformations

Microstructural Evolution

Deformation Mechanism

Alloying Effects

Deformation and Fracture Behavior

Environmental Resistance

Alpha Decomposition

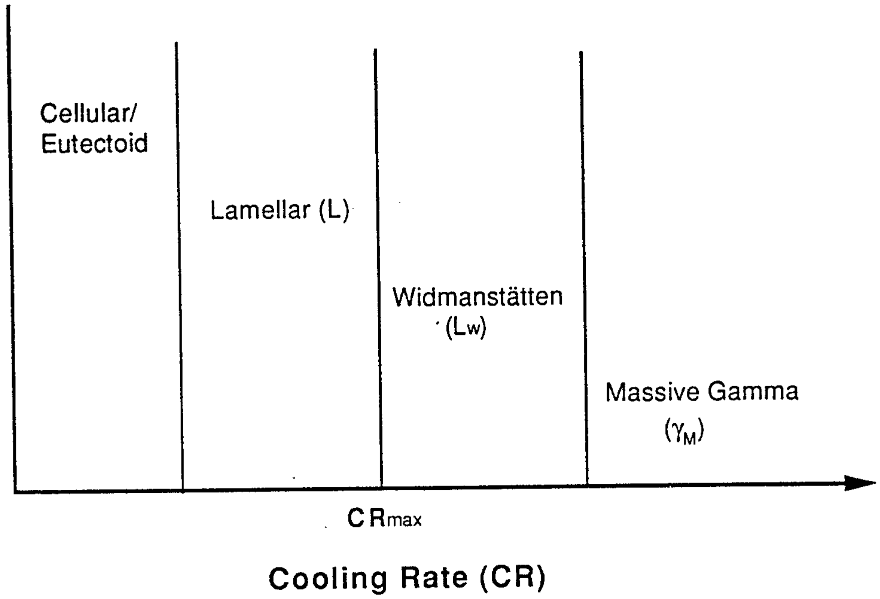
At Very Slow Cooling Rate

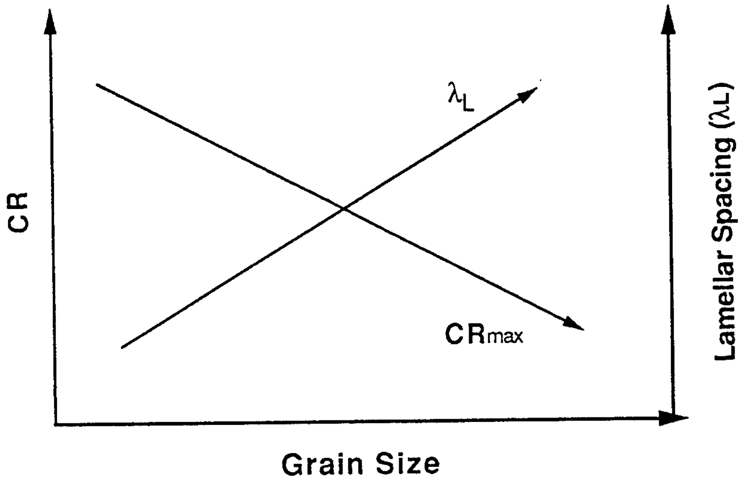
At Intermediate Cooling Rates

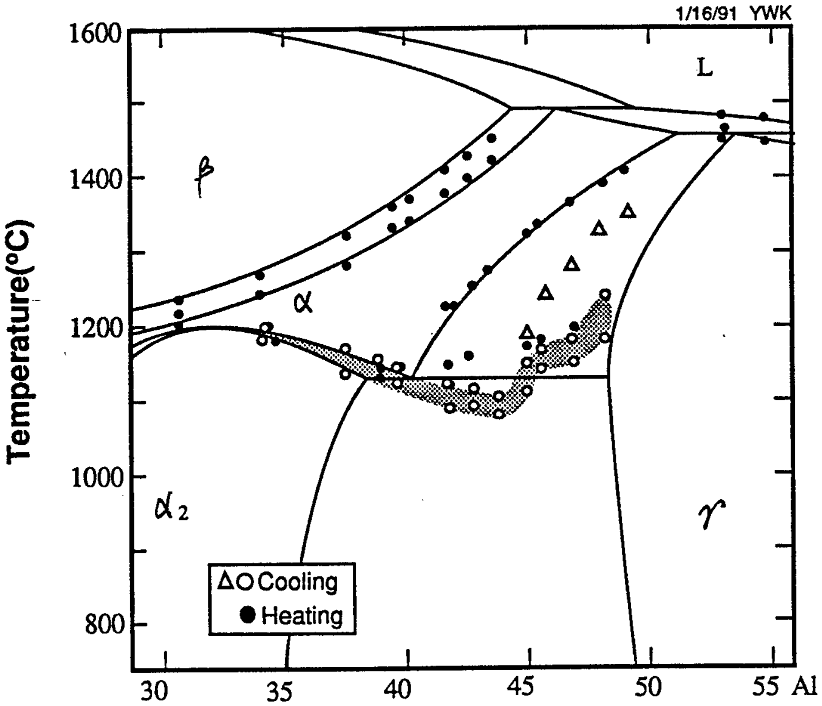
- Lamellar Structure Formation
  - Stacking Fault Mechanism
  - Gamma Precipitation and Growth
- Ordering
  - No Compositional Changes Involved
  - Compositional Changes Involved
- Effects of Composition and Cooling Rate

At Fast Cooling Rates

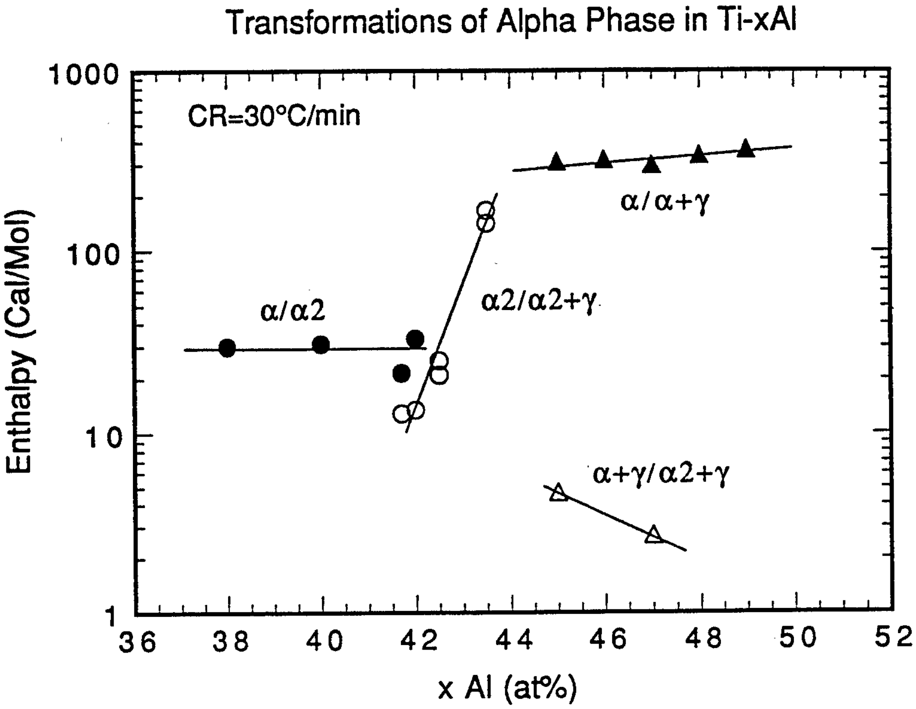
- Widmanstätten Structures
- Massively-Transformed Gamma
- Formation of α_2 Phase


Cellular/
Eutectoid
Lamellar (L)
Widmanstätten
(Lw)
Massive Gamma
(γM)
CRmax
Cooling Rate (CR)

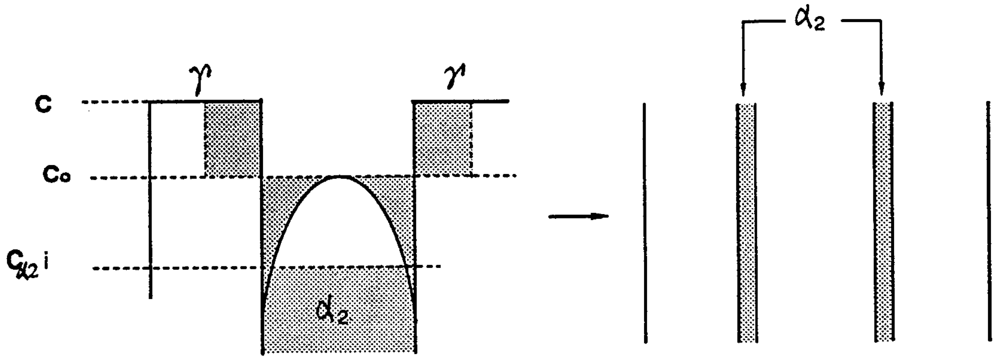

λL
CR
CRmax
Lamellar Spacing (λL)
Grain Size

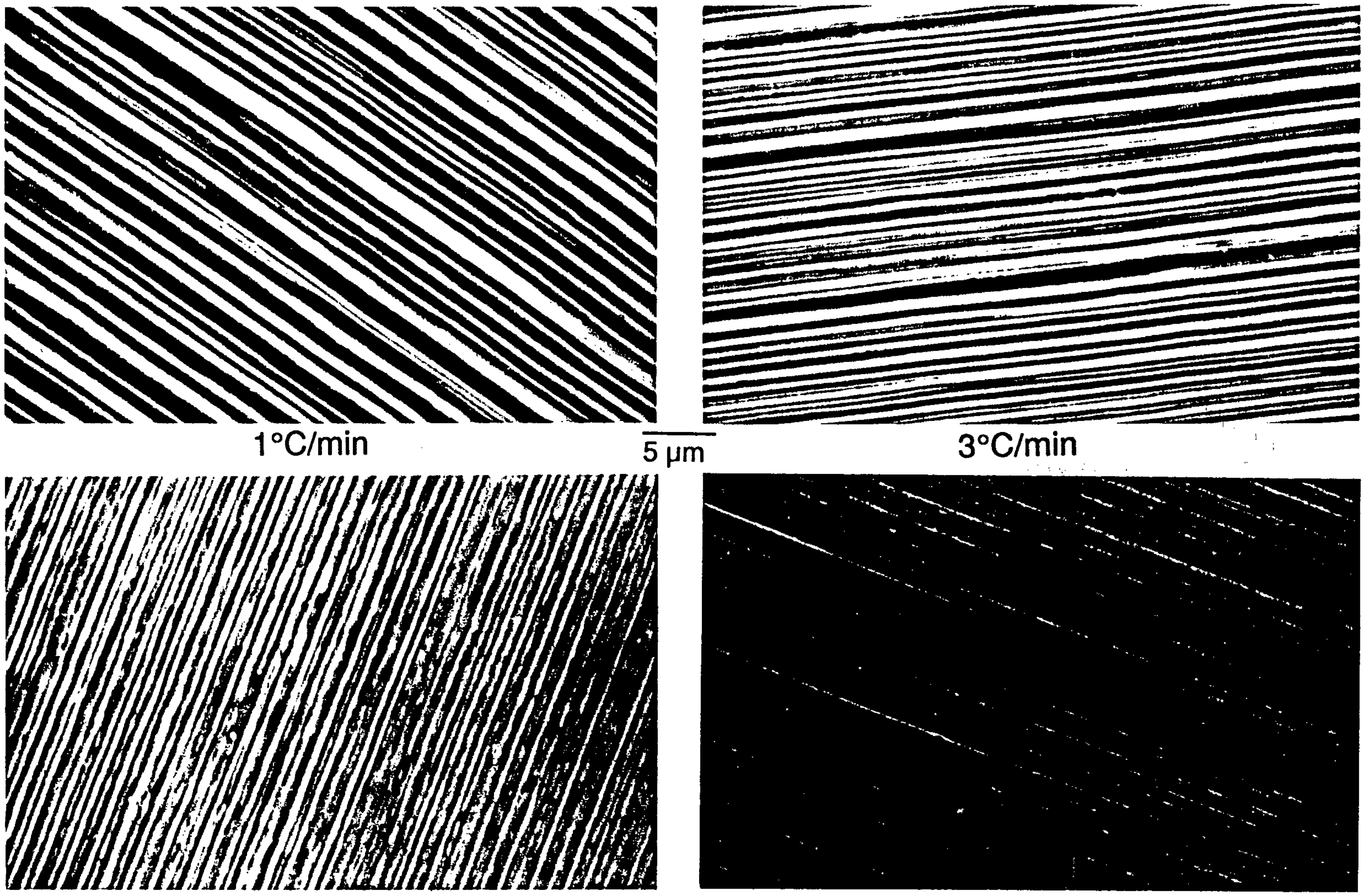


DTA Data at 30°C/min



Transformations of Alpha Phase in Ti-xAl





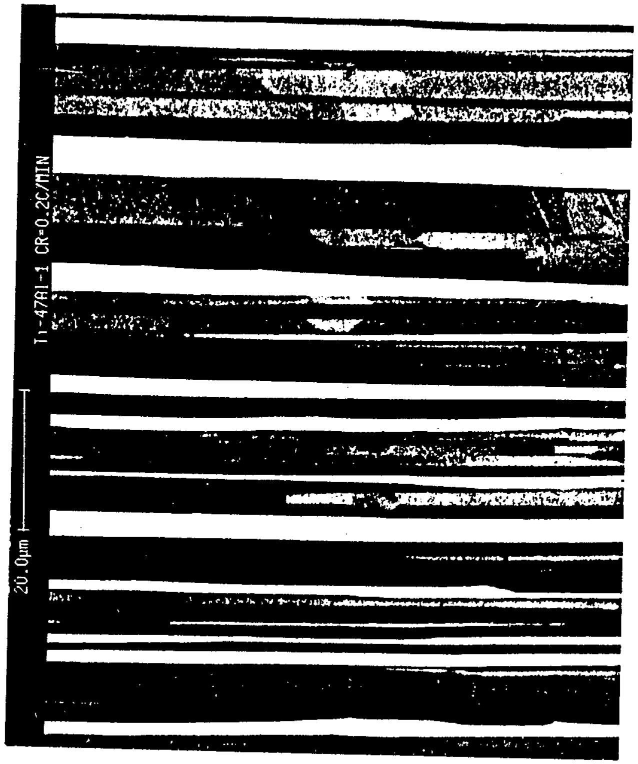
1°C/min 3°C/min

20°C/min 100°C/min

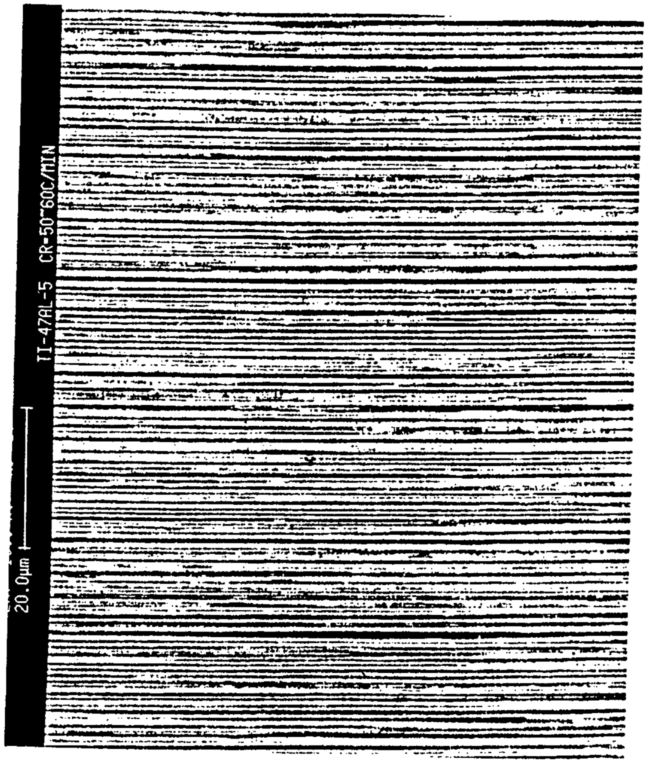
Ti-43Al : Homogenized and DTA Cooled

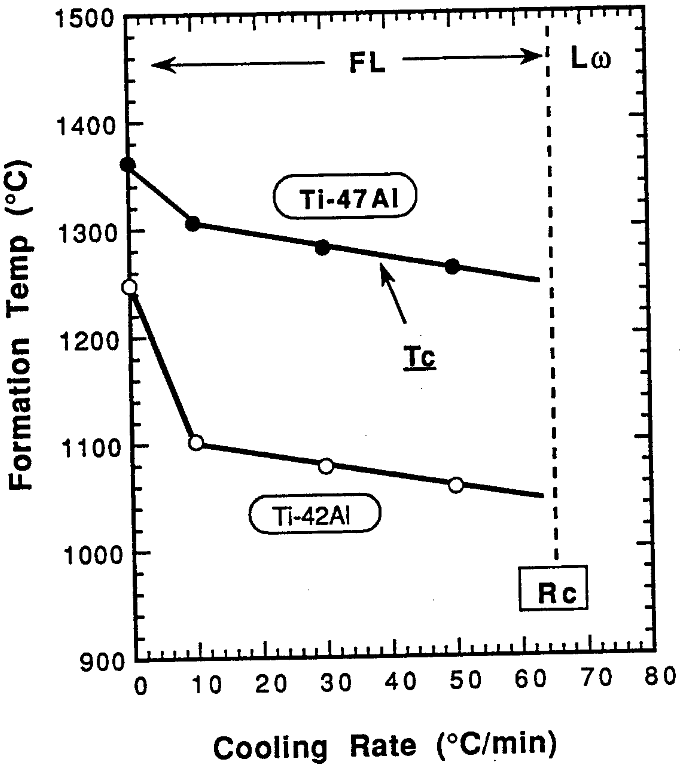
Cooling Rate vs Lamellar Spacing
(Ti-47Al)

0.2 °C/min



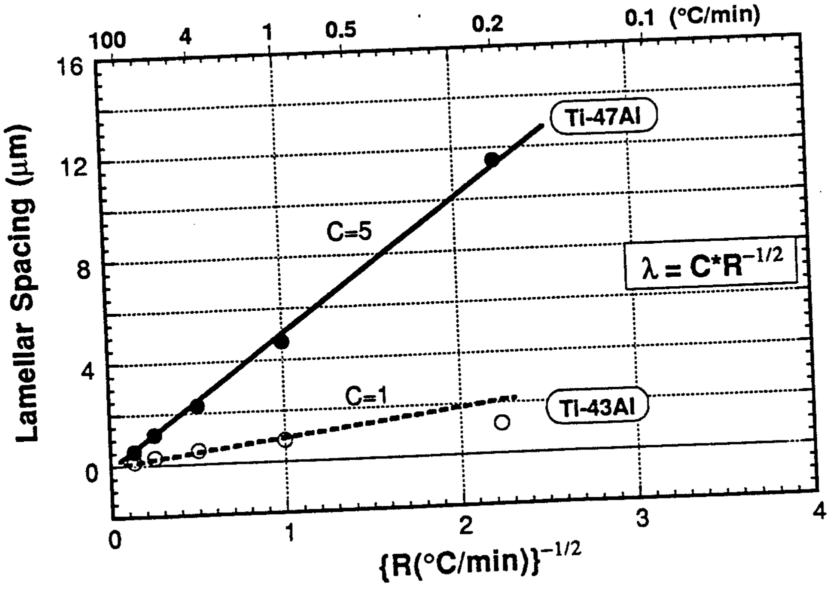
50°C/min



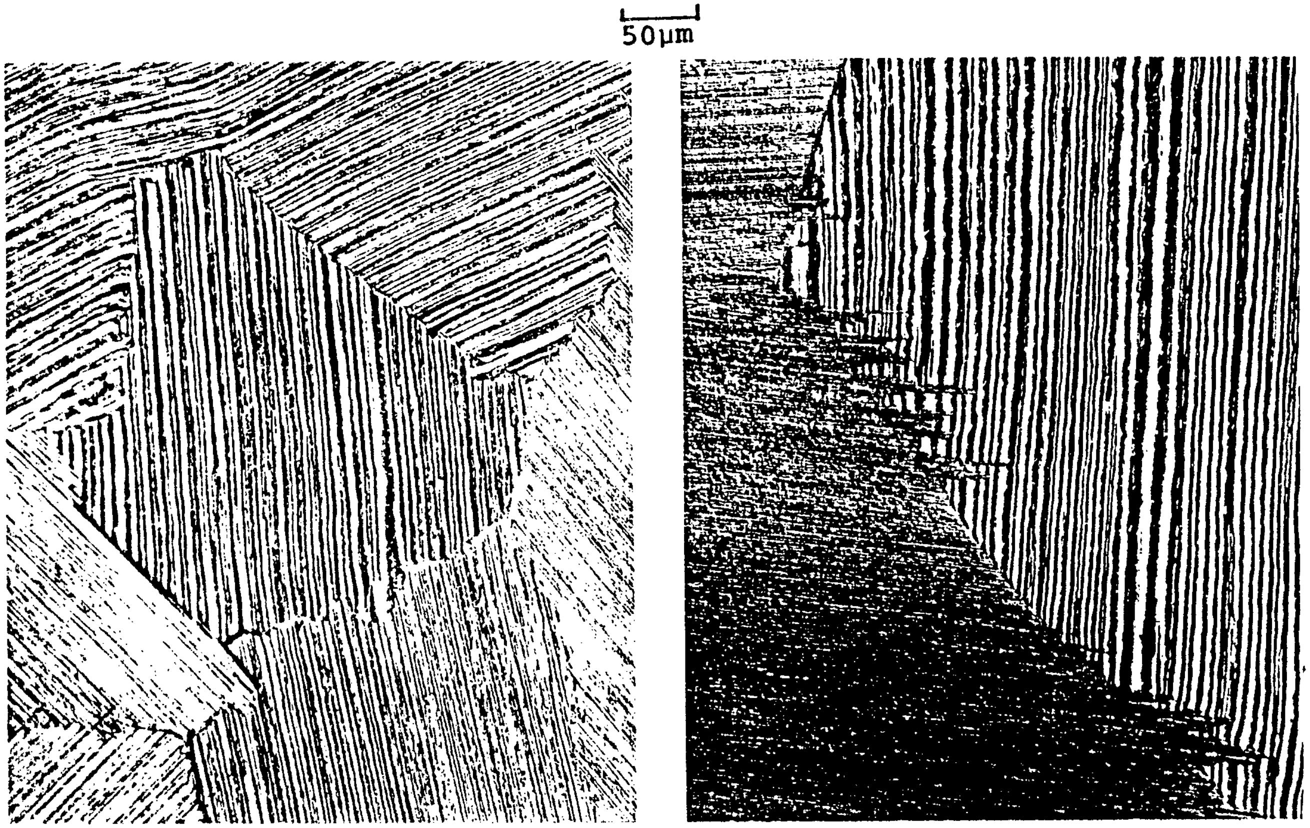


Kim (94)

Cooling Rate (R) vs Lamellar Spacing (λ)



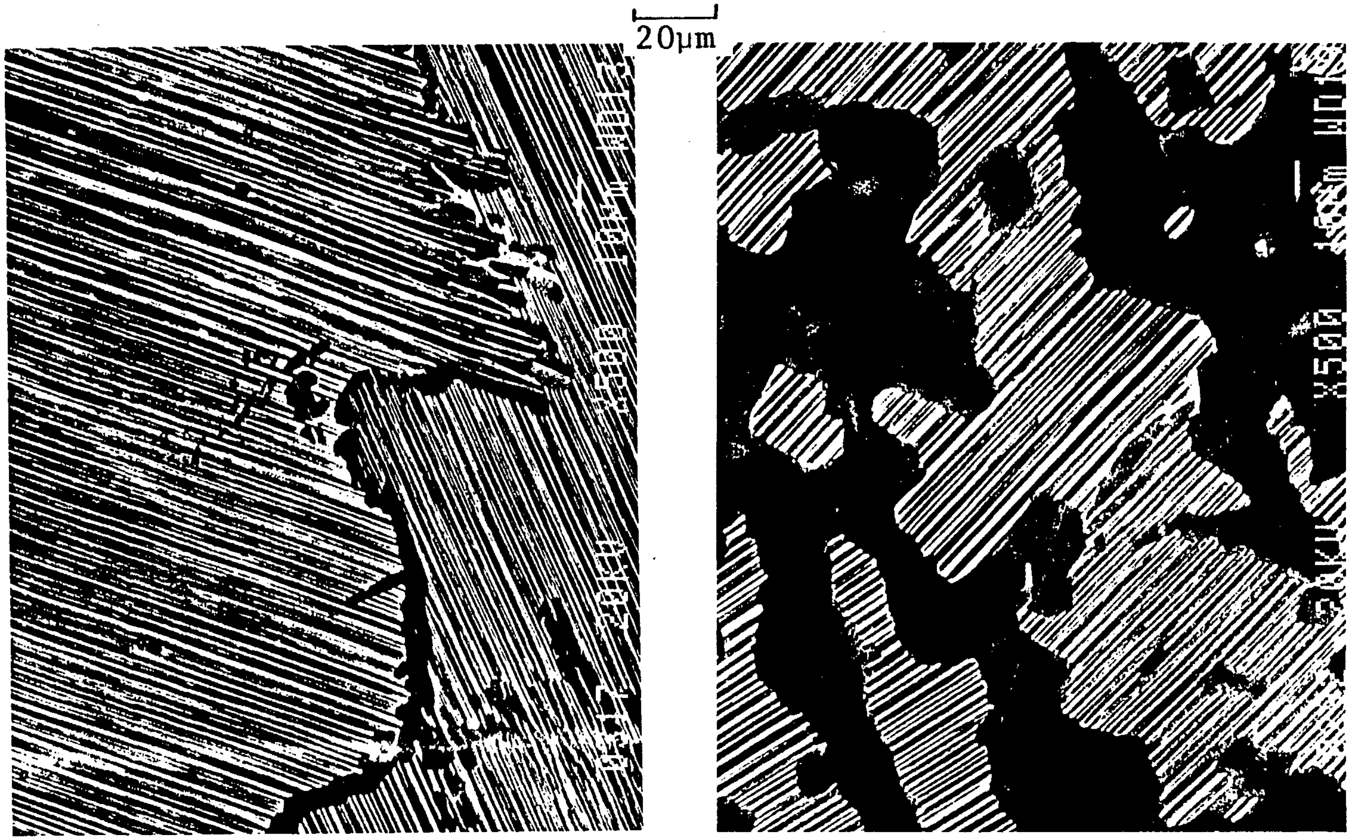
Kim (94



Ti-43Al: Cooled at 5°C/min

Ti-47Al: Cooled at 30°C/min

DTA specimens of homogenized alloys



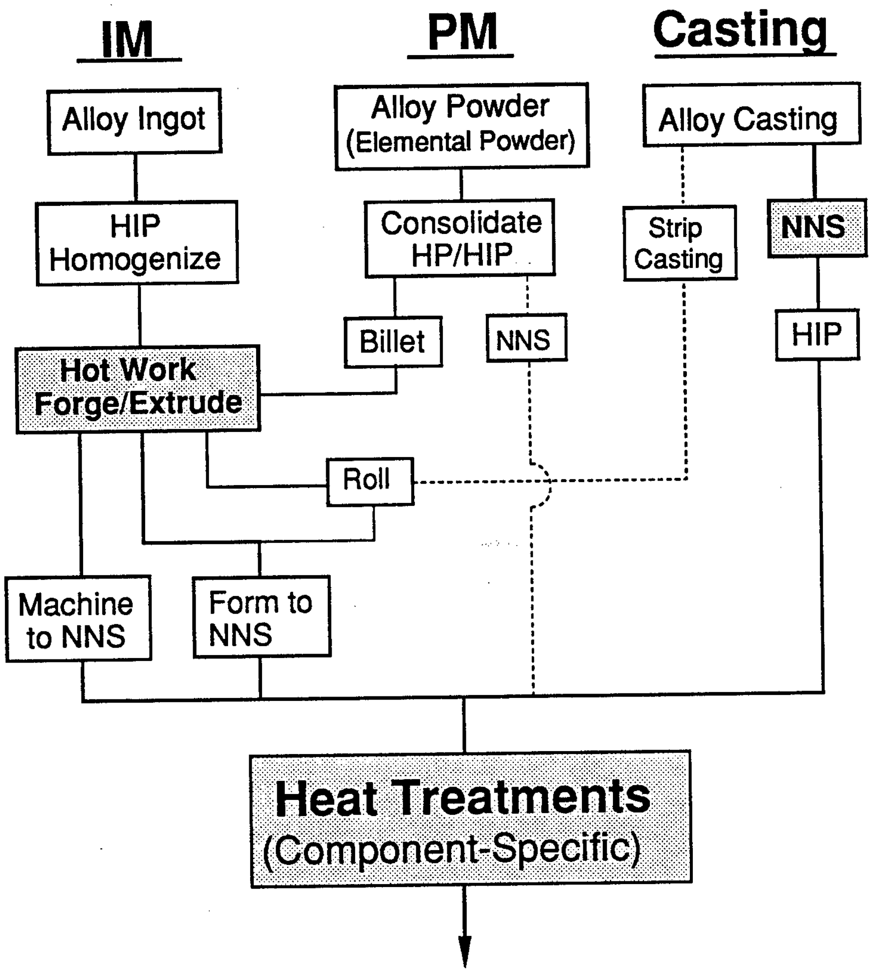
Ti-47Al-1.1 wt%Ox
1350°C/6 hr + 1000°C/24 hr/WQ

Ti-51Al-1.1 wt%Ox
1350°C/6 hr/FC

Cast alloys

Processing Routes for Gamma Alloys

Kim (90-95)



IM

Alloy Ingot

HIP Homogenize

Hot Work Forge/Extrude

Roll

Machine to NNS

Form to NNS

PM

Alloy Powder (Elemental Powder)

Consolidate HP/HIP

Billet

NNS

Casting

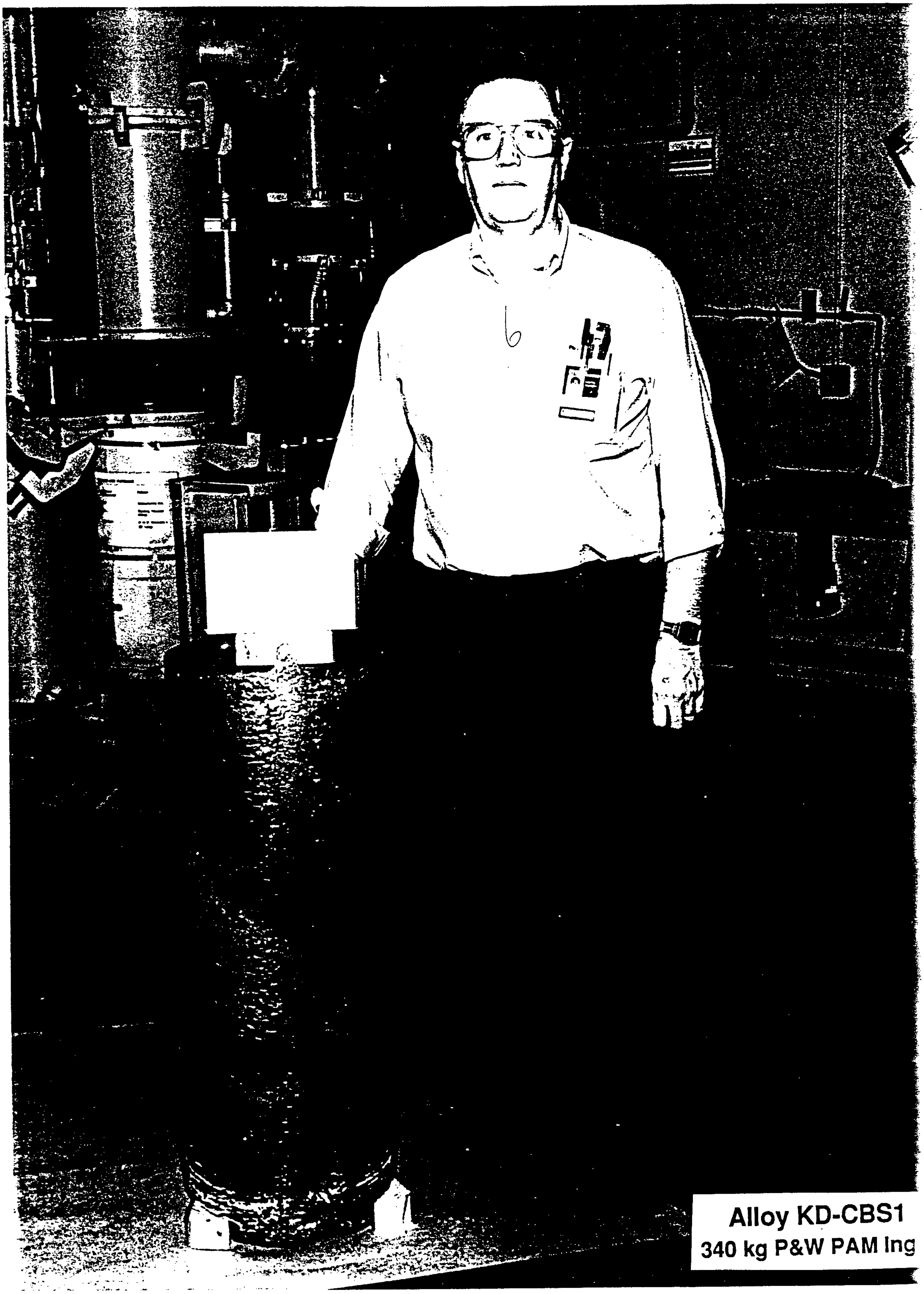
Alloy Casting

Strip Casting

NNS

HIP

Heat Treatments
(Component-Specific)



Alloy KD-CBS1

340 kg P&W PAM Ing

Microstructural Evolution and Control

Principle

Phase Relation and Transformation

In Practice

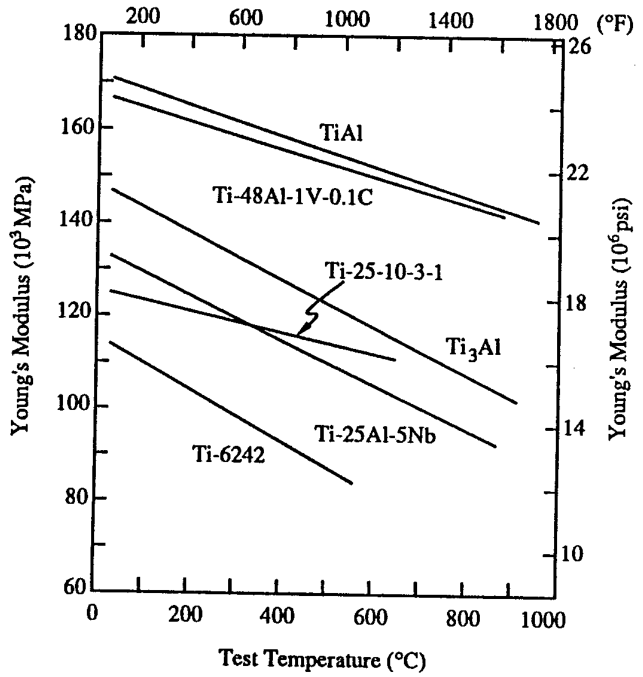
Formation/Growth Kinetics, Distribution and Morphology Depend on Starting Microstructural and Compositional Conditions.

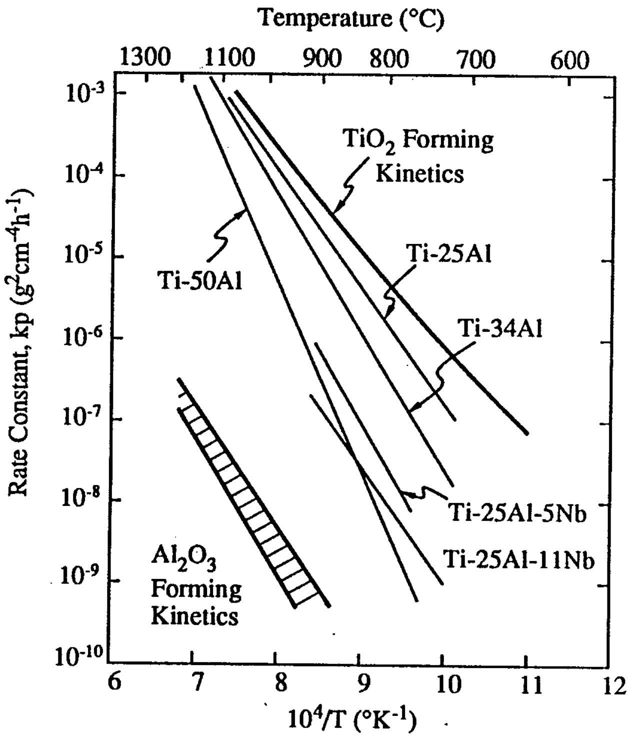
Controlling Factors

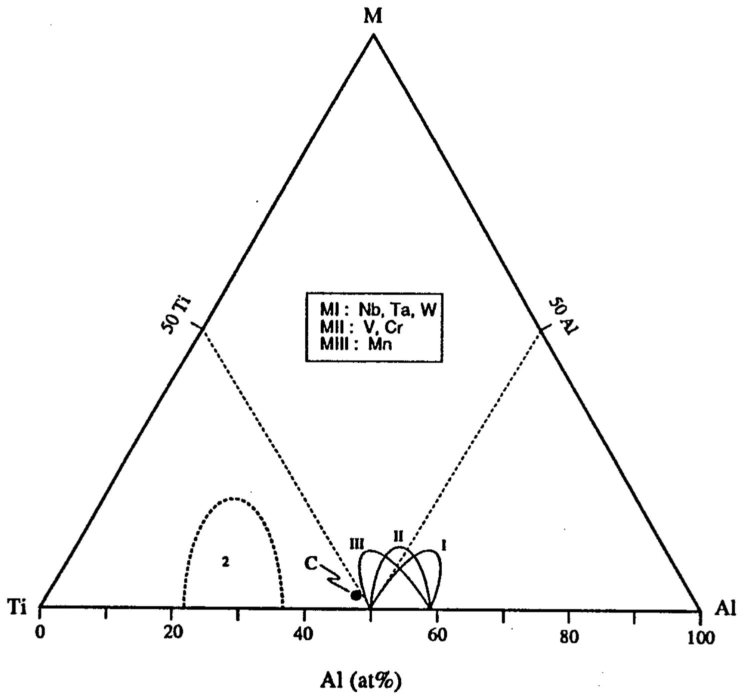
Temperature and Time
Heating Rate, Cooling Rate, and Scheme
Aging Method and Condition

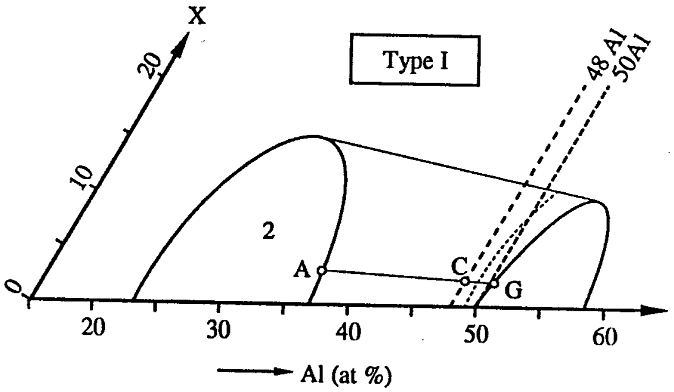
Starting Material

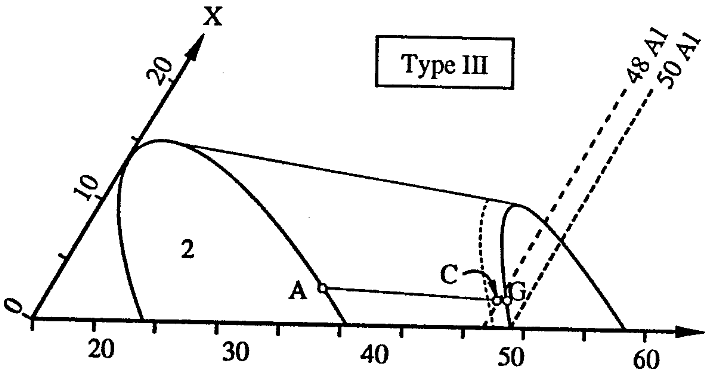
Cast Product
Ingot Wrought-Processed Material
PM Processed Material
Material Processed by Other Processes

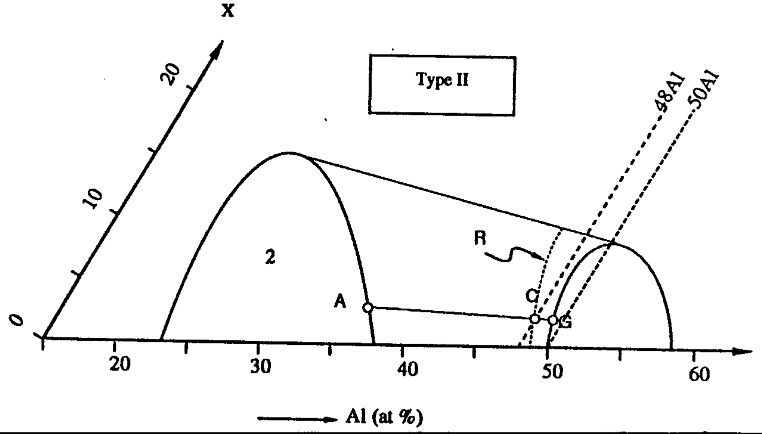

200
600
1000
1400
1800 (°F)
180
160
140
120
100
80
60
26
22
18
14
10
0
200
400
600
800
1000
TiAl
Ti-48Al-1V-0.1C
Ti-25-10-3-1
Ti$_3$Al
Ti-25Al-5Nb
Ti-6242
Young's Modulus (10^{3}MPa)
Young's Modulus (10^{6}psi)
Test Temperature (°C)


Temperature (°C)
1300
1100
900
800
700
600
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
6
7
8
9
10
11
12
TiO$_2$ Forming Kinetics
Ti-25Al
Ti-34Al
Ti-50Al
Ti-25Al-5Nb
Ti-25Al-11Nb
Al$_2$O$_3$ Forming Kinetics
Rate Constant, kp (g^{2}cm^{-4}h^{-1})
10^4/T (°K^{-1})


M
MI : Nb, Ta, W
MII : V, Cr
MIII : Mn
50 Ti
50 Al
2
C
III
II
I
Ti
Al
0
20
40
60
80
100
Al (at%)


Type I
X
0
10
20
2
A
C
G
48 Al
50Al
20
30
40
50
60
Al (at %)


Type III
X
0
10
20
2
A
C
G
48 Al
50 Al
20
30
40
50
60


Type II
x
0
10
20
2
A
R
C
G
48Al
50Al
20
30
40
50
60
Al (at %)

Processing

Ingot Preparation

Methods: ISM; PAM; VAR; VAR-Skull
Size Limitations (?)
Compositional/Microstructural Issues

NNS Casting

Investment vs. Permanent-Mold
Issues: Refinement; Porosity/Hip-Cycle
Thin-Section Casting

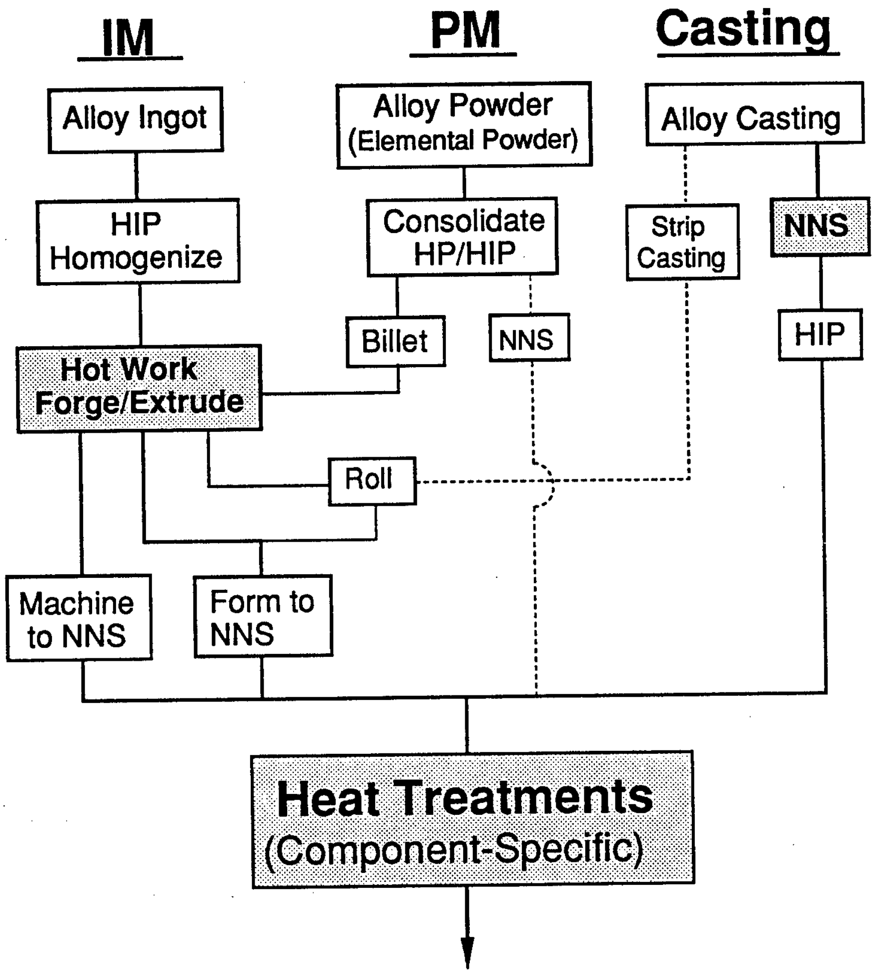
Wrought Processing

Primary: Conversion; Mill Production
Secondary: Forming, Rolling, etc.
Heat-Treatment Cycles
Joining; Machining

Other Processes

Processing Routes for Gamma Alloys

Kim (90-95)



Microstructure Control in Castings

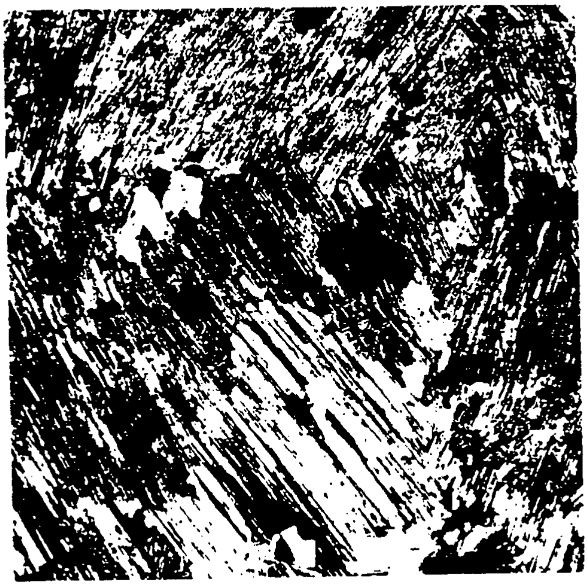
Standard Alloys

- Ti-47Al-(1-2)Cr-(2-4)(Nb,Ta,W)-(0-0.2)Si
- As-Cast Microstructures
  - Non-uniform; Lamellar Base
- Controlled Microstructures
  - Refining and Uniformization
  - Practical: Casting Duplex
  - Desired: NL; Refined FL

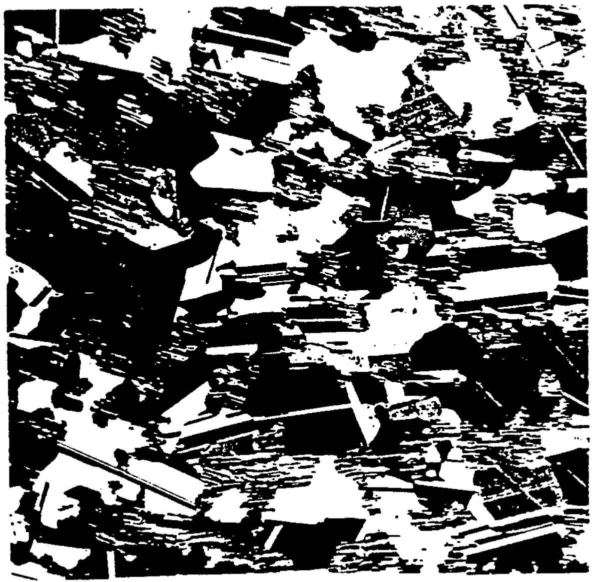
Boride-Containing Alloys

- XD Gamma Alloys
  - Ti-(45, 47)Al-4(Cr,Mn)-2Nb-0.8TiB2
  - TMT-Type Microstructures
- Others: IHI; GKSS
- Inoculation by Borides

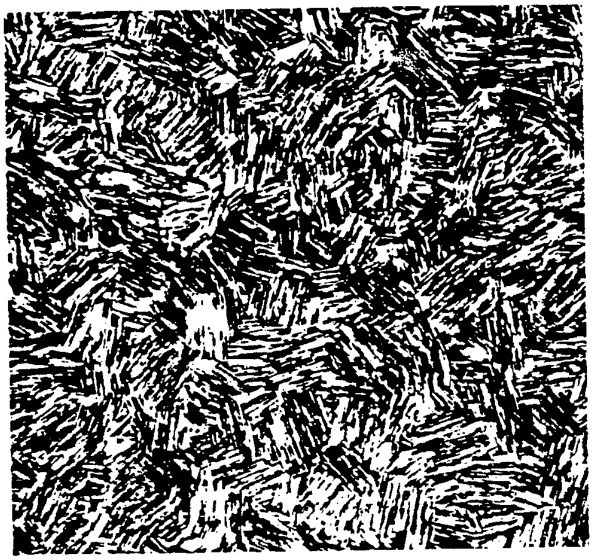
Microstructures in Castings



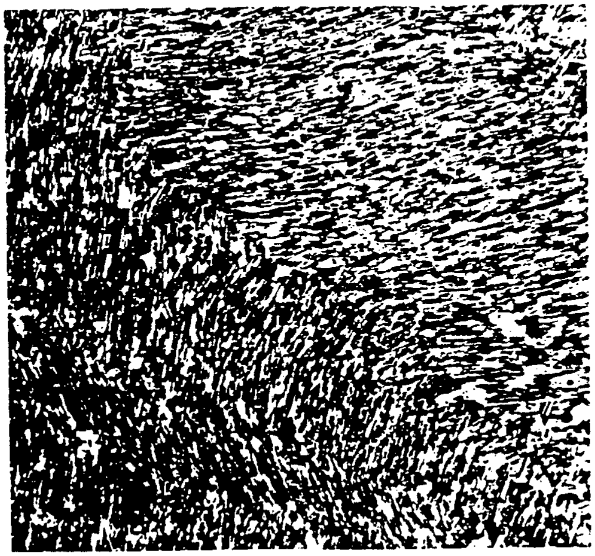
Cast and HIP'ed



Casting Duplex



XD (HIP'ed)



GKSS, As Cast

Casting RFL

As-Cast

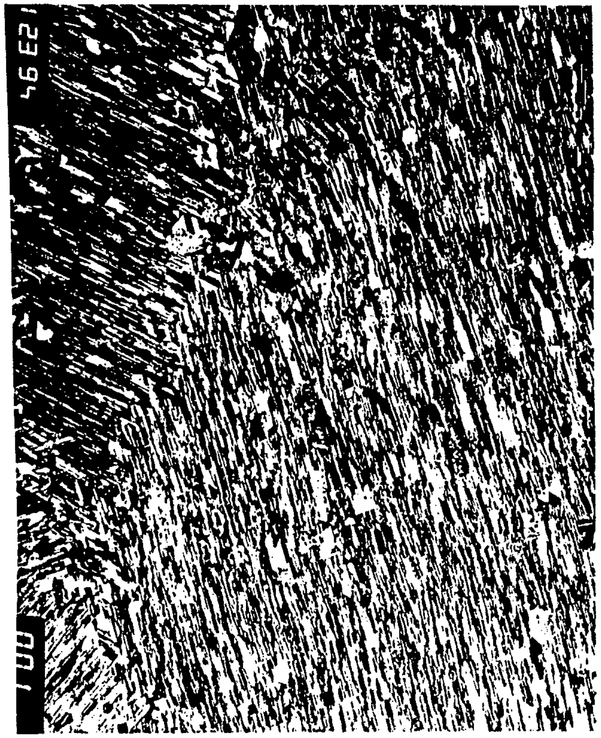
Tα-ΔT Treated

100 µm

[redacted]

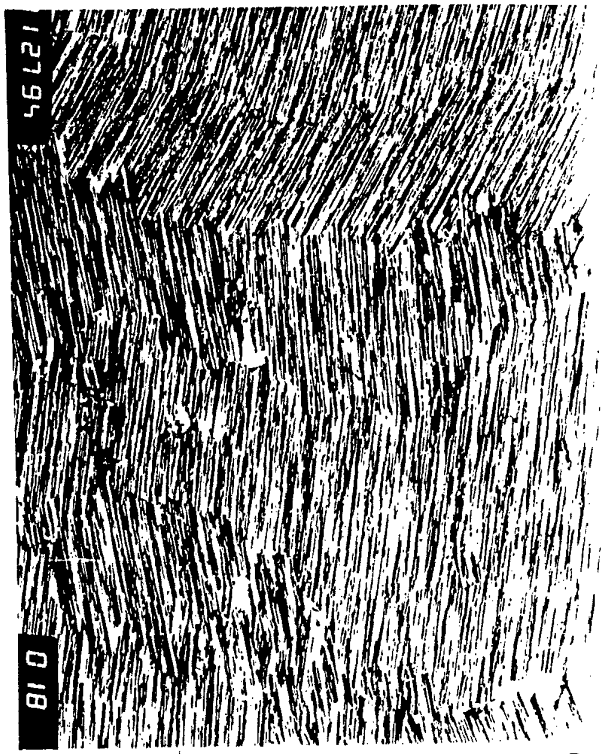
309-1A: 1320/2h 200X

309-09: 1440/½h 200X

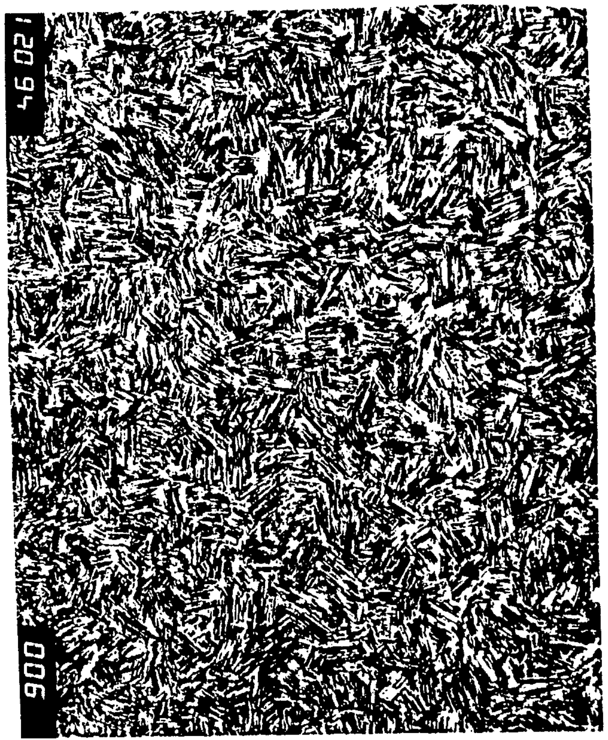


GKSS 100x As RECIEVED. P.L

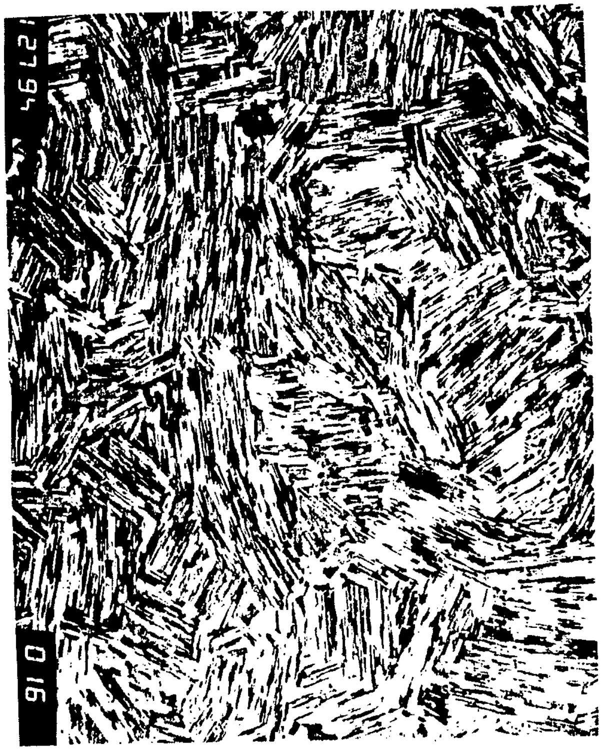
GKSS-3 1320/2Hr/FC/1000 100x P.L.



GKSS-2 1350/40m/FC/1000 100x P.L



XD-01 50x Cast



XD0L-3 1320°/2Hr/FC/1000 100x P.L.

XD01-2 1370°/40min/F.C/1000 100x P.L.

Microstructure Control in Wrought Alloys

Standard Alloys

Ti-47Al-(0-3)(Cr,Mn,V)-(0-6)(Nb,Ta,Mo,W)

As-Processed Microstructures
- Fine Mixture of Gamma and Alpha-2

Heat Treatments Yield
- Standard Microstructures

Standard Microstructures

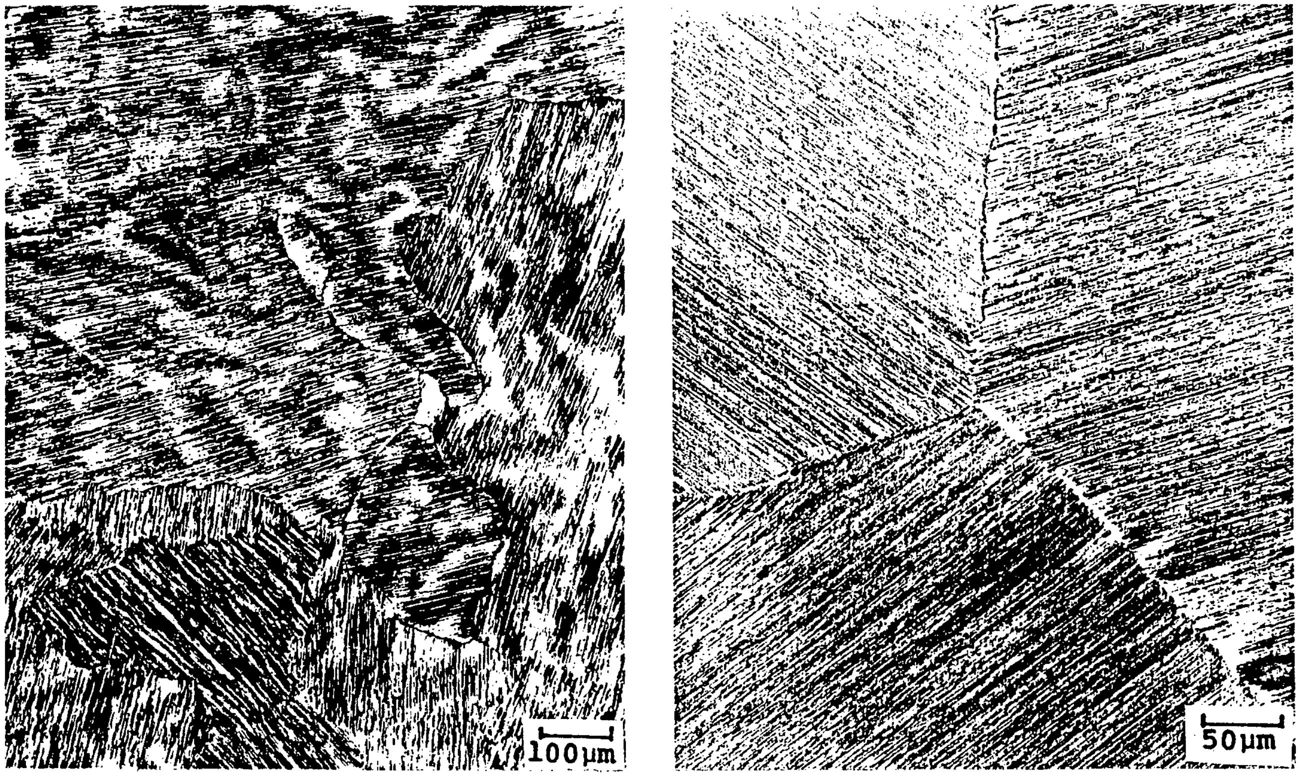
Types
- Near-Gamma (NG)
- Duplex (DP)
- Nearly-Lamellar (NL)
- Fully-Lamellar (FL)

Inverse El/K1c Relationship

Difficulties in Designing

Effort on Fundamental Understanding

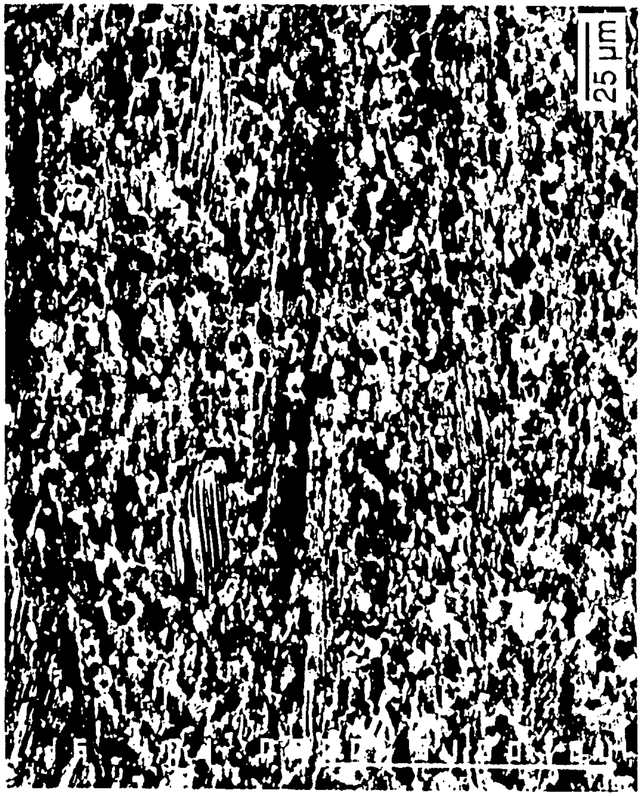
Designed Microstructures



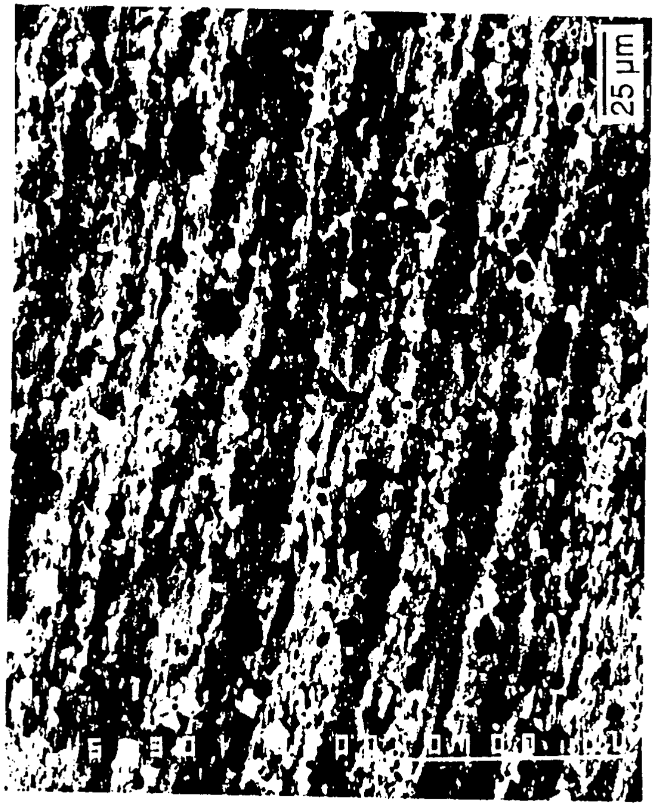
1300°C/1 HR/OQ + 900°C/1 HR/AC

1380°C/2 HR/CC + 1180°C/30 MIN/AC

TI-46AL ALLOY CIGAR



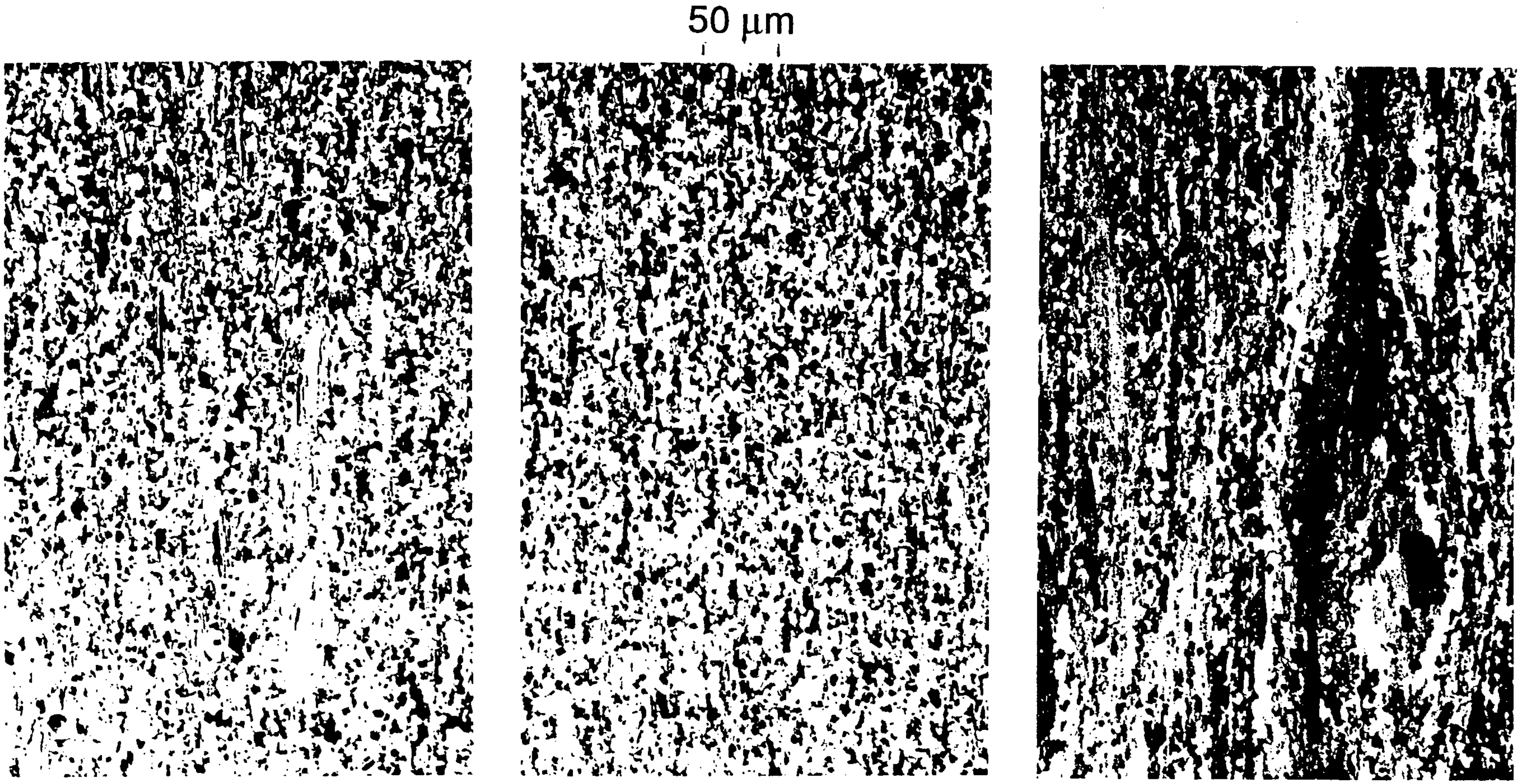
K5 (Ti-46.2Al-2Cr-3Nb-0.2W)



K5WSB (K5+0.3W+0.2Si+0.1B)

Alloy K5's: **Isothermally-Forged** (1150°C/70/70)

d

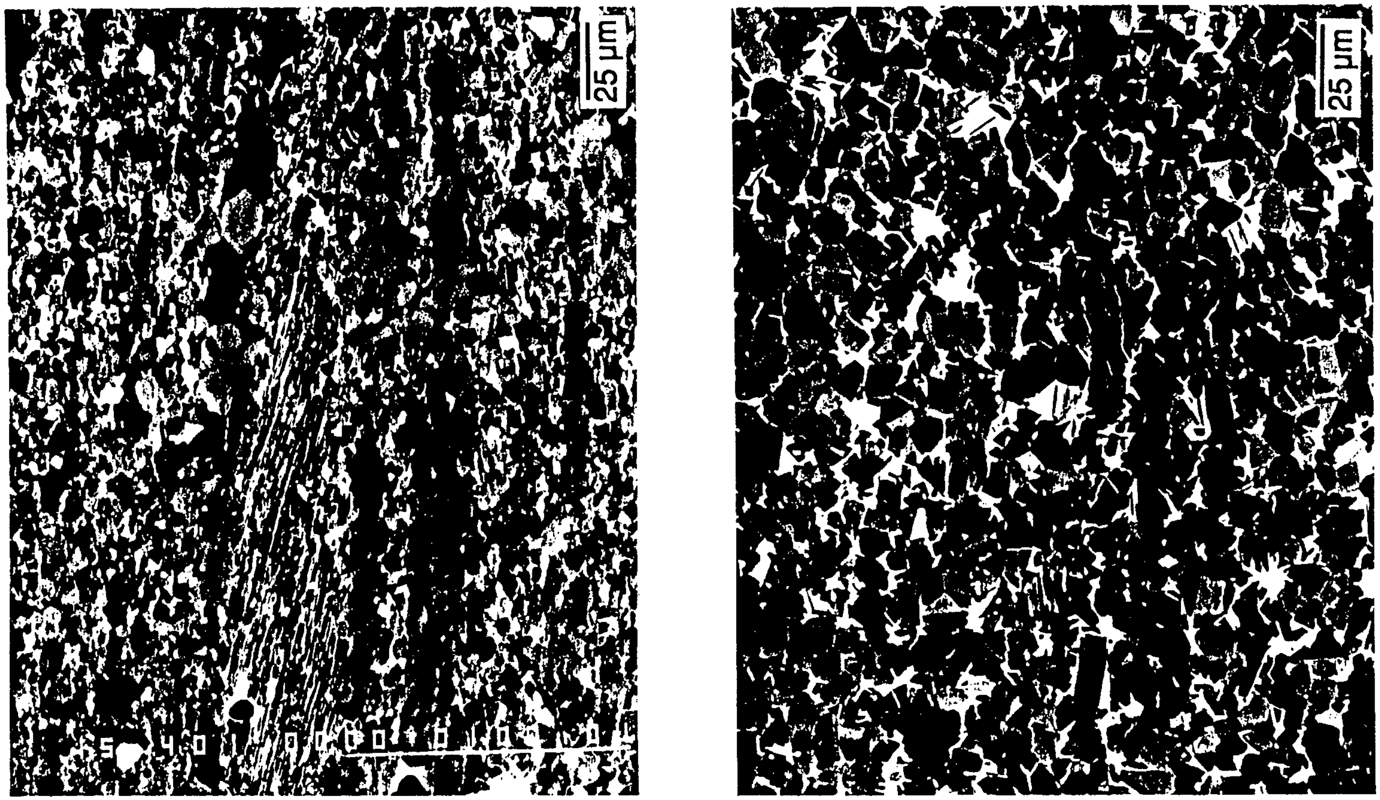


Ti - 47Al - x_1Si

Ti - 47Al - x_2Si

Ti - 48Al - x_2Si

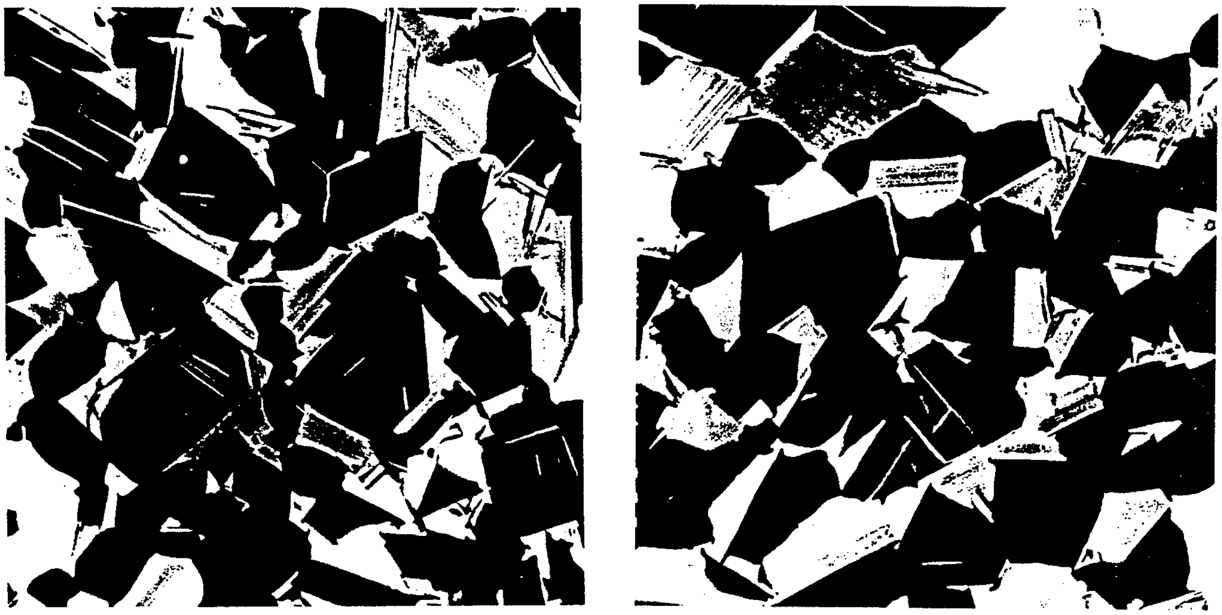
Isothermally forged(85%) microstructures



1150°C/70/70

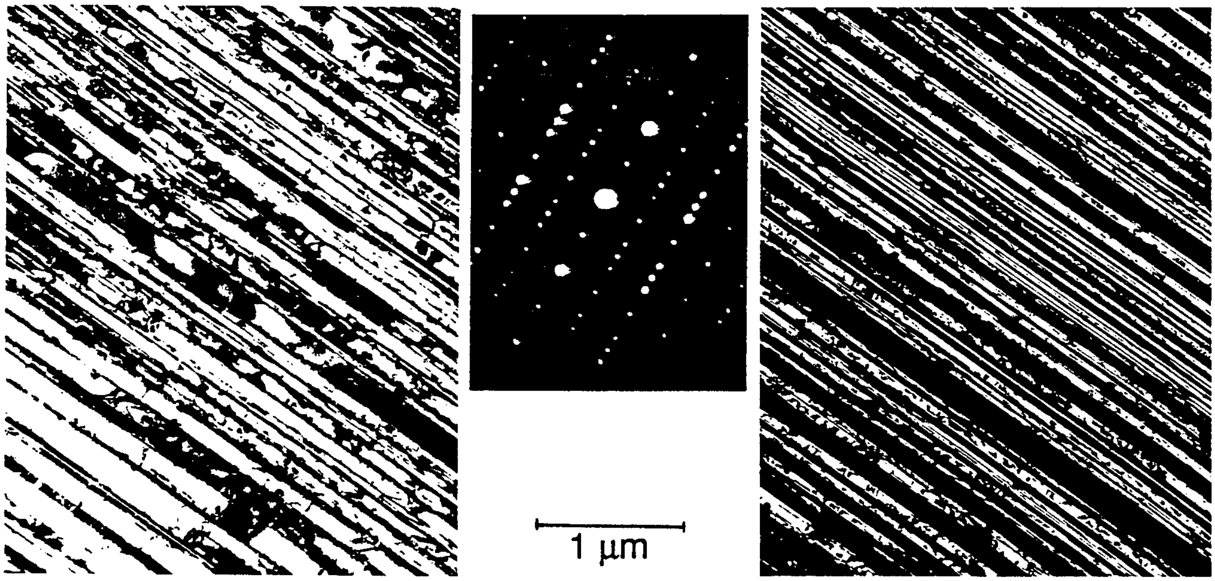
1270°C/3h/FC

Alloy K5: **Isothermally-Forged and Duplex-Treated**



T_α-70°C / 4hr / AC

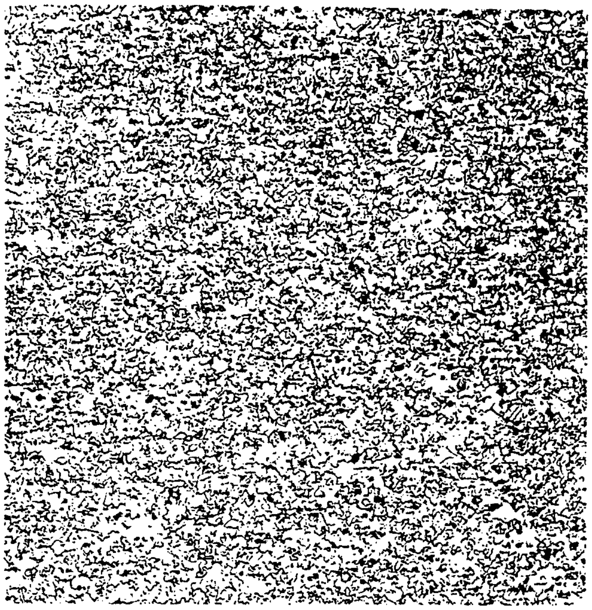
T_α-70°C / 24 hr / AC



Lamellar Structures : Light-to-Gray Areas

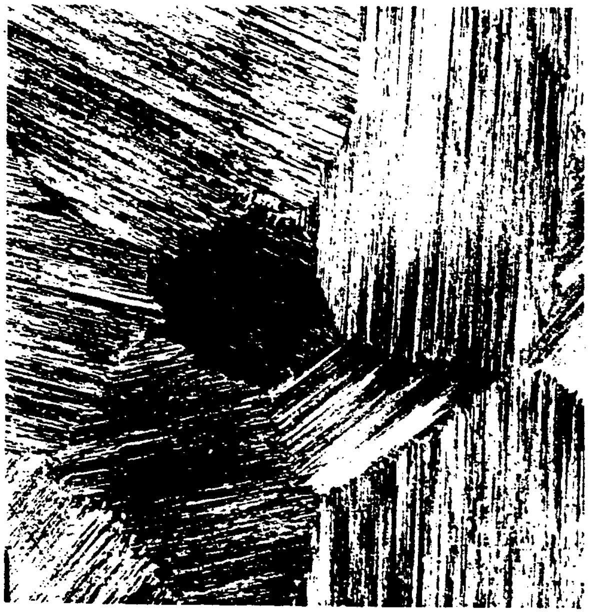
Alloy G1 : Forged + (α+γ) Treated + Air Cooled

Microstructures of Gamma Alloys

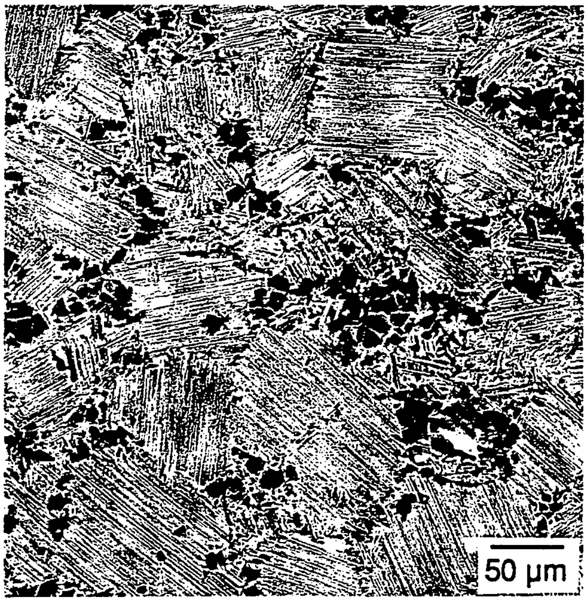


Duplex

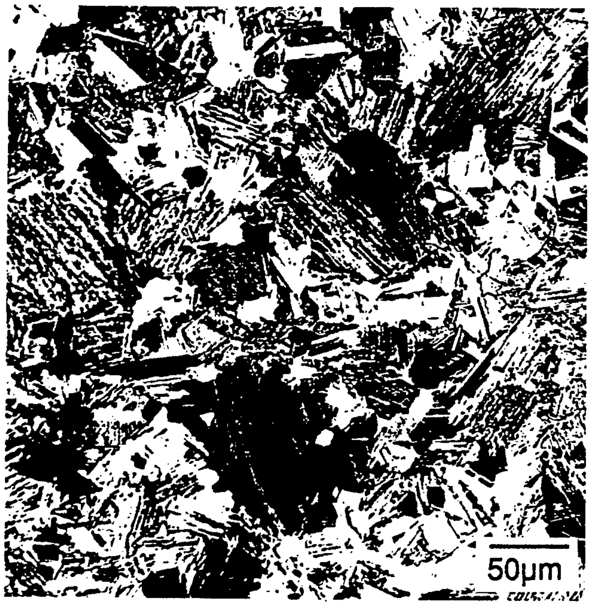
200 µm



Fully-Lamellar (FL)



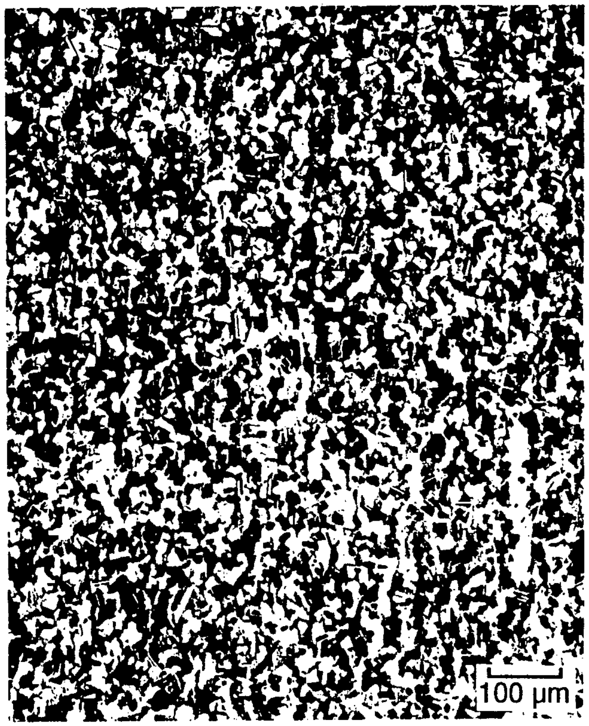
Nearly-Lamellar (NL)



NL

Alloy K5 (Ti-46.5Al-2Cr-3Nb-0.2W)

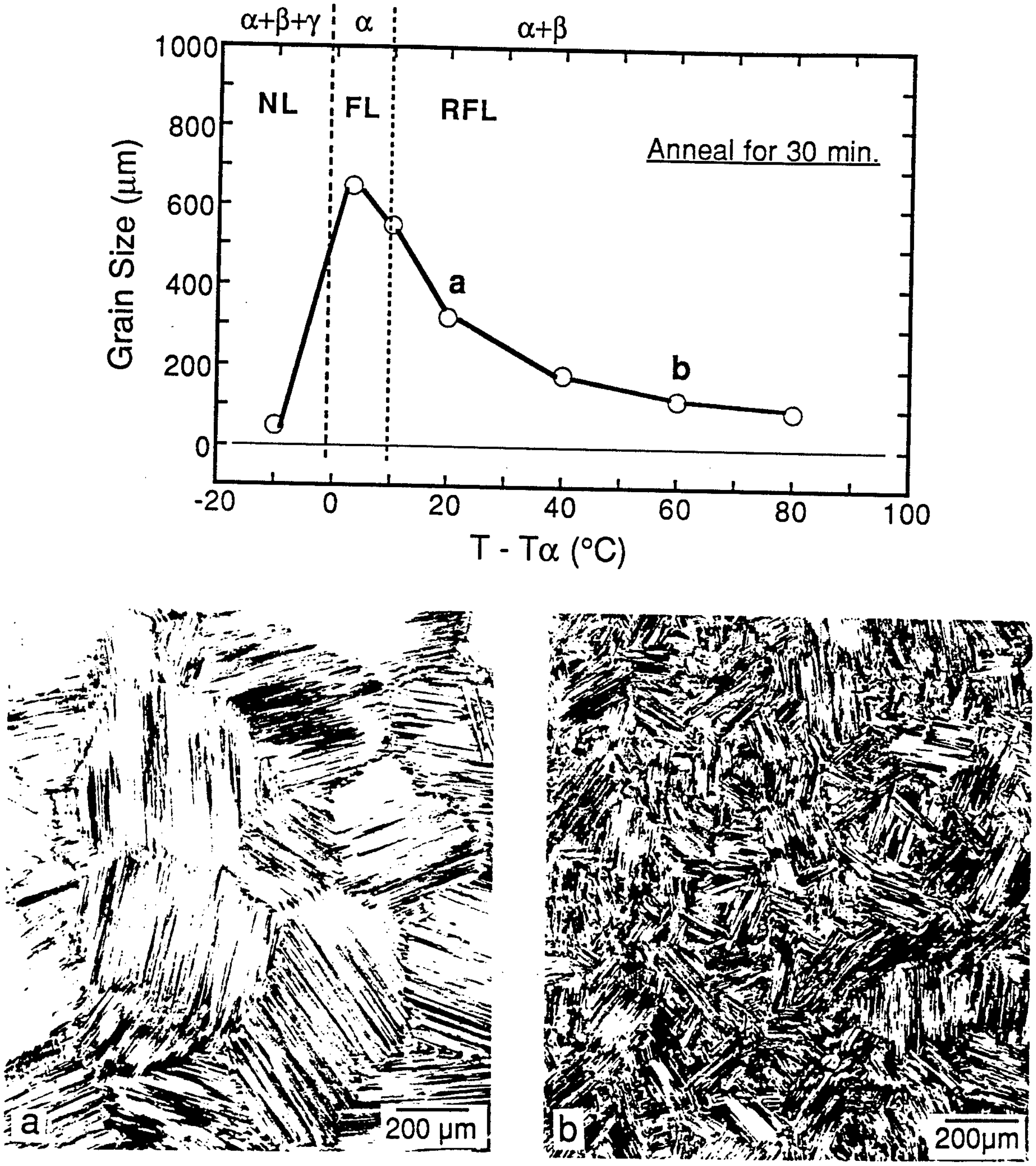
Duplex



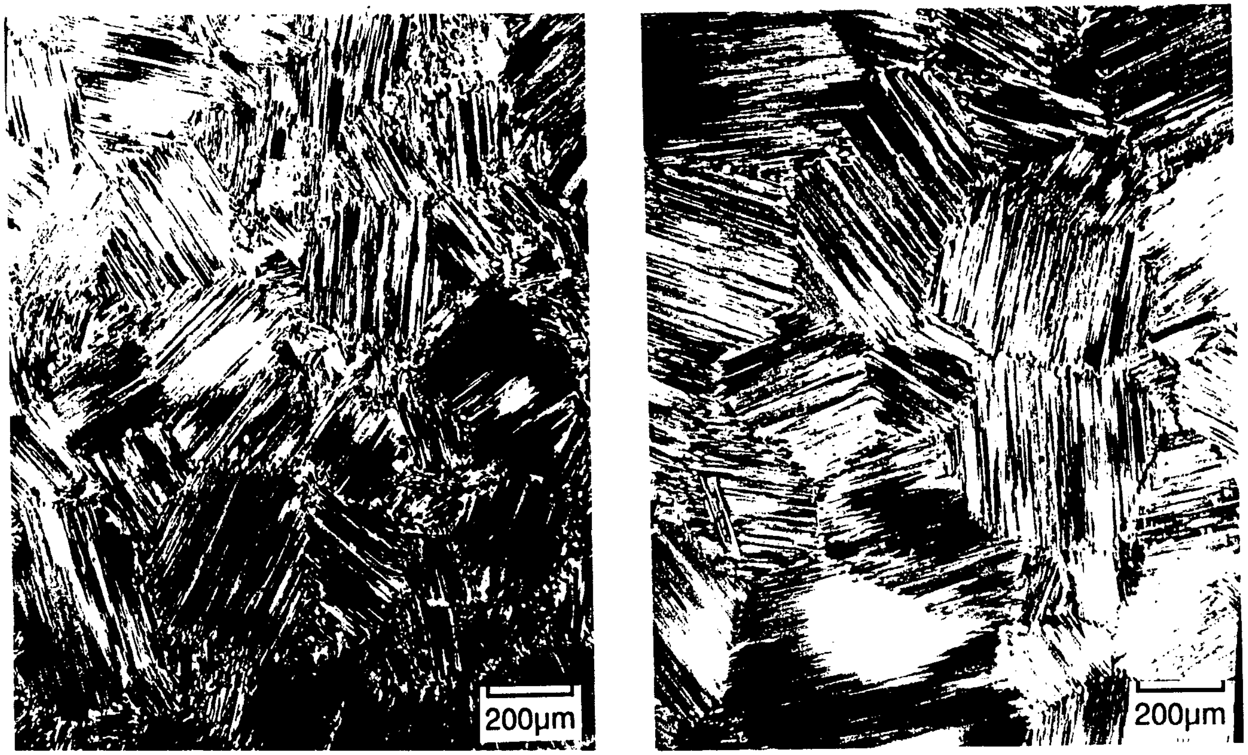
HW + (α+γ)-Treated

Fully-Lamellar

HW + α-Treated



Lamellar Grain Size Control in Wrought Alloy K5



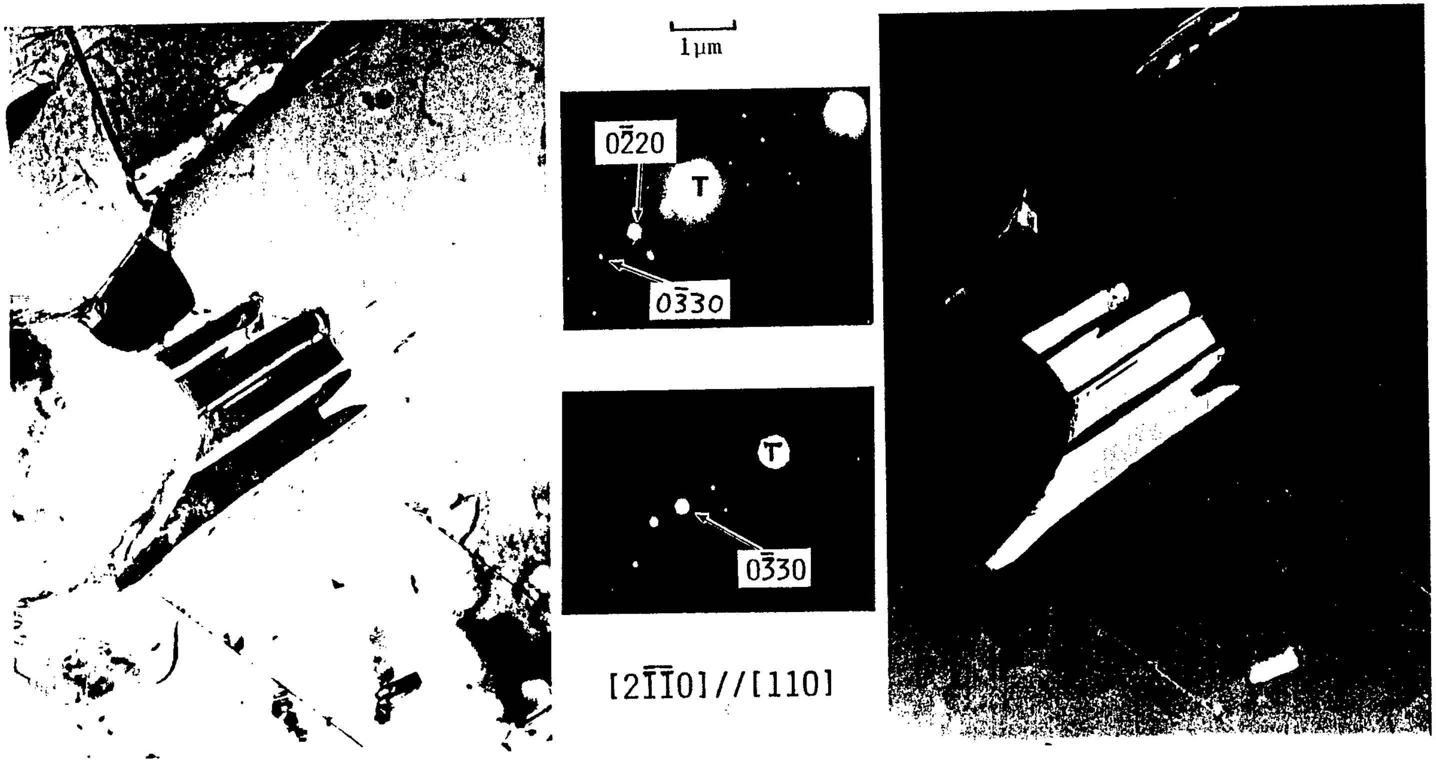
Cooling Condition Effect on RFL of Alloy K5

Alloy K5: Ti-46.4Al-2.1Cr-3Nb-0.2 W

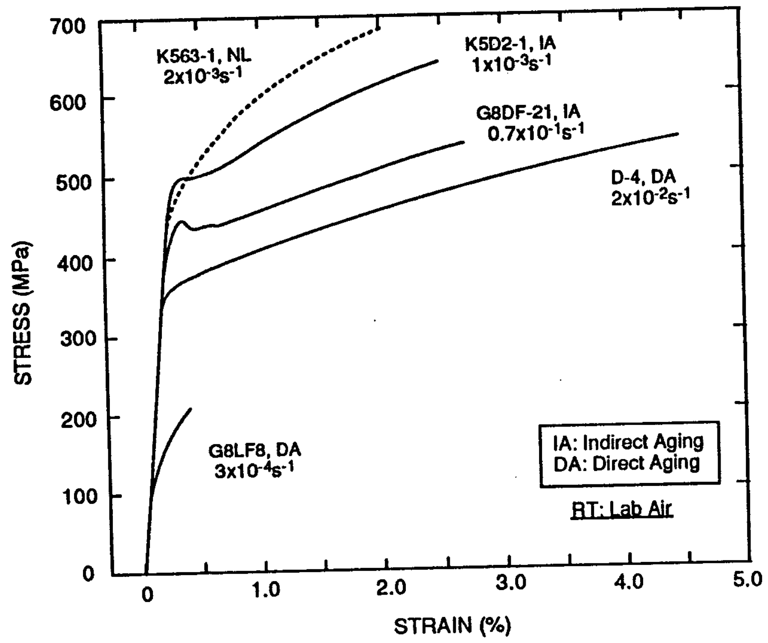
K5L-19

K5L-12

Wrought Alloy K5 after High Temperature Treatments

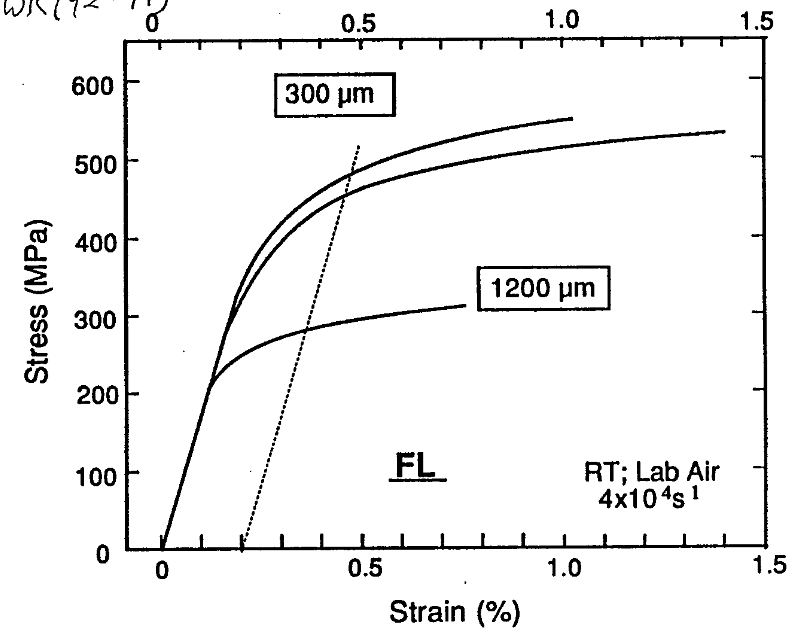


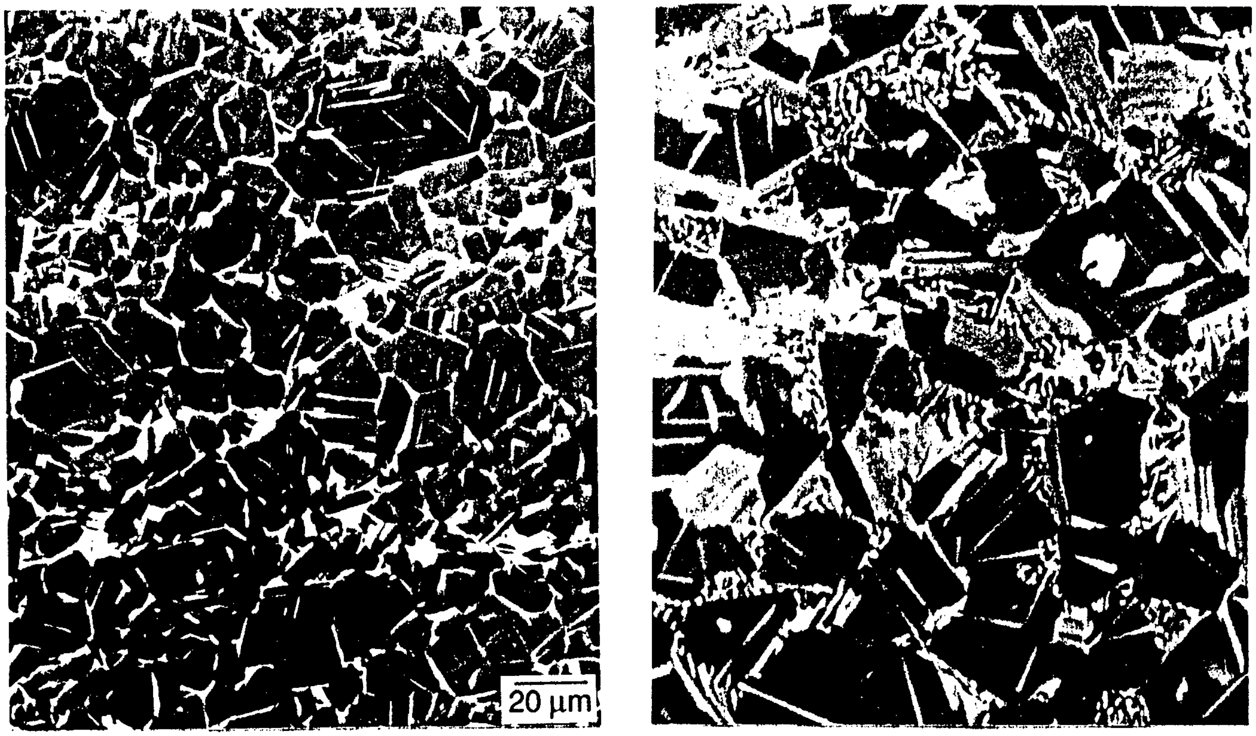
ALLOY G16 FORGED (88%) AND HEAT TREATED (1200°C/2 HR/AC + 1000°C/24 HR/AC)



RT Tensile Curves in Duplex/NL Microstructures

YWK (92-94)

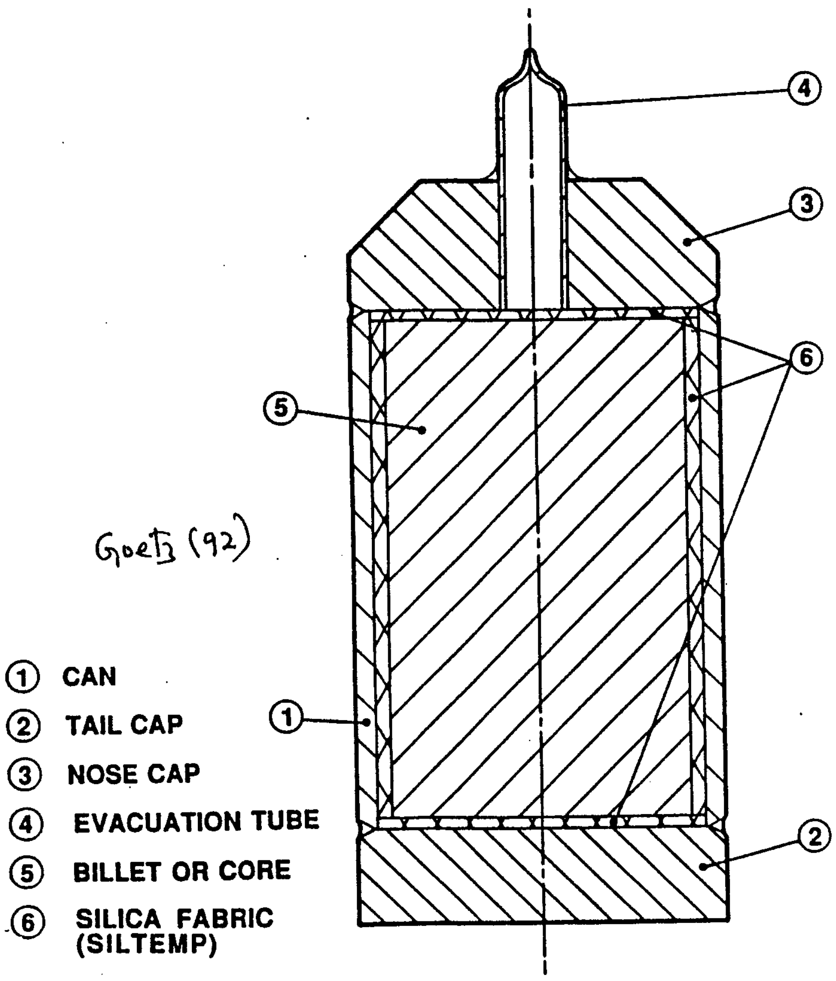




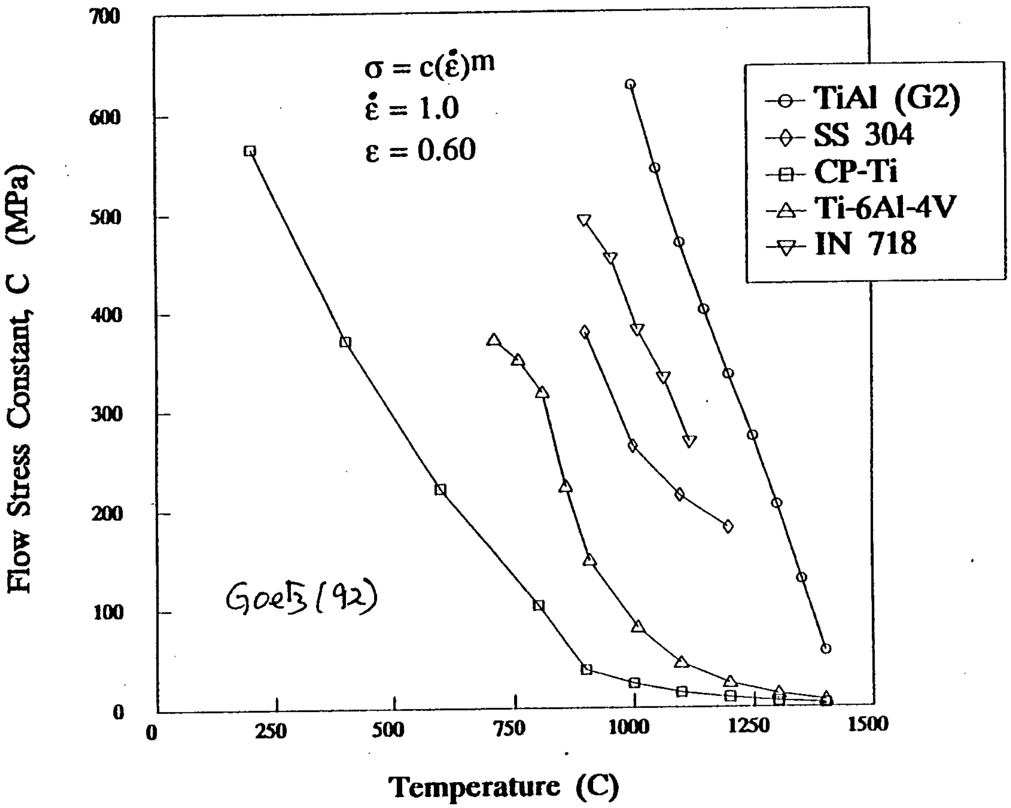
Directly Aged

Indirectly Aged

Duplex Microstructures in Alloy G1



Goetz (92)



Goetz (92)

Structure/Property Relationships

General Mechanical Behavior

Tensile
Fracture Toughness
Creep
Fatigue; FCG,

Inverse Ductility/FT Relationship

Deformation and Fracture Behavior

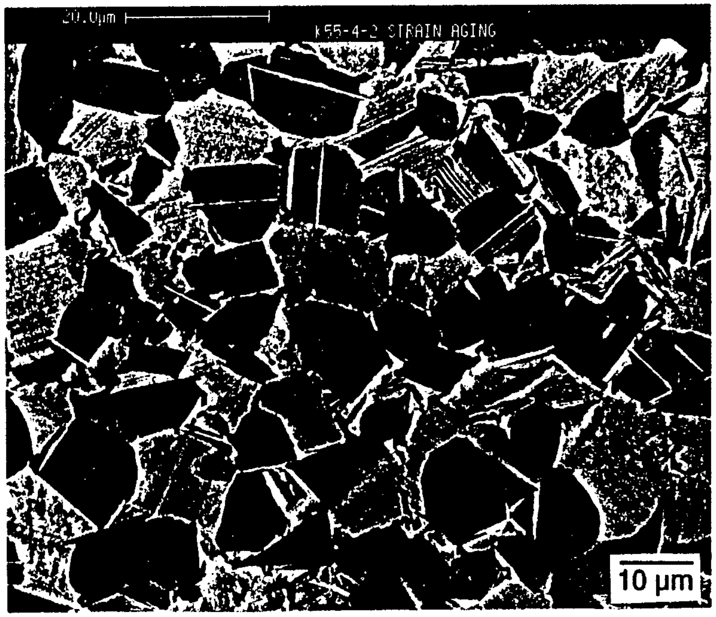
Tensile Loading
Cyclic Loading
Creep Loading

Damage Tolerance and Life Prediction

Microstructure Optimization

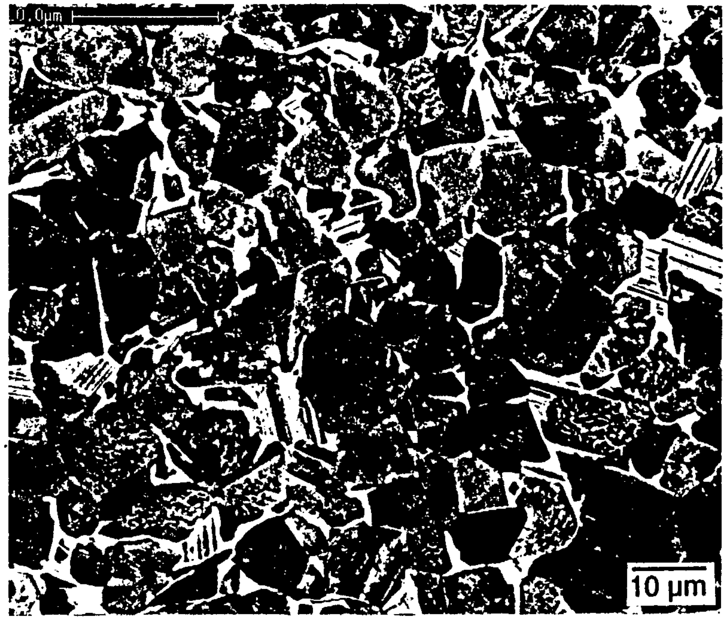
Alloy K5 Duplex

1270°C/4h/AC/RT



Weak Yield Point

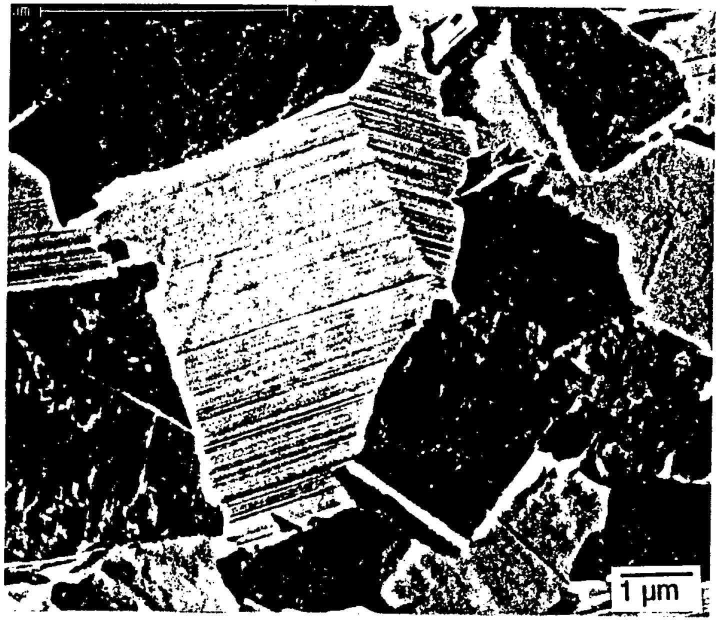
1270°C/4h/FC/900°C/AC
+ 900°C/48h/AC



Pronounced Yield Point

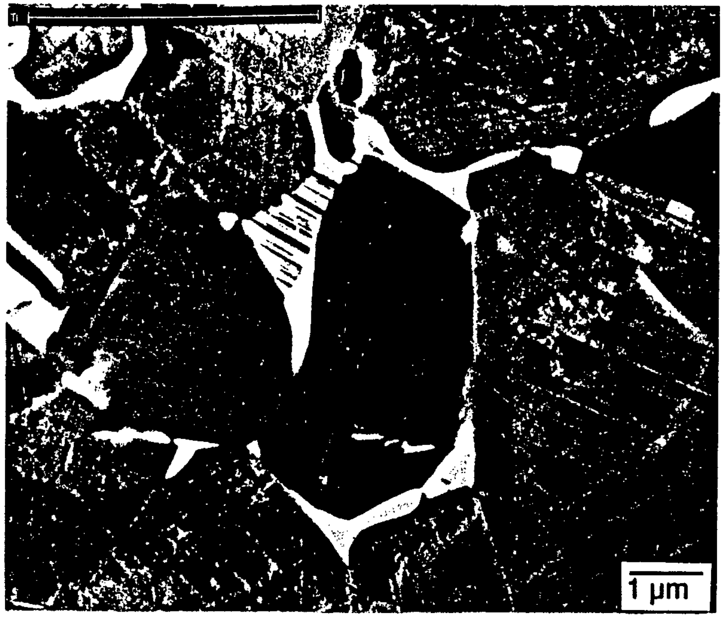
K5 Duplex: ε_t=0.5%

Weak Yield Point



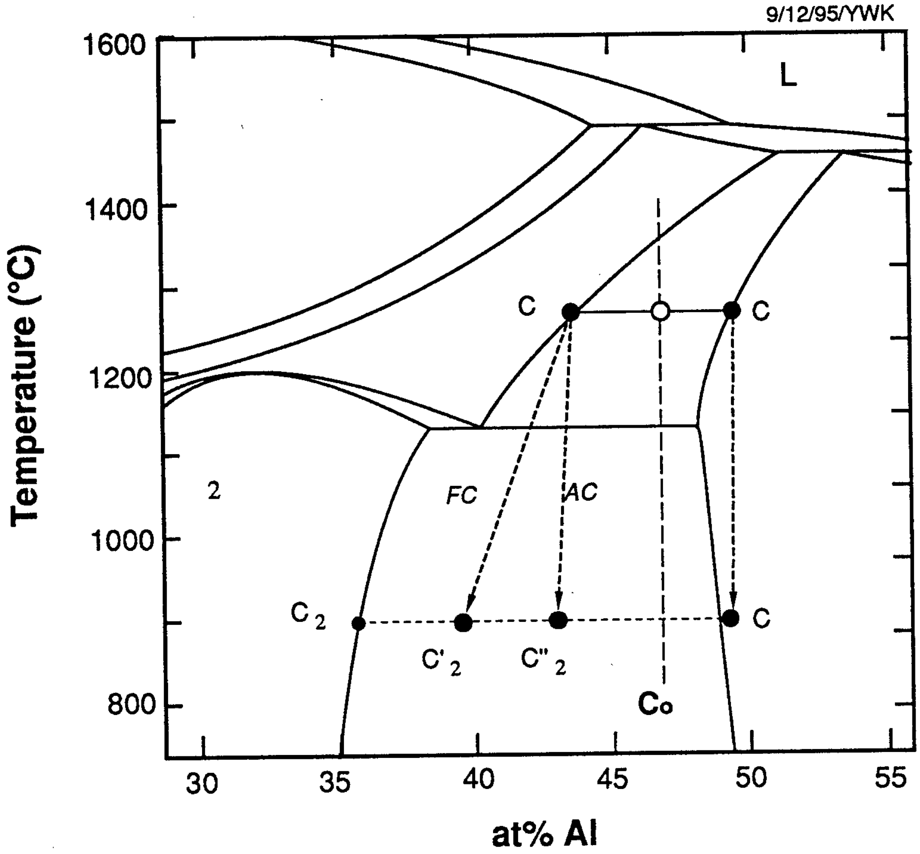
1270°C/4h/AC/RT

Strong Yield Point

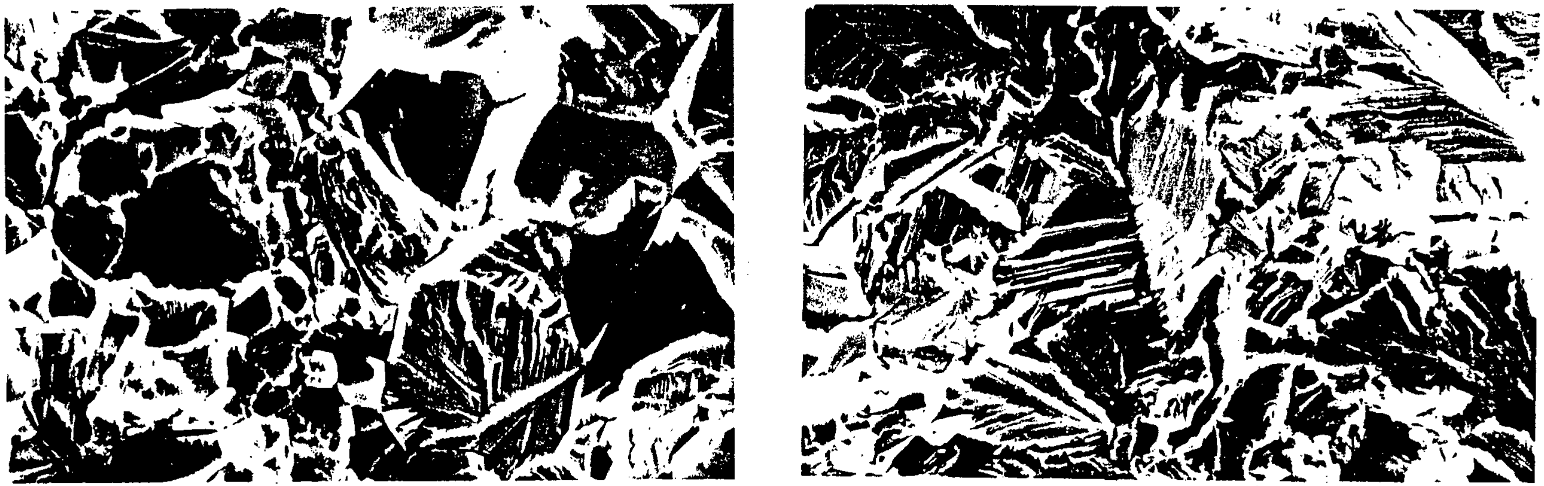


1270°C/4h/FC/900°C/AC + 900°C/48h/AC

Duplex (+) Treatment and Cooling

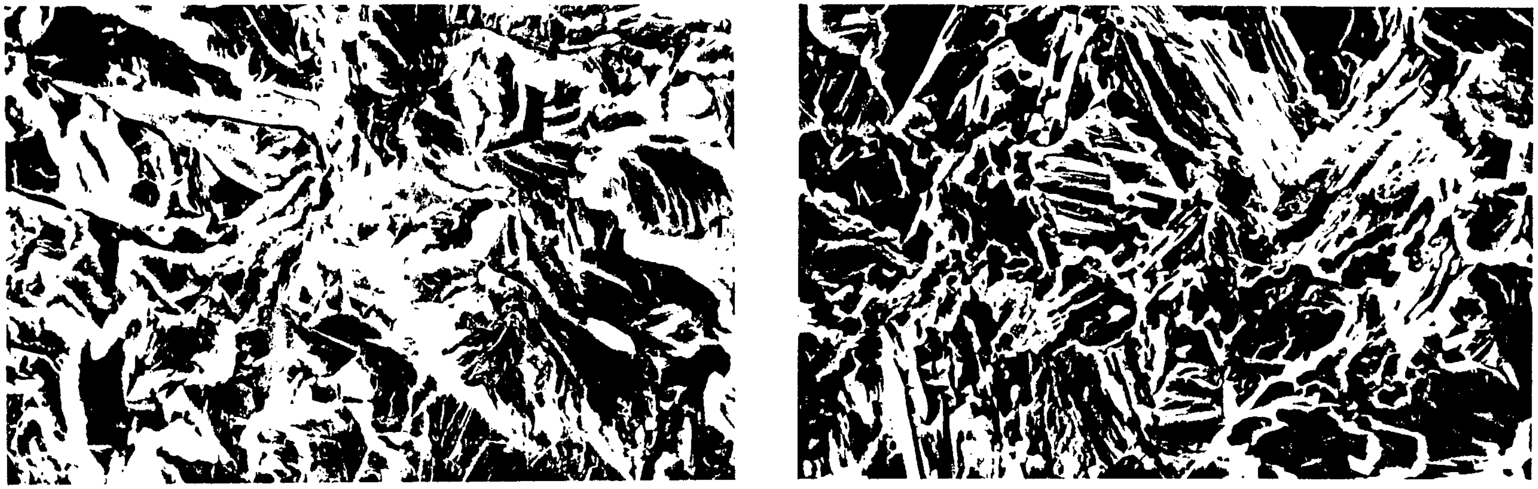


9/12/95/YWK



Near Gamma

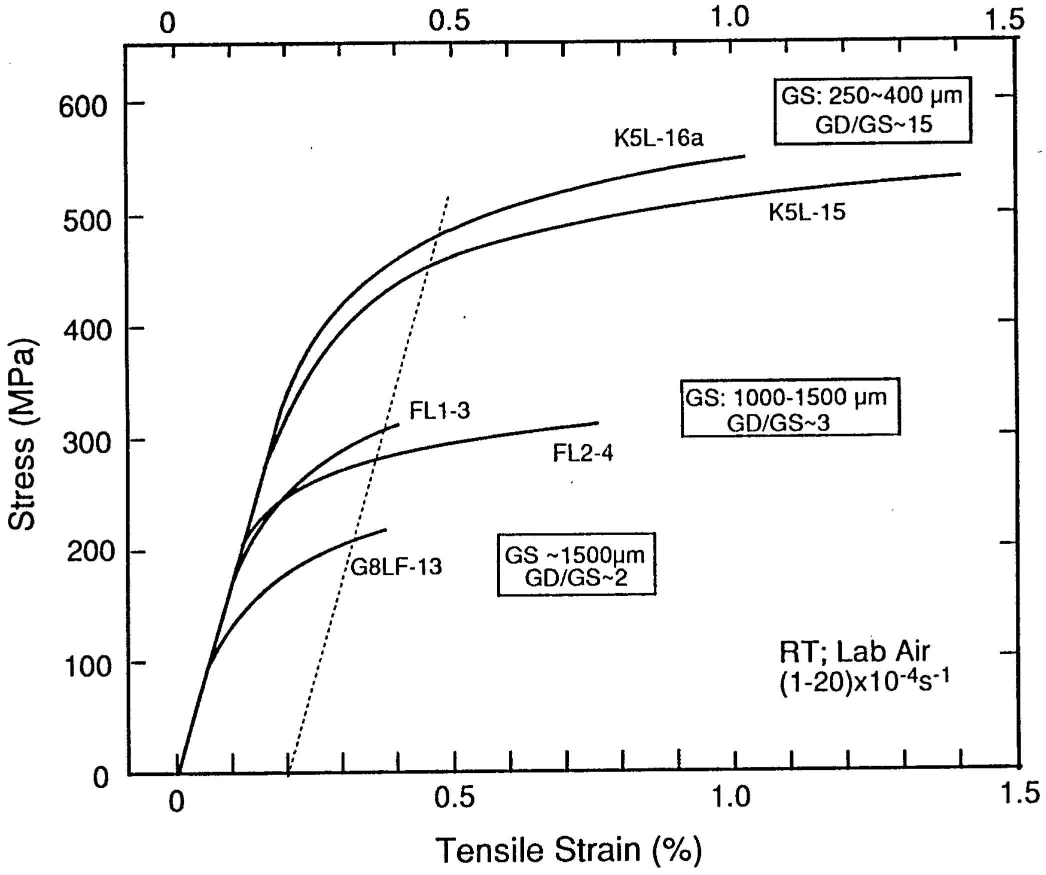
a Duplex with direct aging



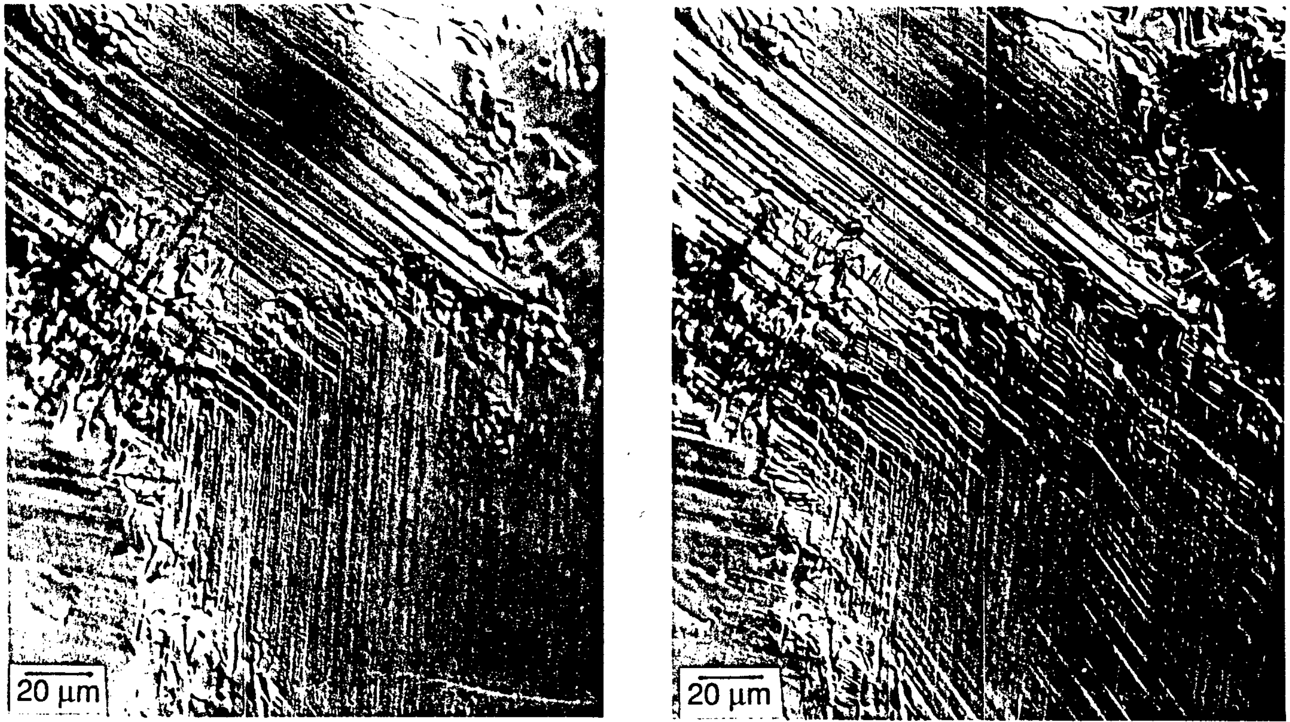
a Duplex with indrect aging

A Nearly-Lamellar with indrect aging

Tensile Fracture Surfaces of Alloy G1 in Various Microstructural Conditions



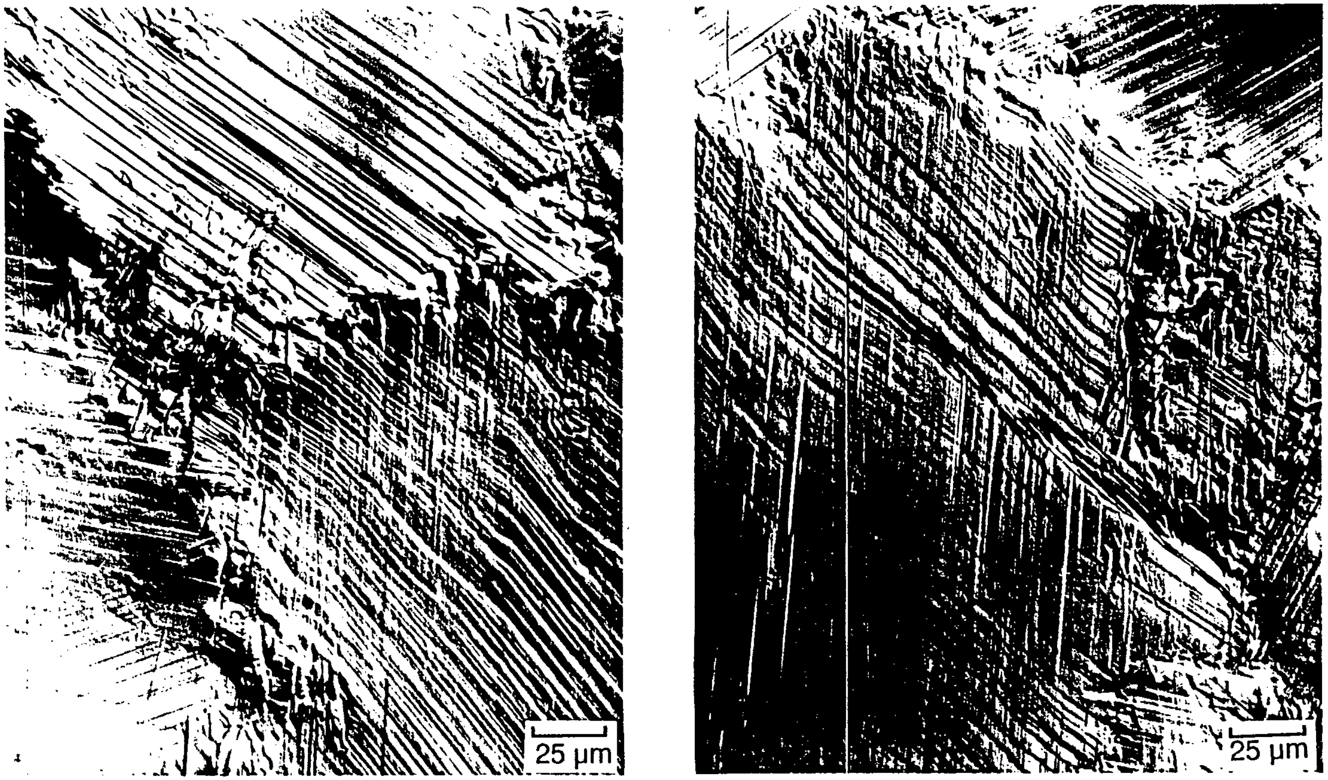
Tensile Curves of Fully-Lamellar Gamma Materials



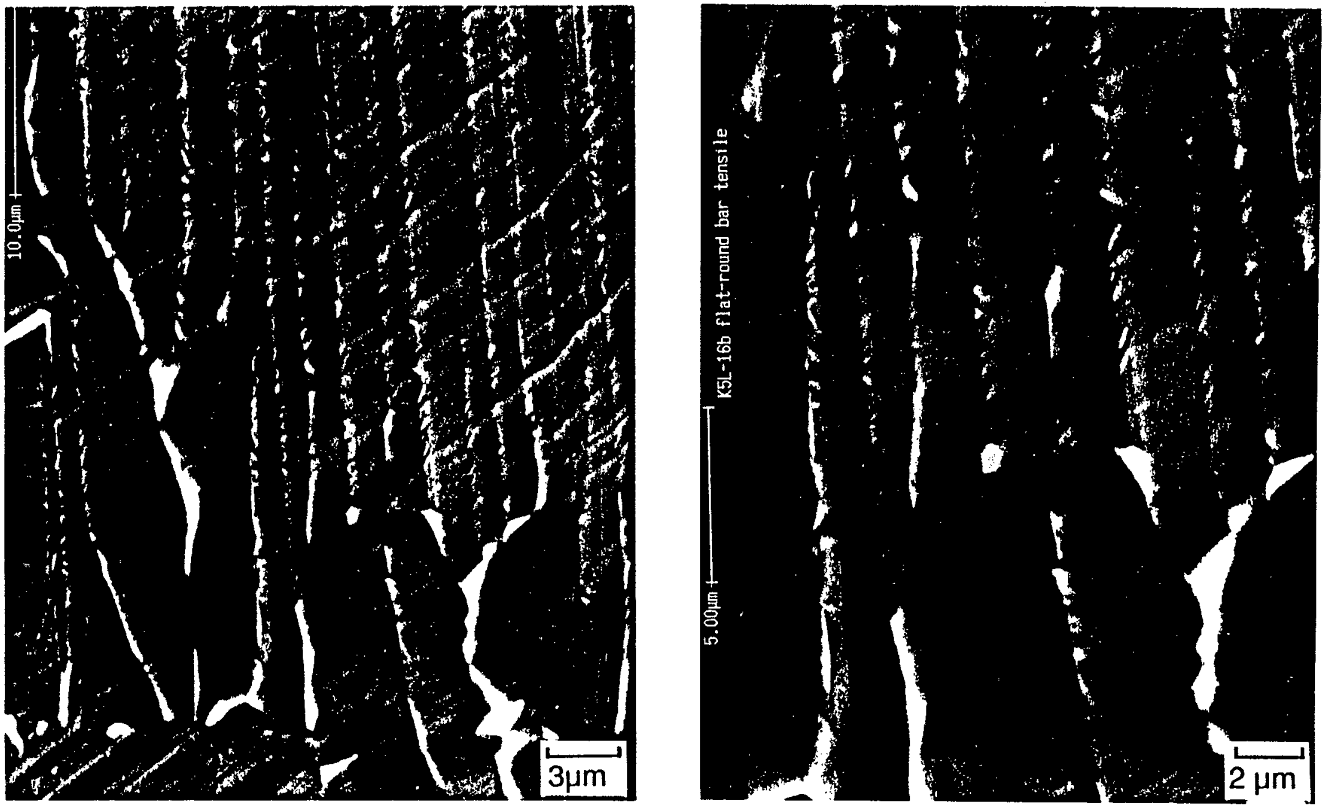
ε_1/σ_1 = 0.3 %/ 427 MPa

ε_3/σ_3 = 0.55 %/ 493 MPa

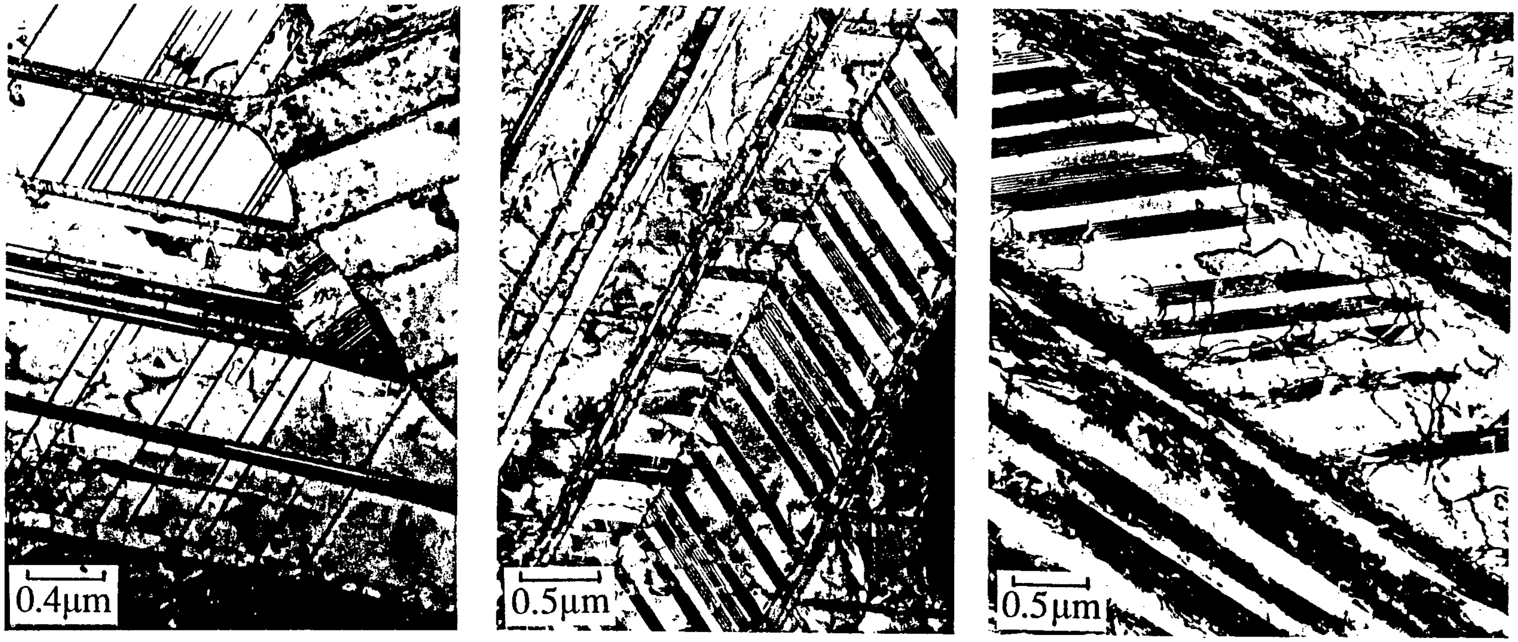
Alloy K5 RFL Flat Gage Tensile Specimen Surface Deformed at RT
(σ_o/σ_y=328/474 MPa ; λ_L=0.3 μm)



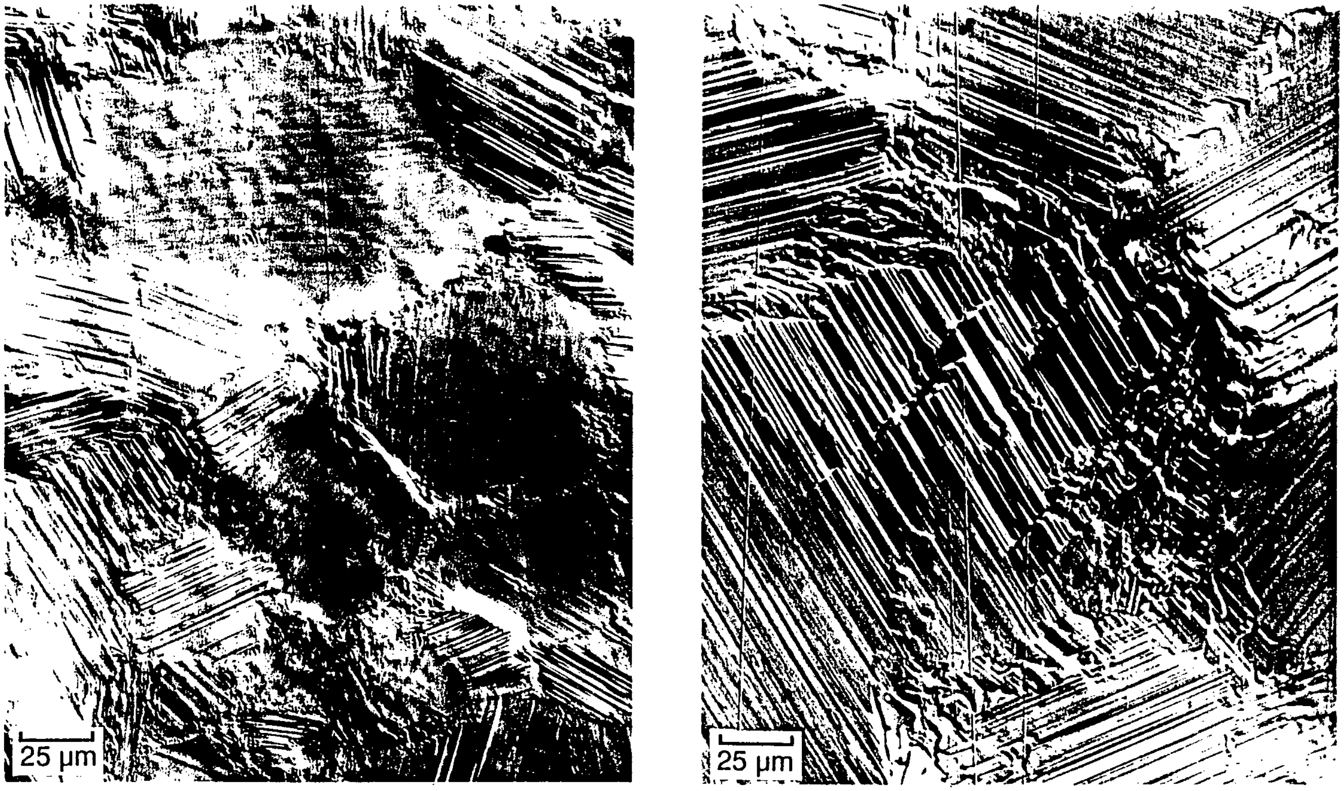
RT Tensile Deformation/Strain-Accomodation Observed on Electropolished Surfaces of Alloy K5 RFL Specimens at σ/ε=528 MPa/1.21% (σ_0/ε_0=328/0.19)



BSE Image of RT Tensile Deformation/Strain-Accomodation near GB's on Surfaces of Alloy K5 RFL Specimens at σ/ε=528 MPa/1.21% (ε_0=0.19)

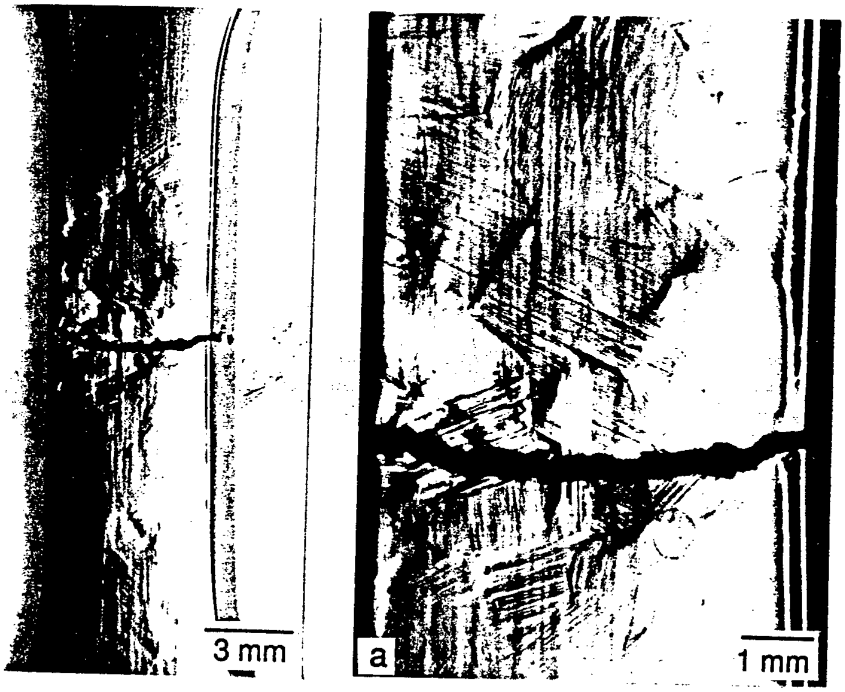


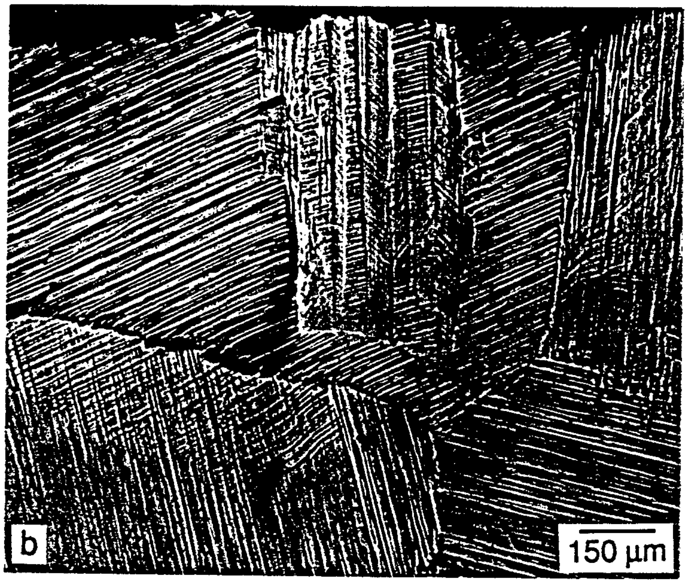
Deformed Microstructure of Alloy G1 at 1.9% Tensile Strain

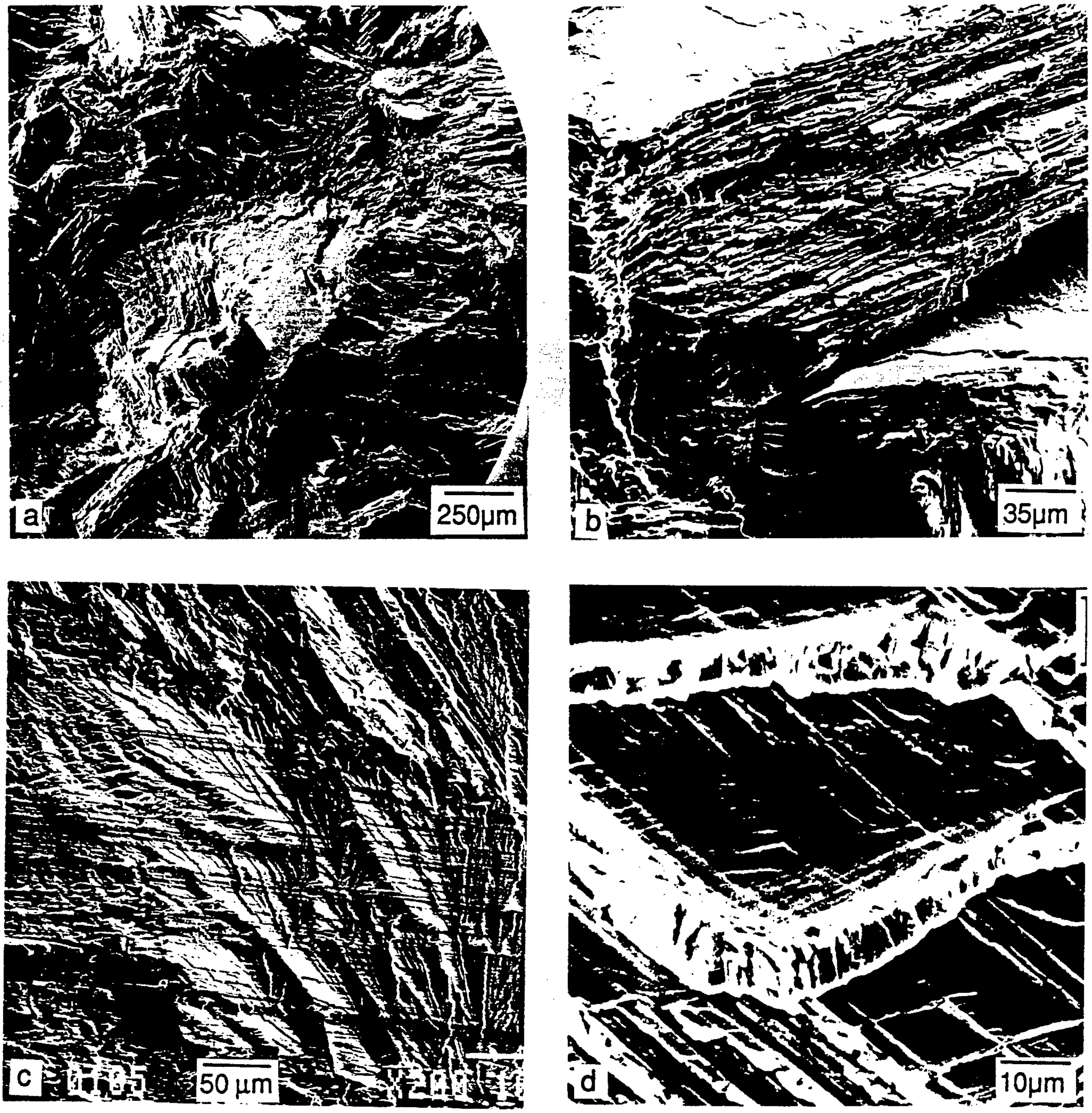


Alloy K5 RFL Tensile Specimen Flat Gage Surface Deformed at RT

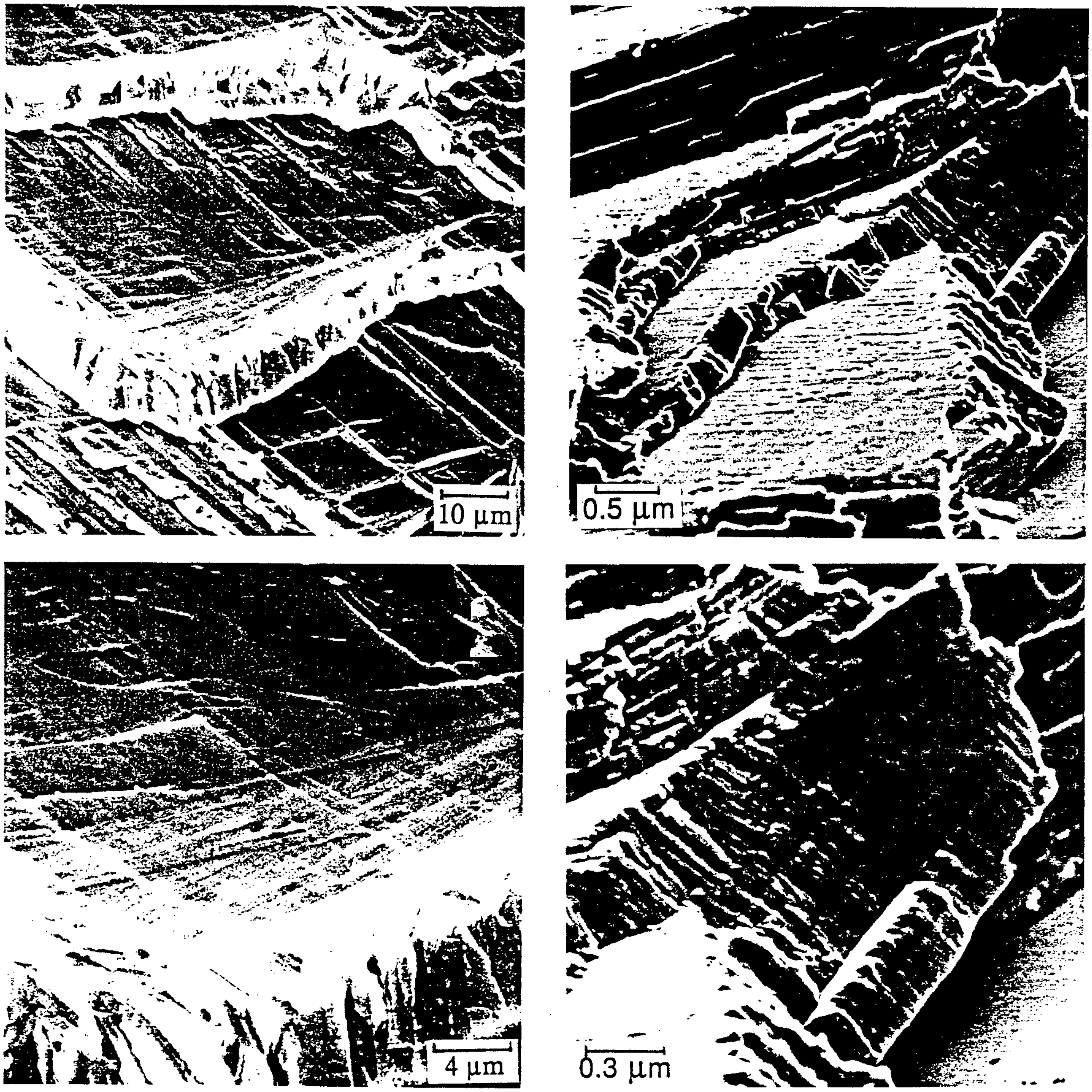
σ_5/ε_5 =524 MPa/0.78% (σ_0/ε_0=328/0.19)


3 mm
a
1 mm


b
150 µm



RT Tensile Transgranular Fracture of FL Gamma Alloys: (a) Overall, (b) Interlamellar and Translamellar, (c, d) Translamellar Cleavage with Interlamellar Deformation

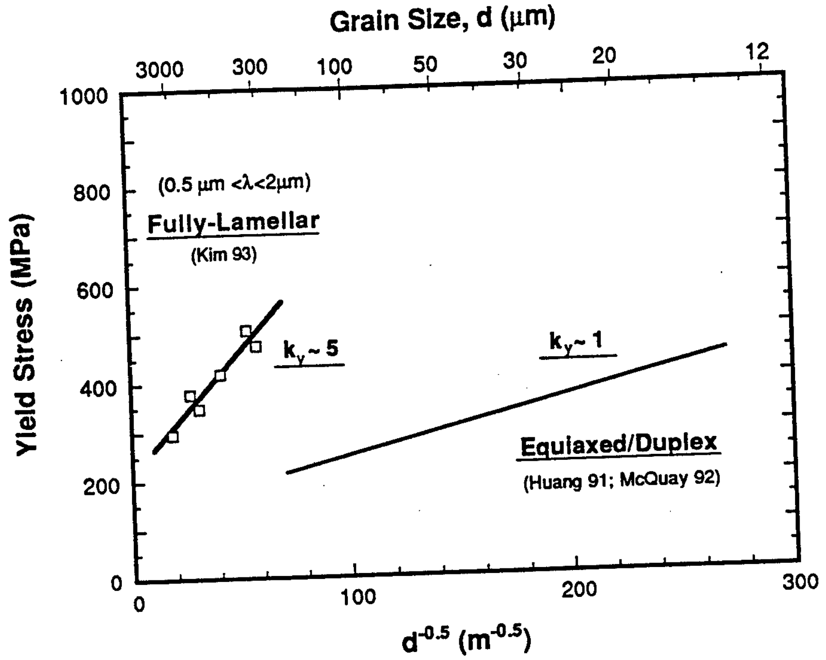


Fully-Lamellar

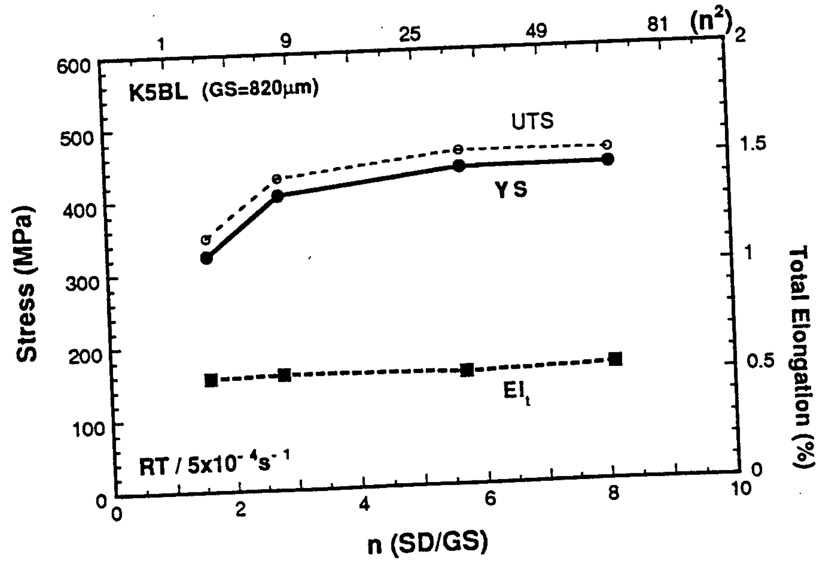
Duplex

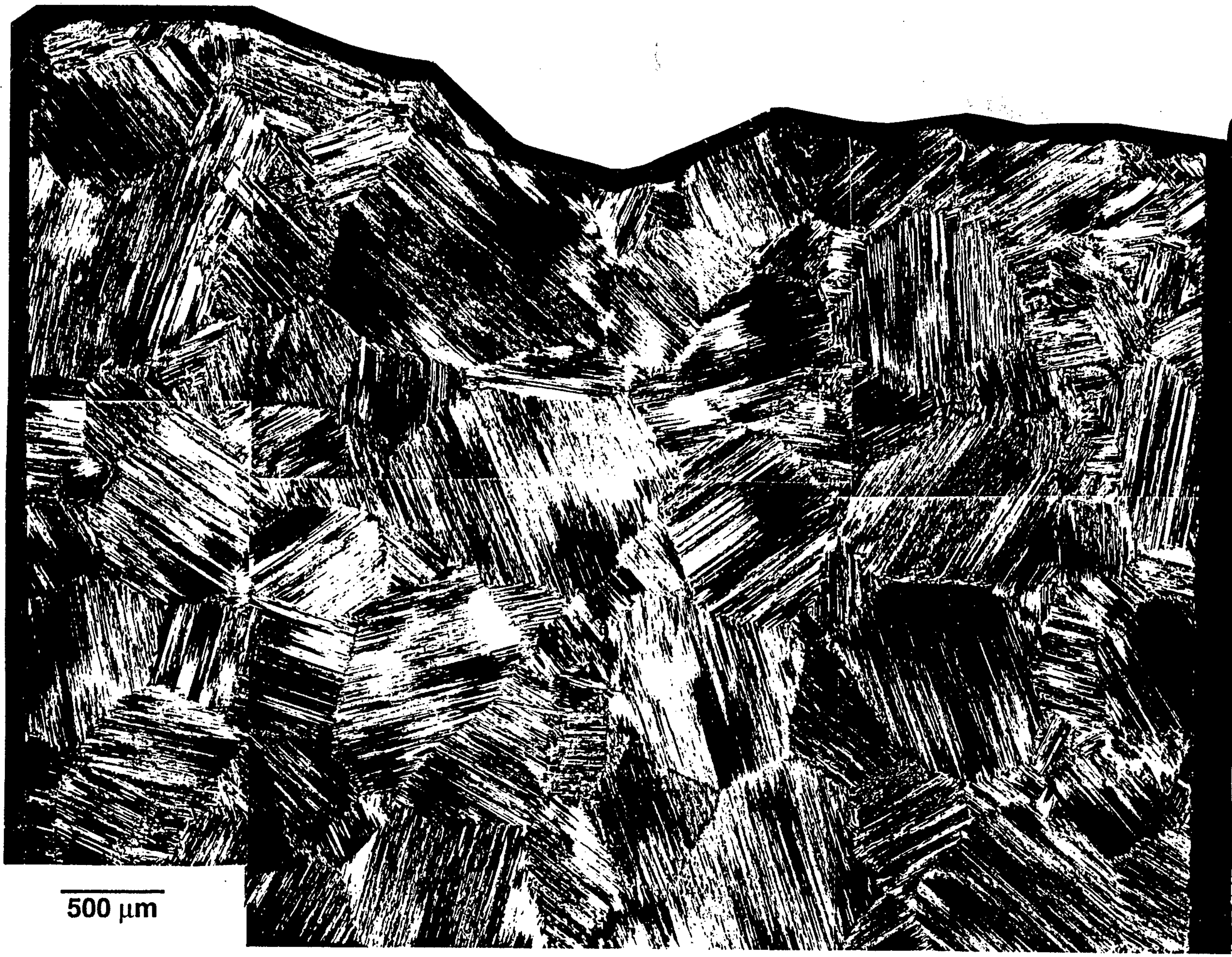
RT Tensile Fracture Features of TiAl alloys in FL and Duplex Microstructural Conditions

Grain-Size//Yield-Stress Relations in TiAl



Specimen/Grain Size Effect on Tensile Properties



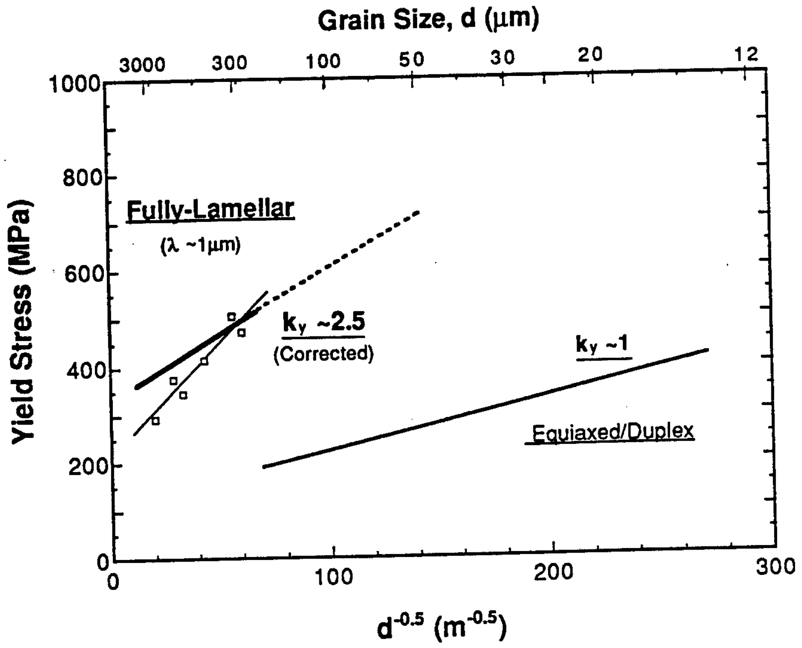


Specimen-Diameter/Grain-Size = 8.2:1

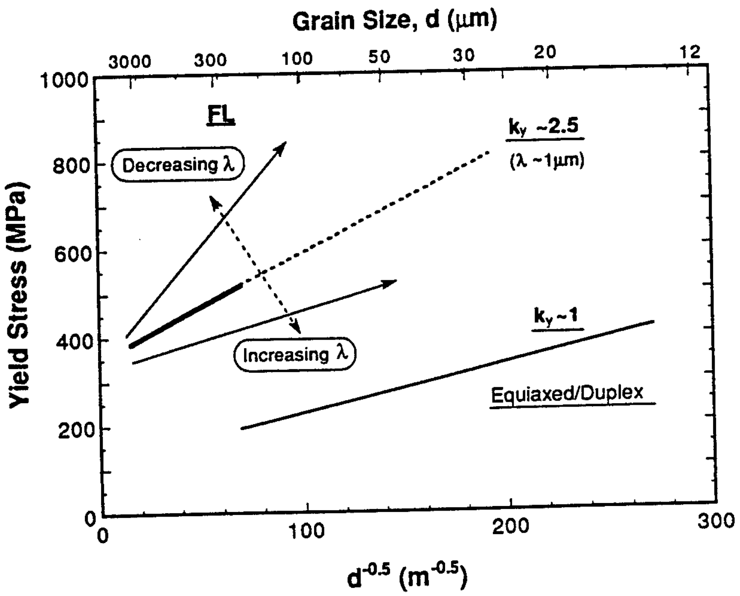
SD/GS=1.5:1

√

Corrected Hall-Petch Relation in FL TiAl



Hall-Petch Relations in TiAl Alloys



Hall-Petch Relations in TiAl Alloys

Duplex Material

$\sigma_y = \sigma'_o = k_d d^{-1/2}$

k_d ~**1** MPa√m

Relatively isotropic

Fully-Lamellar Material

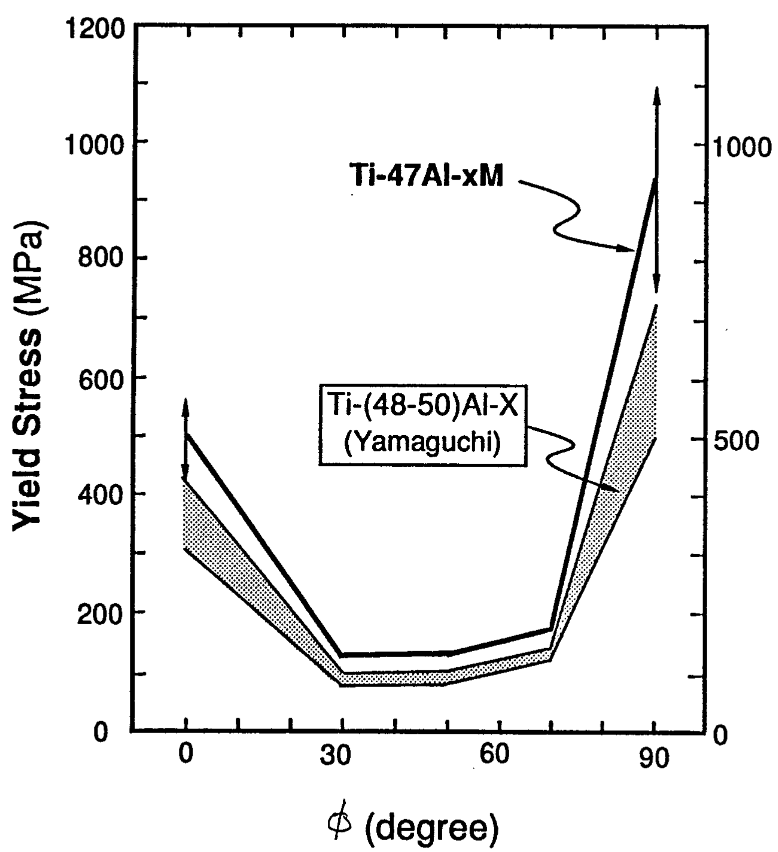
$\sigma_y = \sigma_o + k_{d\lambda} d^{-1/2}$

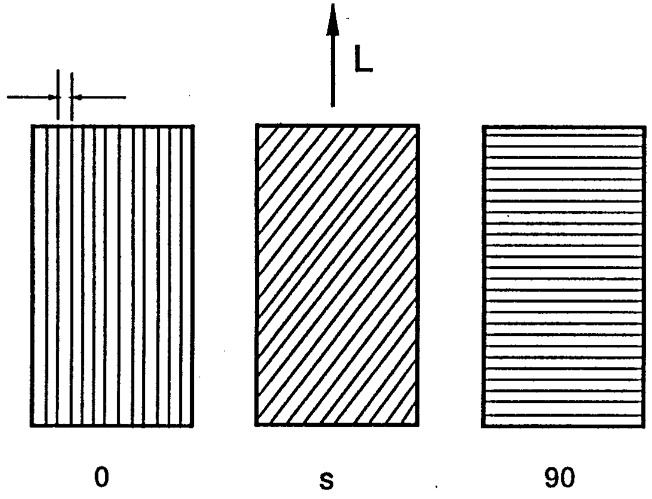
$k_{d\lambda}$ = **2.5** MPa√m (for λ=1 μm)

Combined Effect of d and λ

$k_{dy} = k_d \left(\tau^*_{avg} / \tau^*_s\right) = \text{ftn}\ (\lambda)$

Orientation vs. Yield-Stress in the $(\gamma+\alpha_2)$ Lath Structure





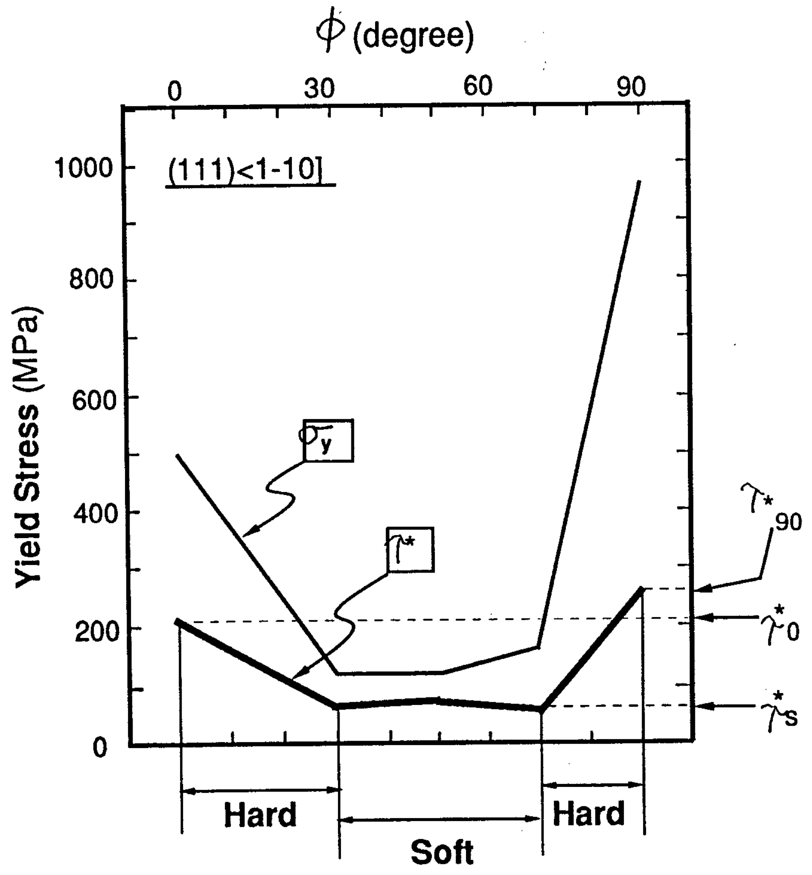
$\underline{\sigma_{90} ; \sigma_0 = f(\lambda, \alpha_2/\gamma, C)}$

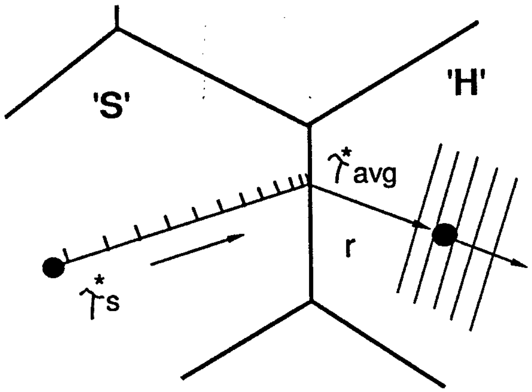
$$\boxed{\sigma_{90} = \sigma_0 + \mathbf{k}\ ^{-1/2}}$$

(**k** = 0.5 MPa m)

Yielding of the $(\gamma+\alpha_2)$ Lath Structure

Ti-(46.5-47)Al- (4-6)(Cr,V,Nb,M)

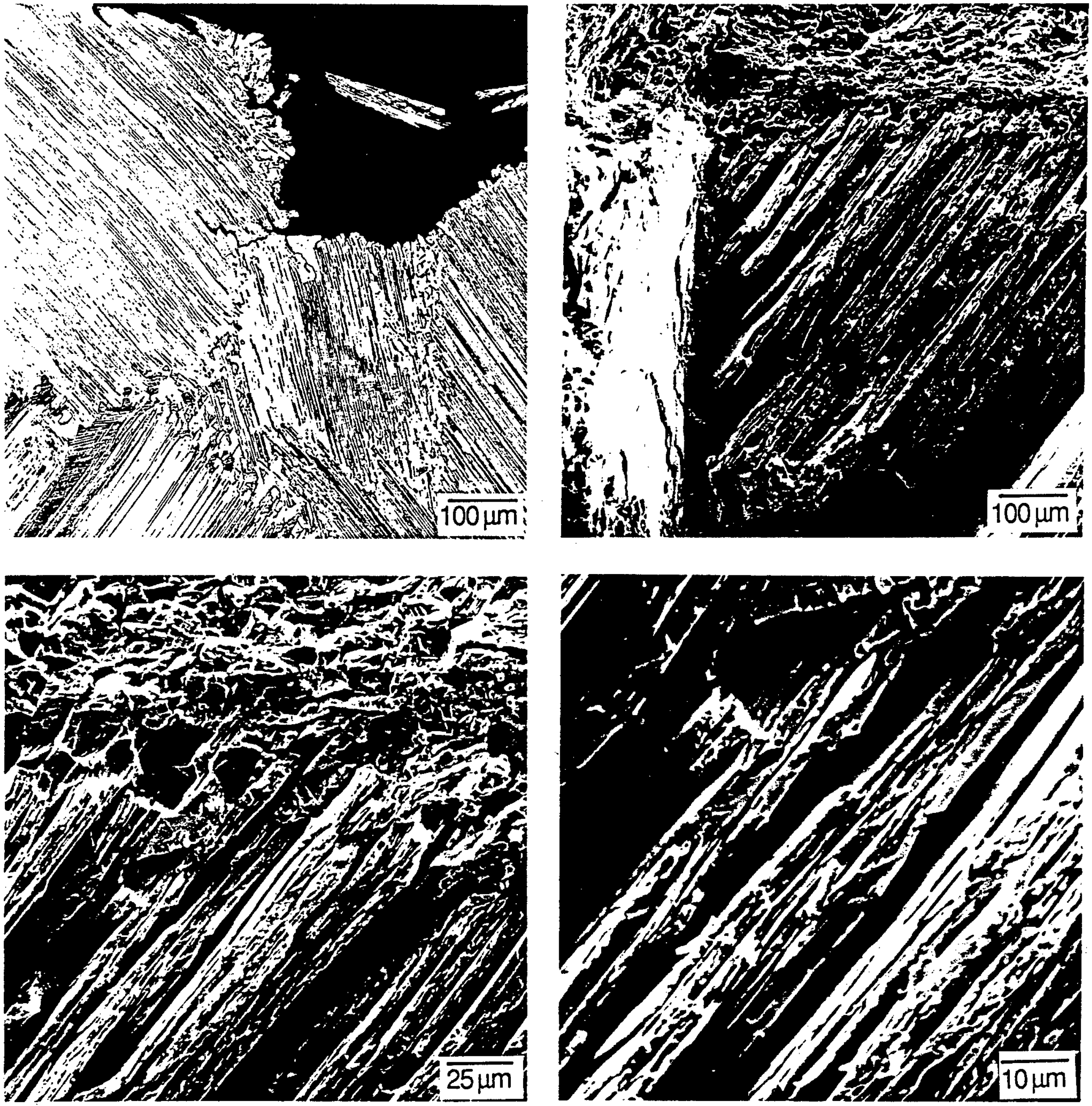




$$\tau^*_{avg} = \frac{\tau^*_{90} + \tau^*_0 + 2\tau^*_s}{4} \qquad (\sim 2.5\ \tau^*_s\ )$$

τ^*_{avg} : Stress required to activate and move dislocations across lath boundaries

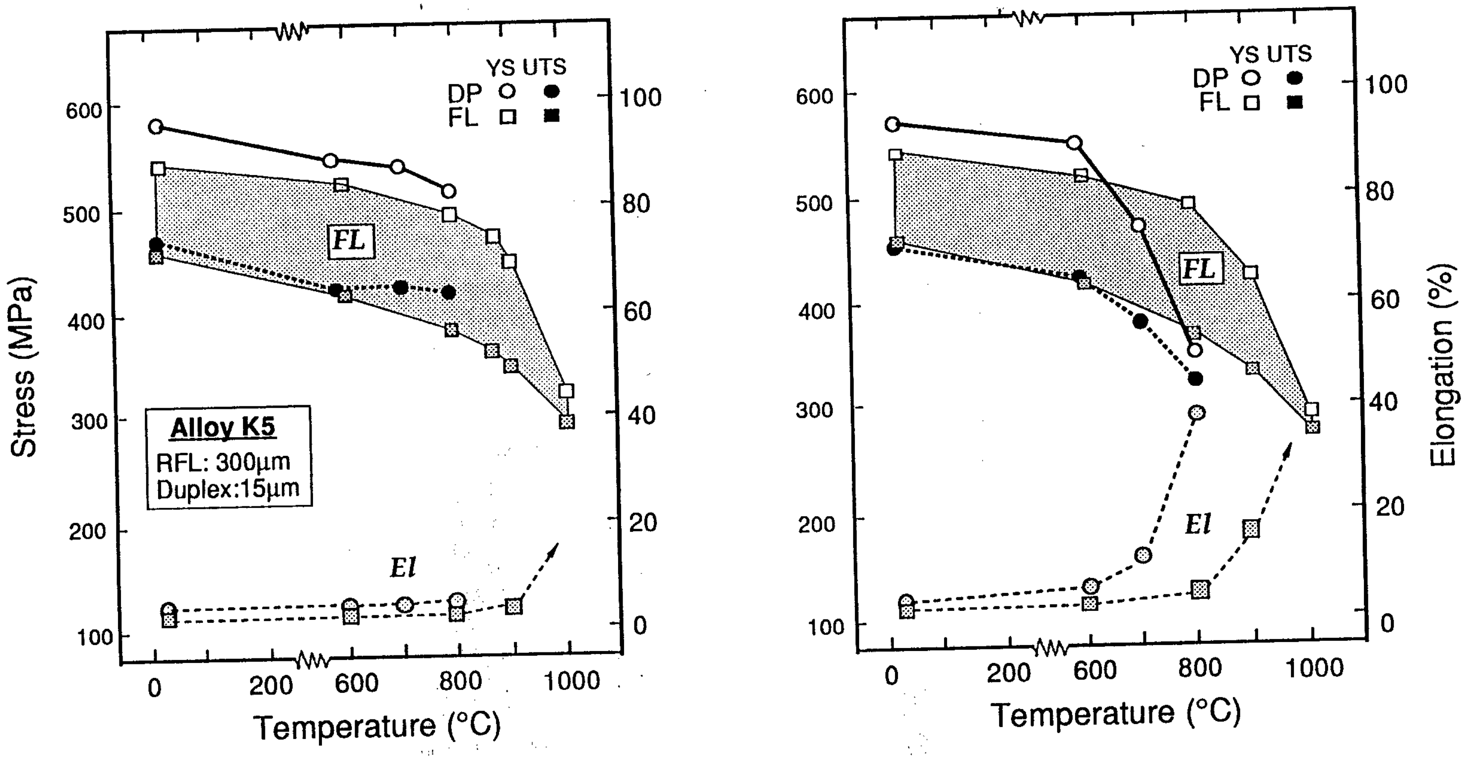
$$\boxed{\mathbf{k_d} = \mathbf{k_d}\ (\tau^*_{avg} / \tau^*_s)} \qquad (\sim 2.5\mathbf{k_d})$$



Tensile Fracture of FL Alloy G5 at 750°C

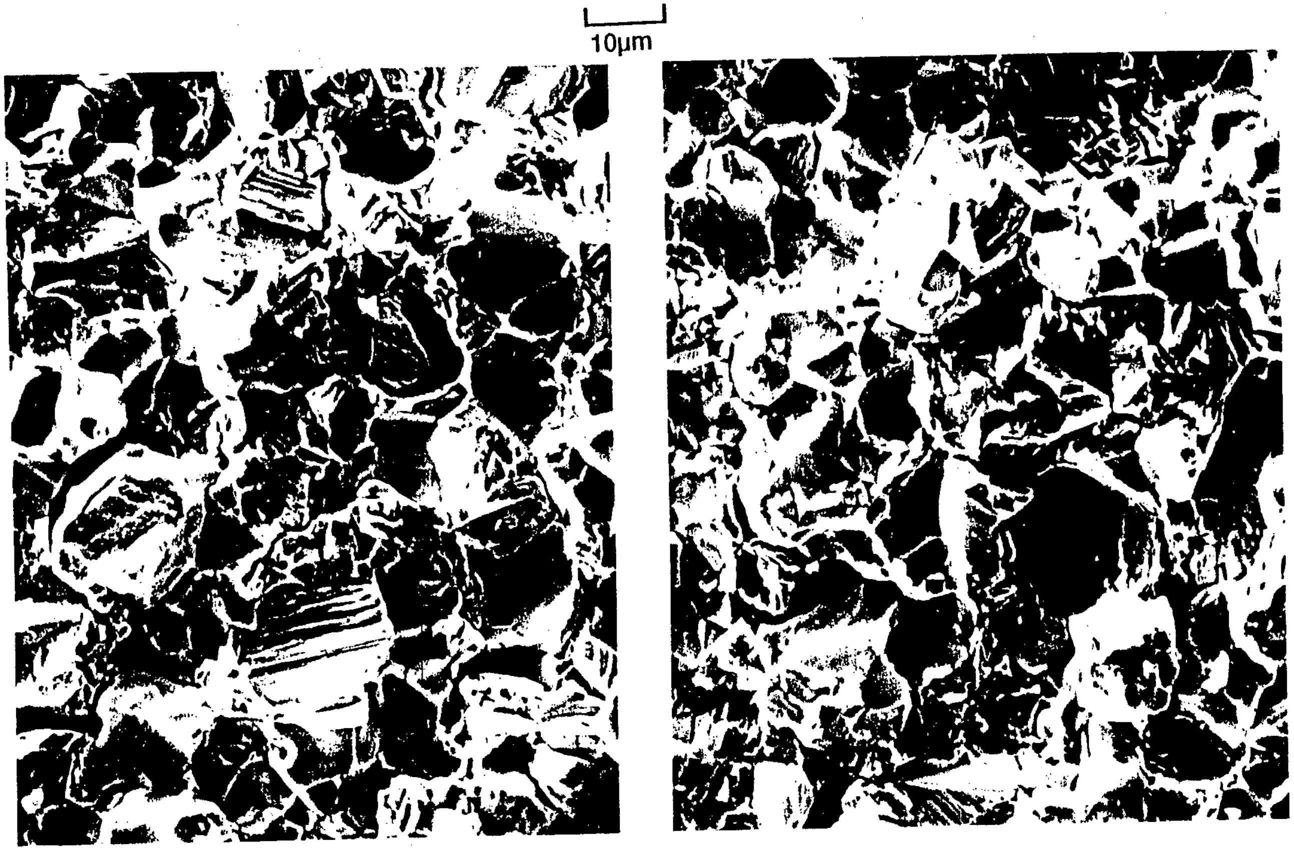
Tensile Properties of Alloy K5

(Dependence on Microstructure, Temperature and Strain Rate)



Strain Rate: $5x10^{-2}s^{-1}$

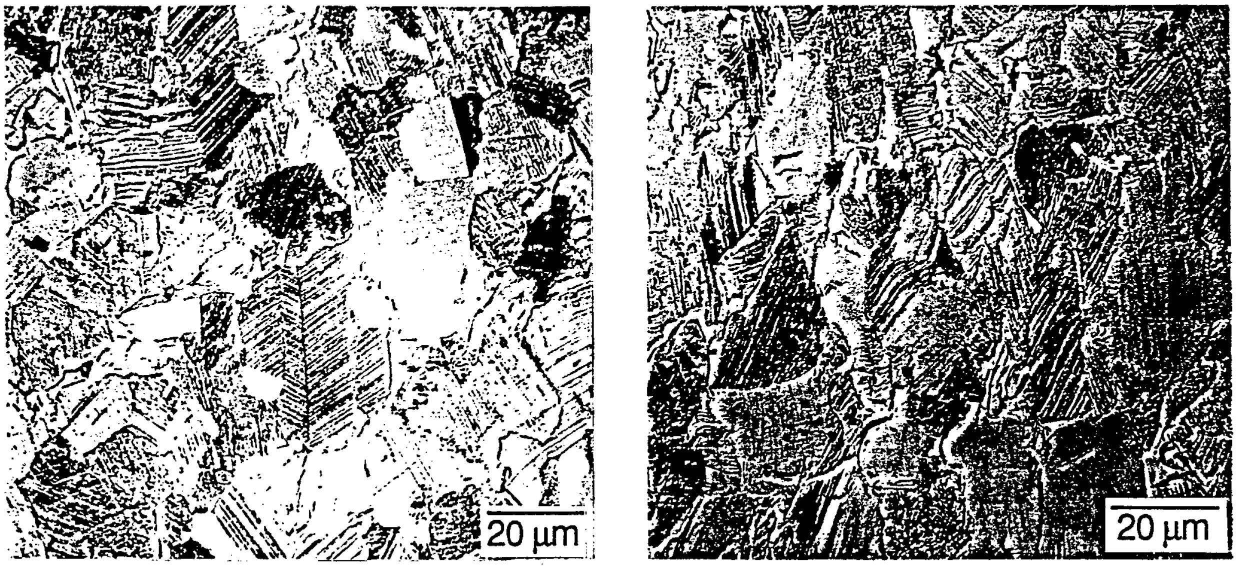
$1x10^{-4}s^{-1}$



Cl Site

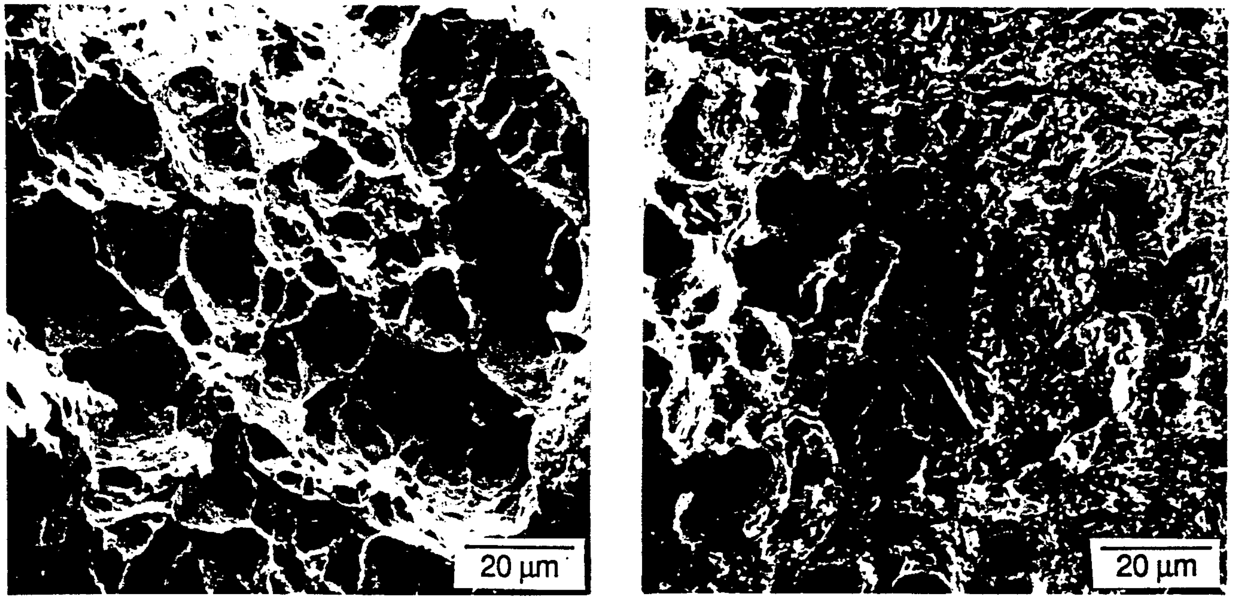
Away from Cl

Tensile Fracture of Alloy K5 (Duplex) in Air at 600°C
[YS/UTS/El : 396/545/3.6]



Far Below Fracture Surface

Just Below Fracture Surface

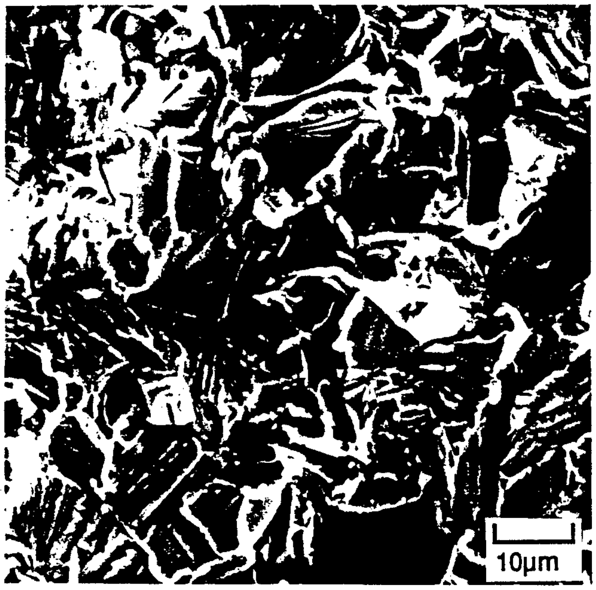


Near Cl site

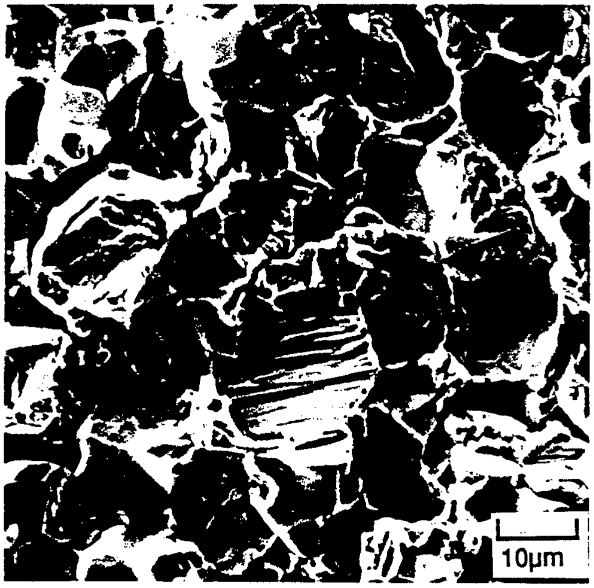
Away From Cl

Tensile Deformation and Fracture of a Duplex Alloy K5 at 800°C in Air

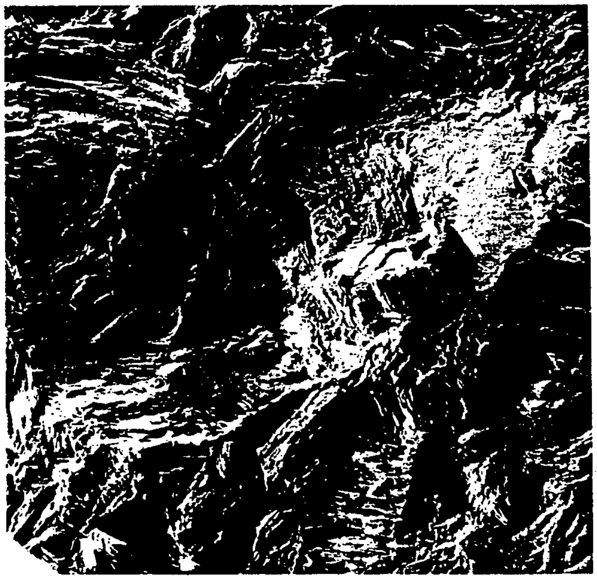
Temperature Effect on Fracture Mode



Duplex at RT



Duplex at 600°C

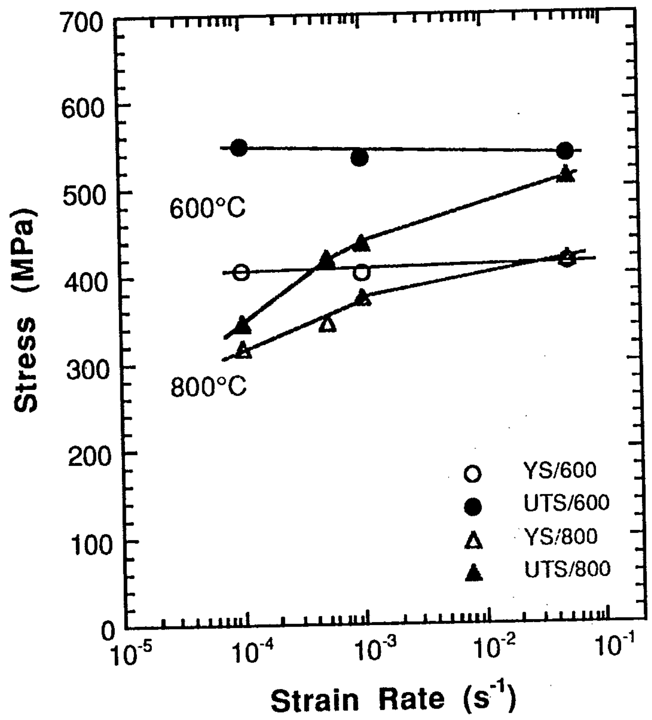


RFL at RT

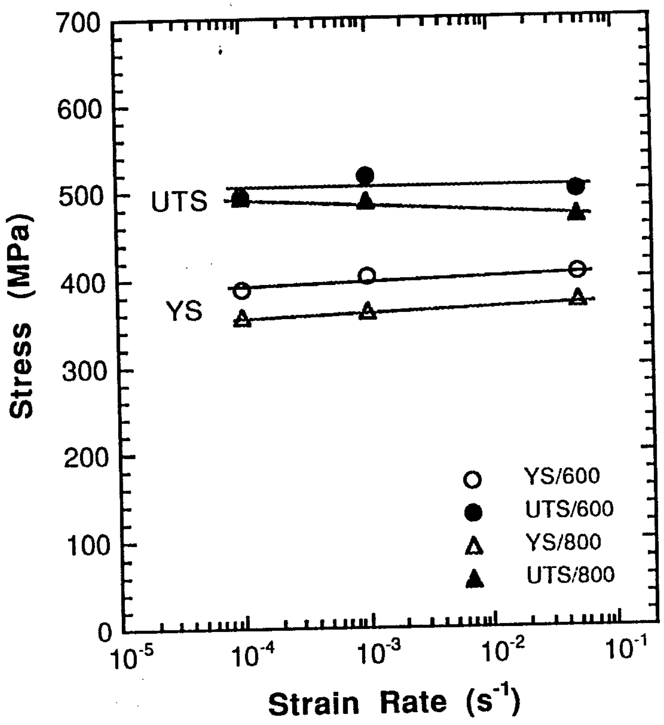
RFL at 800°C

Tensile Properties of Alloy K5

(Dependence on Microstructure, Temperature and Strain-Rate)

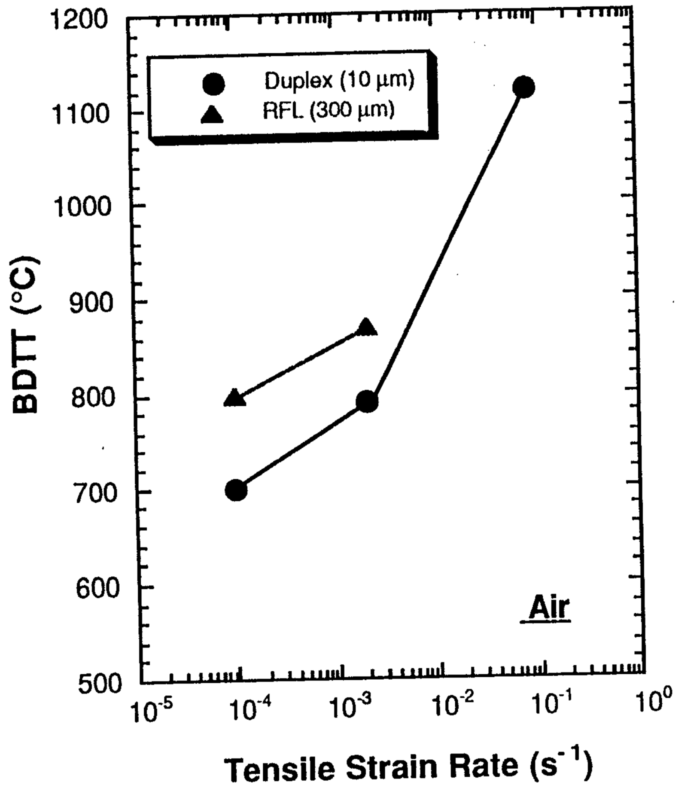


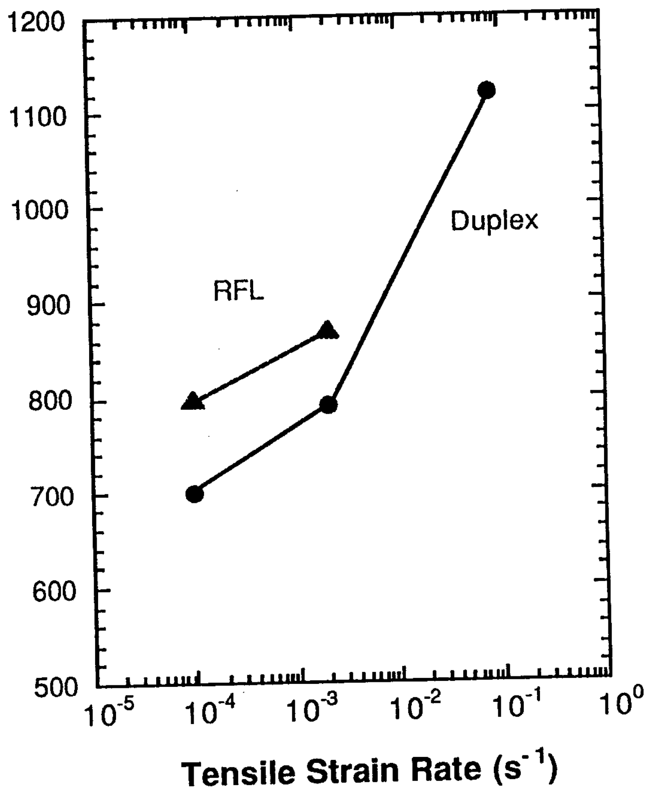
K5-Duplex



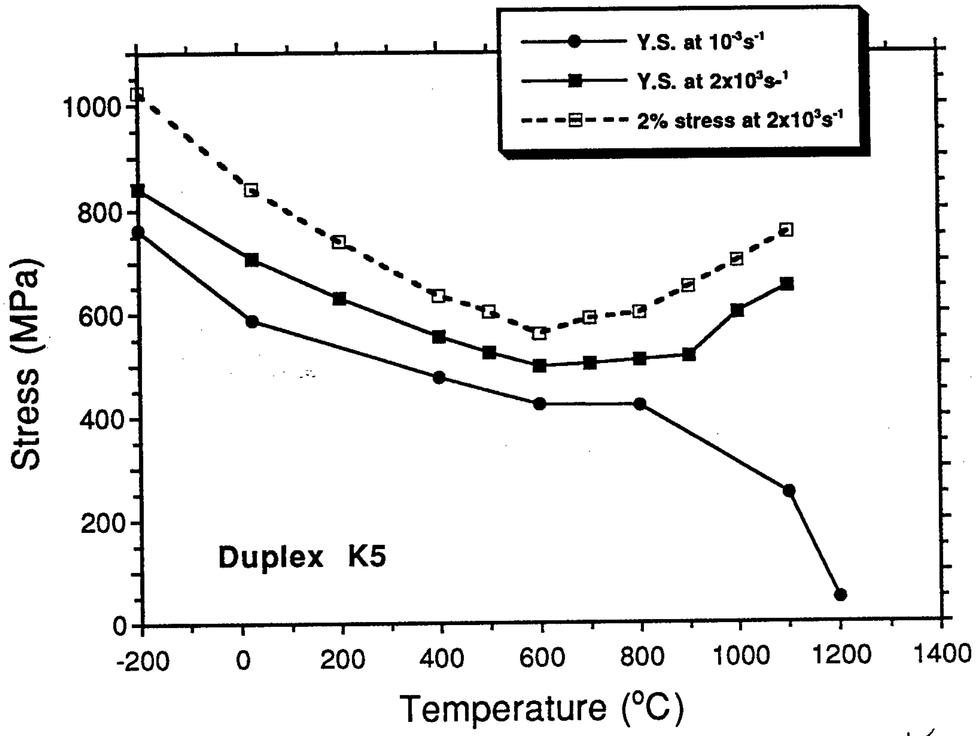
K5-RFL

Effect of Strain Rate on BDT in Alloy K5





Dependence of Flow Stress on Strain-Rate and Temperature



Jin + Kim (95)

Factors Controlling Tensile Properties

Microstructure

- Types: Duplex vs. FL
- Features
  - Grain Size and Morphology
  - GB Morphology
  - Lamellar Spacing (LS)
  - α_2/γ Ratio (α_2 vol%)
- Uniformity

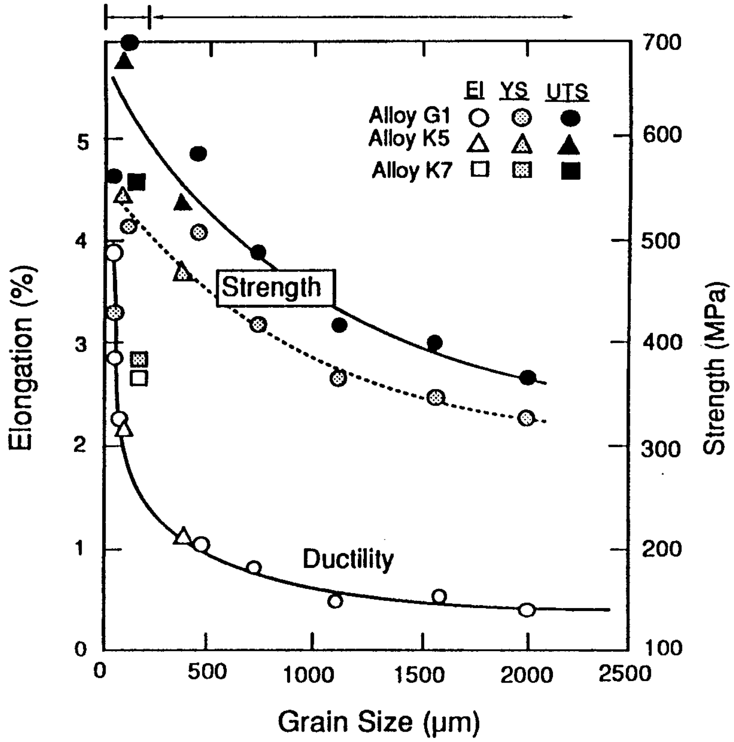
Composition

- α_2/γ Ratio; LS

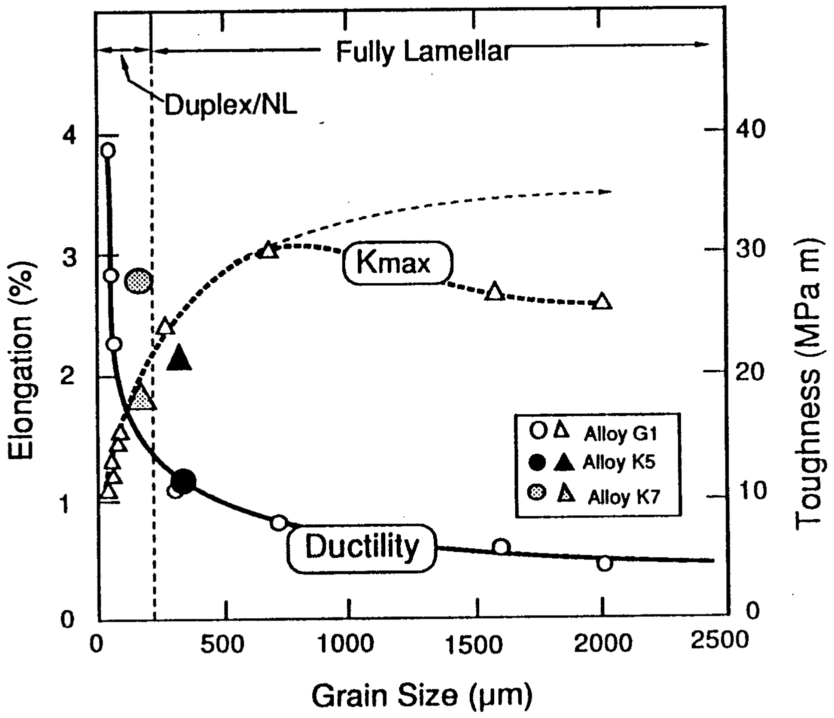
Cleavage Strength

Interfacial Bond Strength

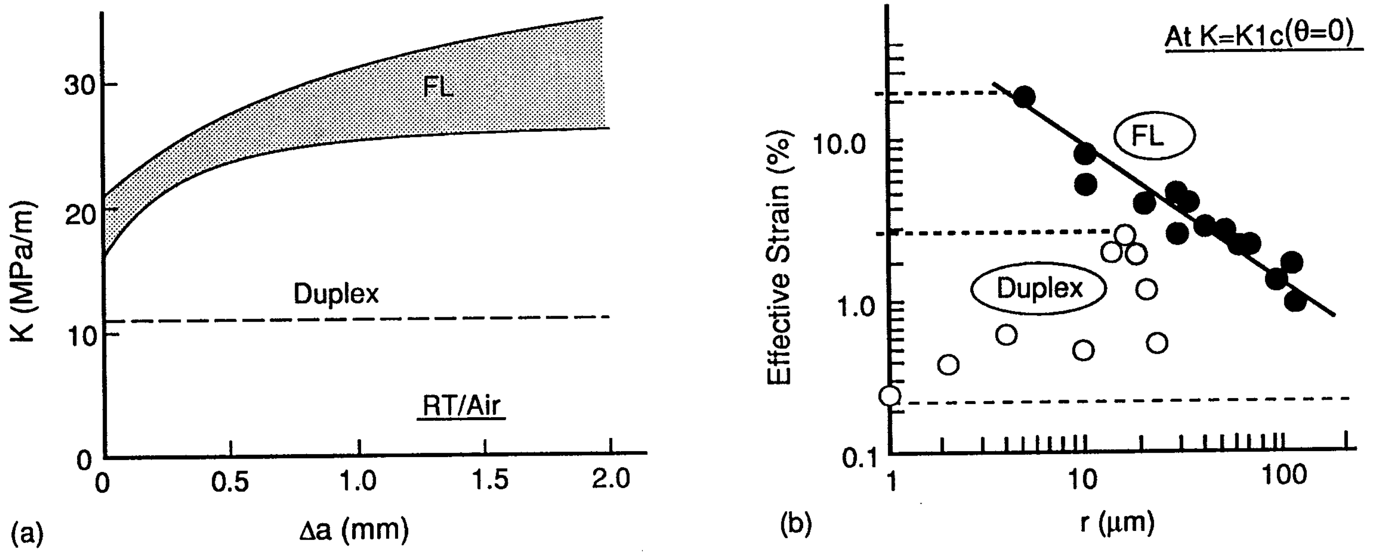
Grain Size Effects on Tensile and Toughness



Ductility and Strength



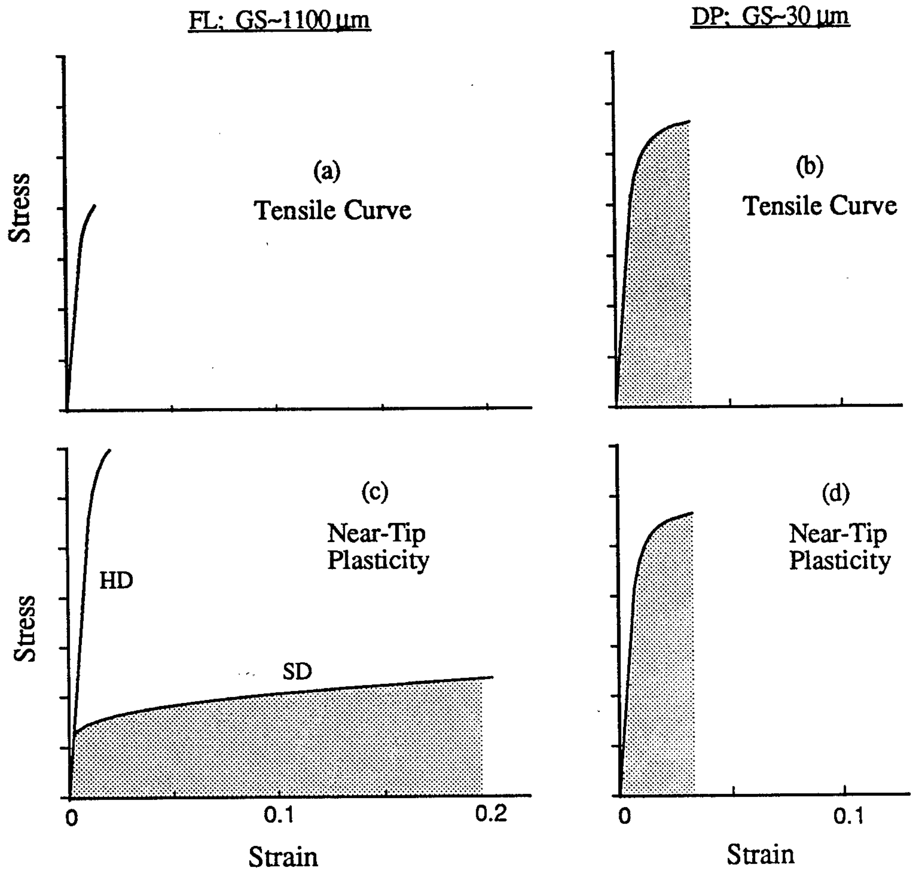
Ductility and Toughness



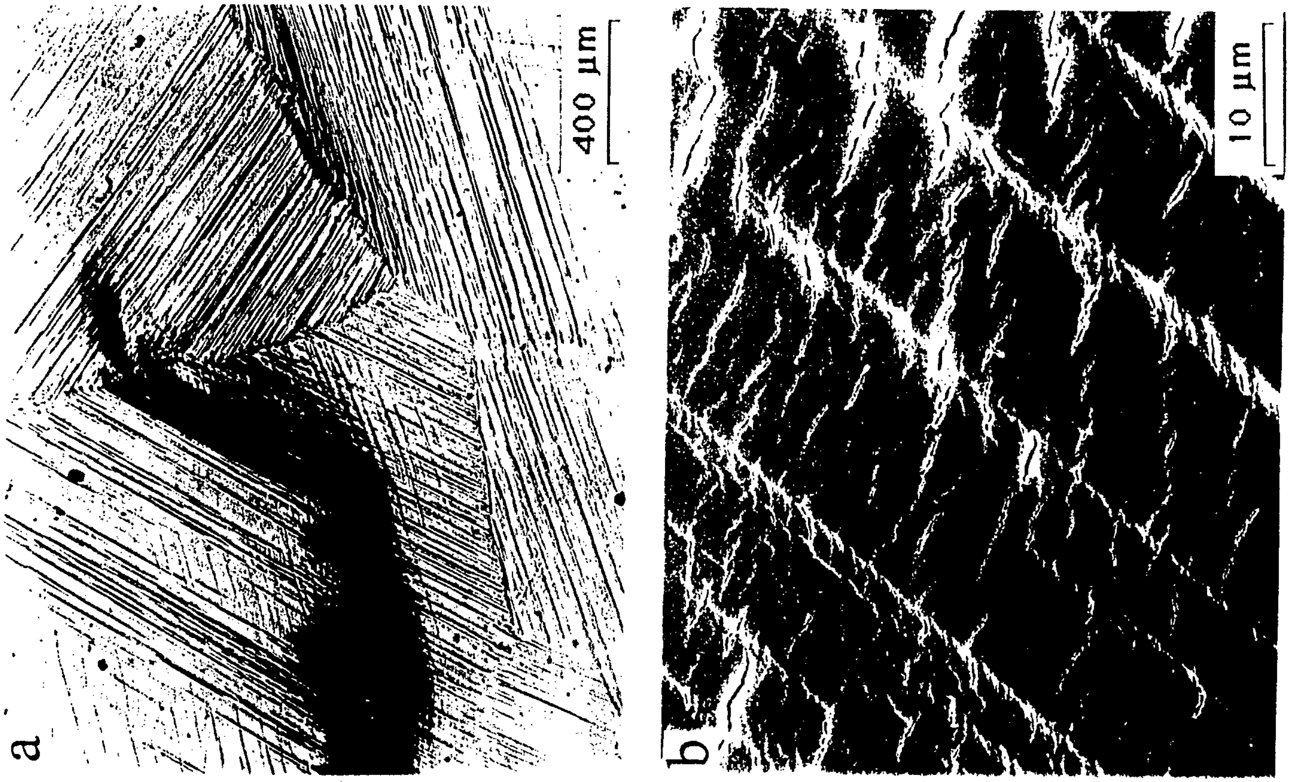
K-Resistance Curves

Near-tip Strain Distribution

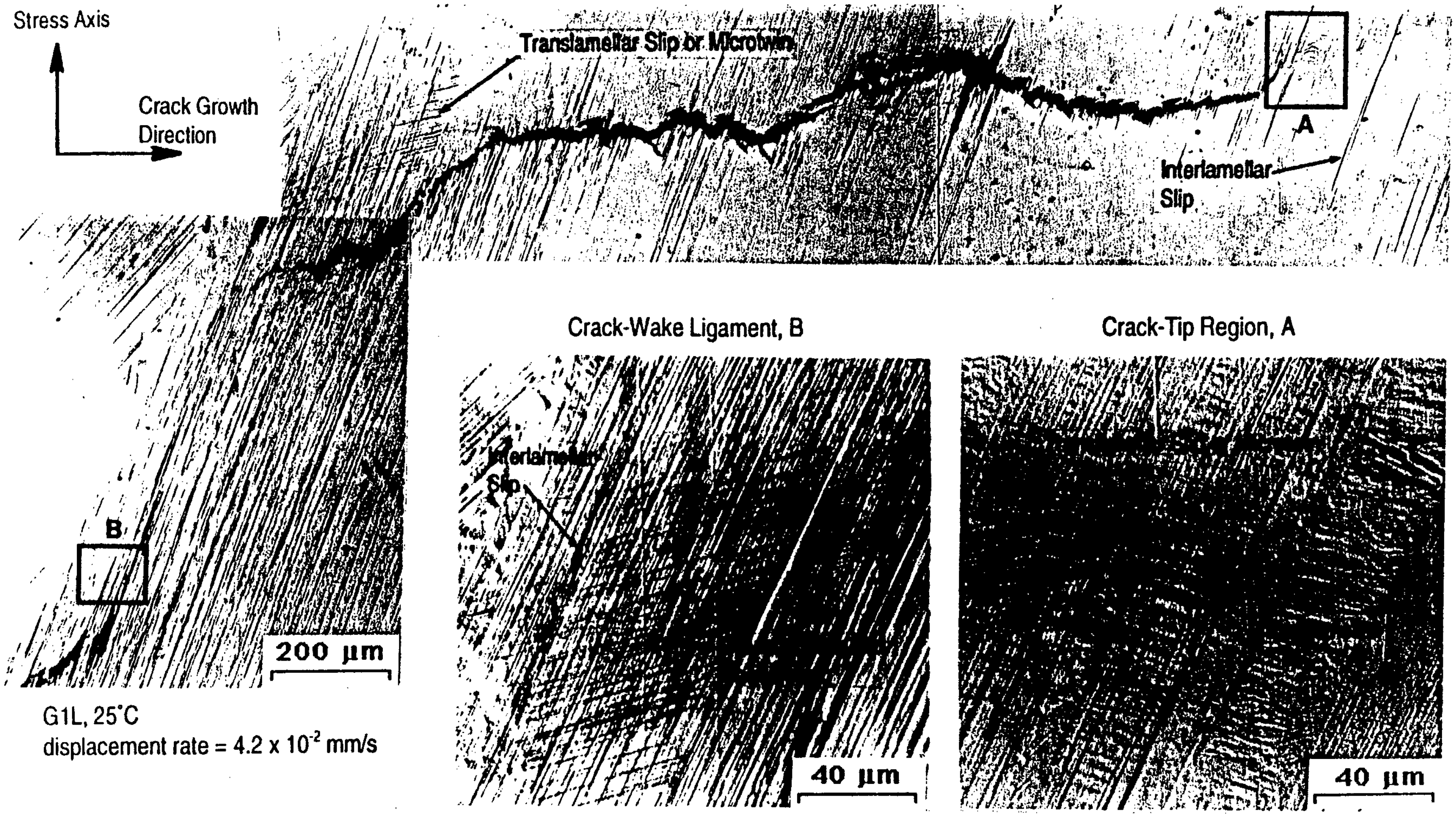
Fracture Resistance and Near-Tip Plasticity at RT



General Tensile Yielding vs. Near-Crack-Tip Plasticity at K_{IC}



Plastic Deformation and Microcking Around the Advancing Crack Tip in a FL Alloy G1 CT Specimen under a Monotonic Tension Loading at RT

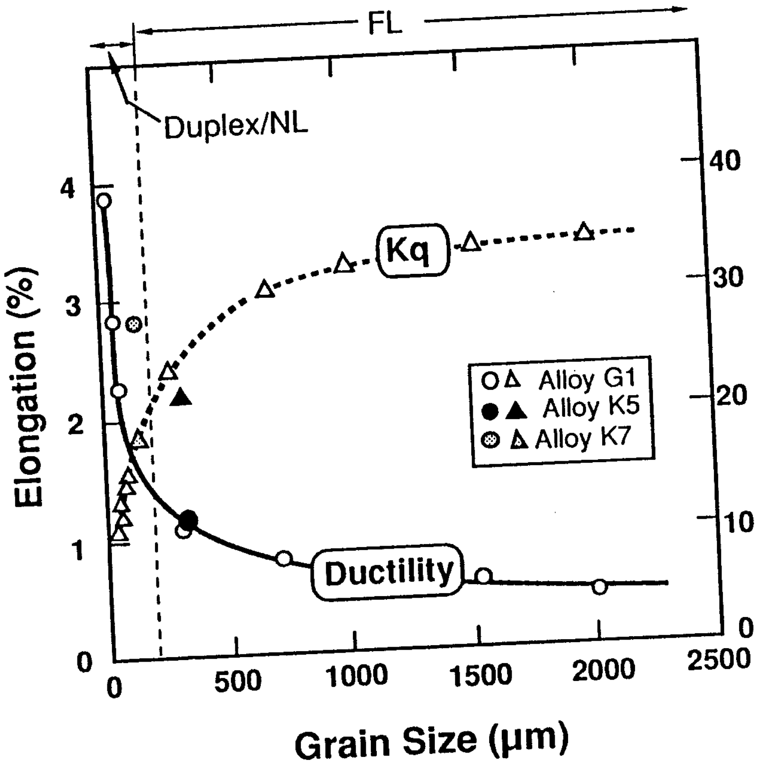


G1L, 25°C
displacement rate = 4.2 x 10^{-2} mm/s

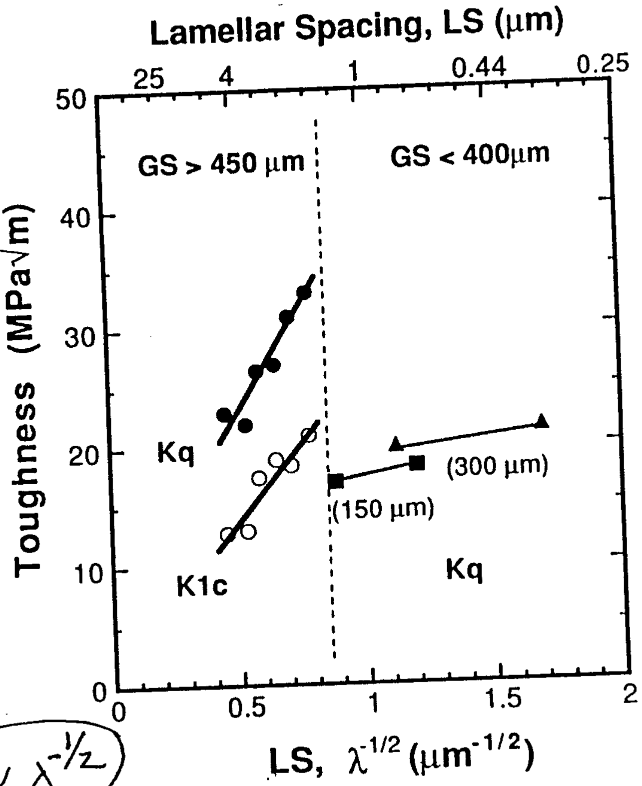
Interlamellar and Translamellar Deformation in Crack-Tip and Ligament Regions

Fracture Toughness

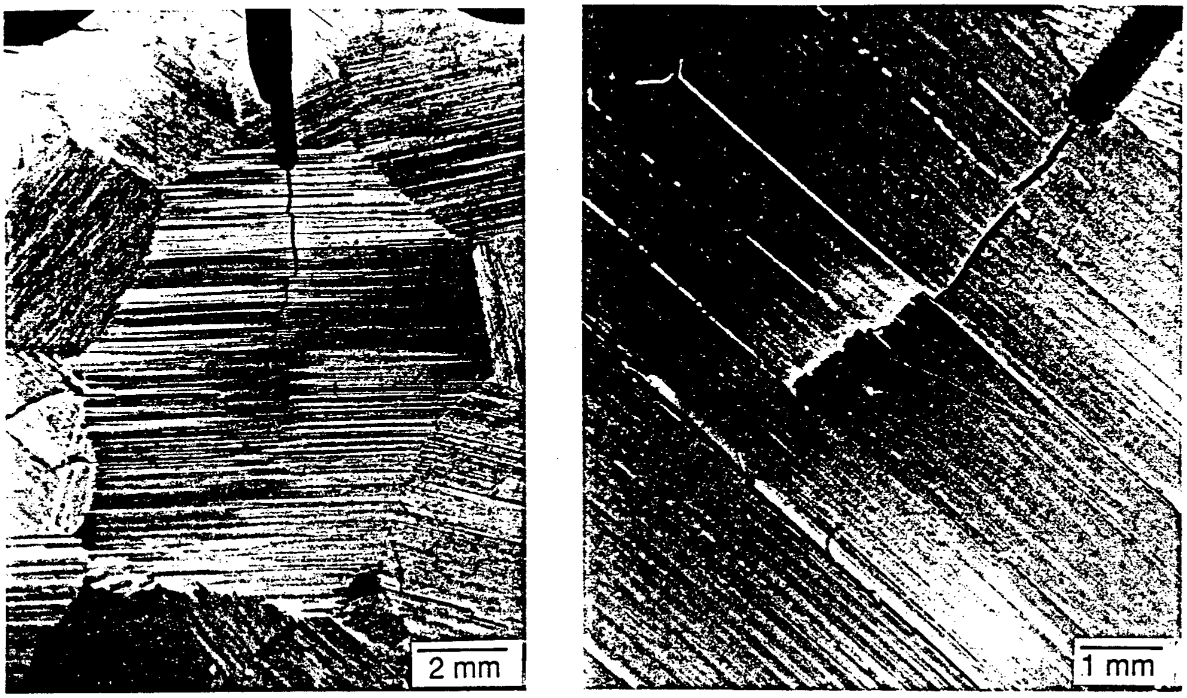
Grain Size Effect

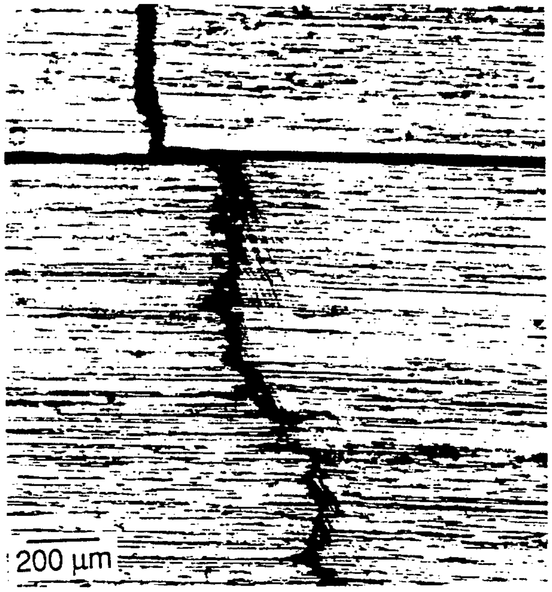


Lamellar Spacing Effect

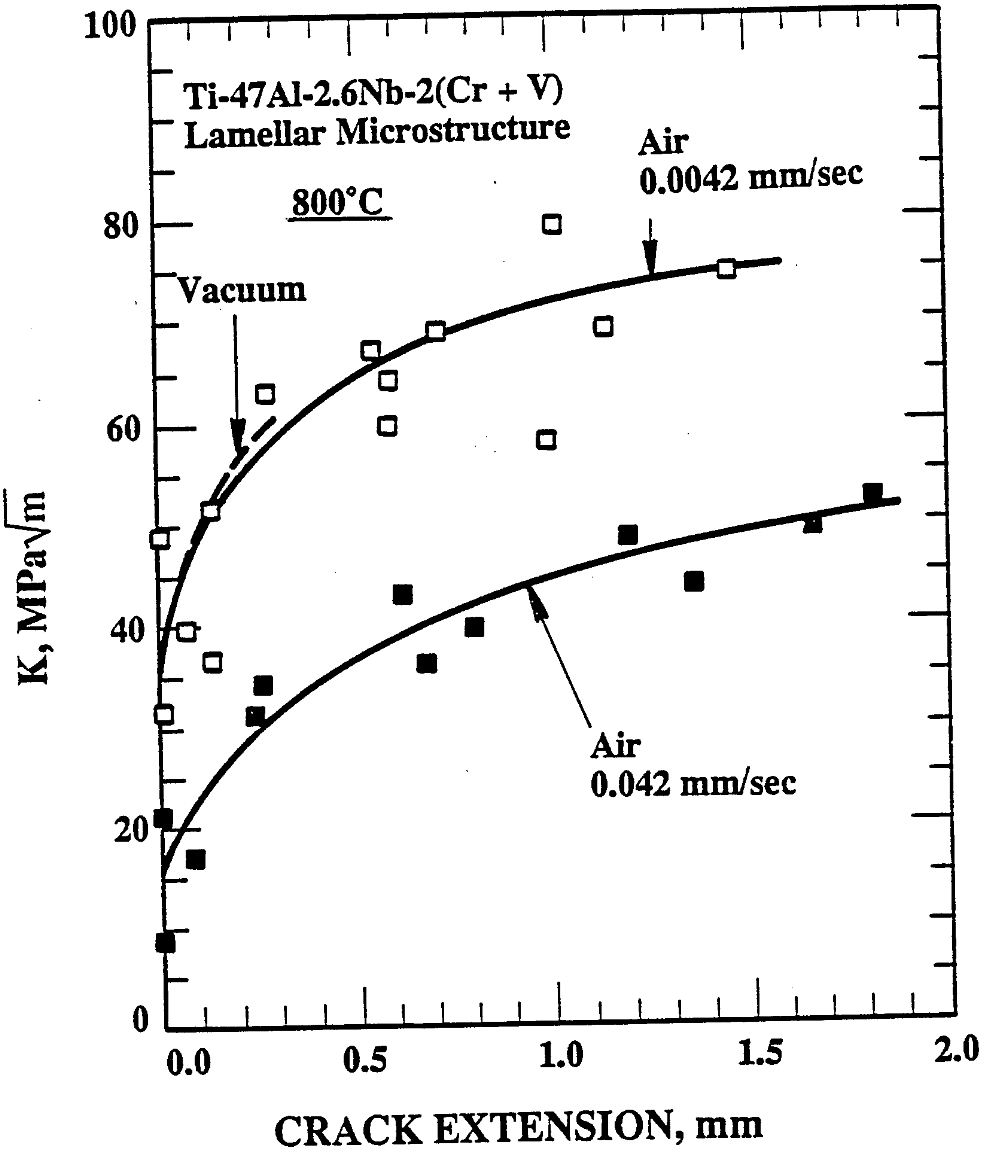


$K \propto \lambda^{-1/2}$

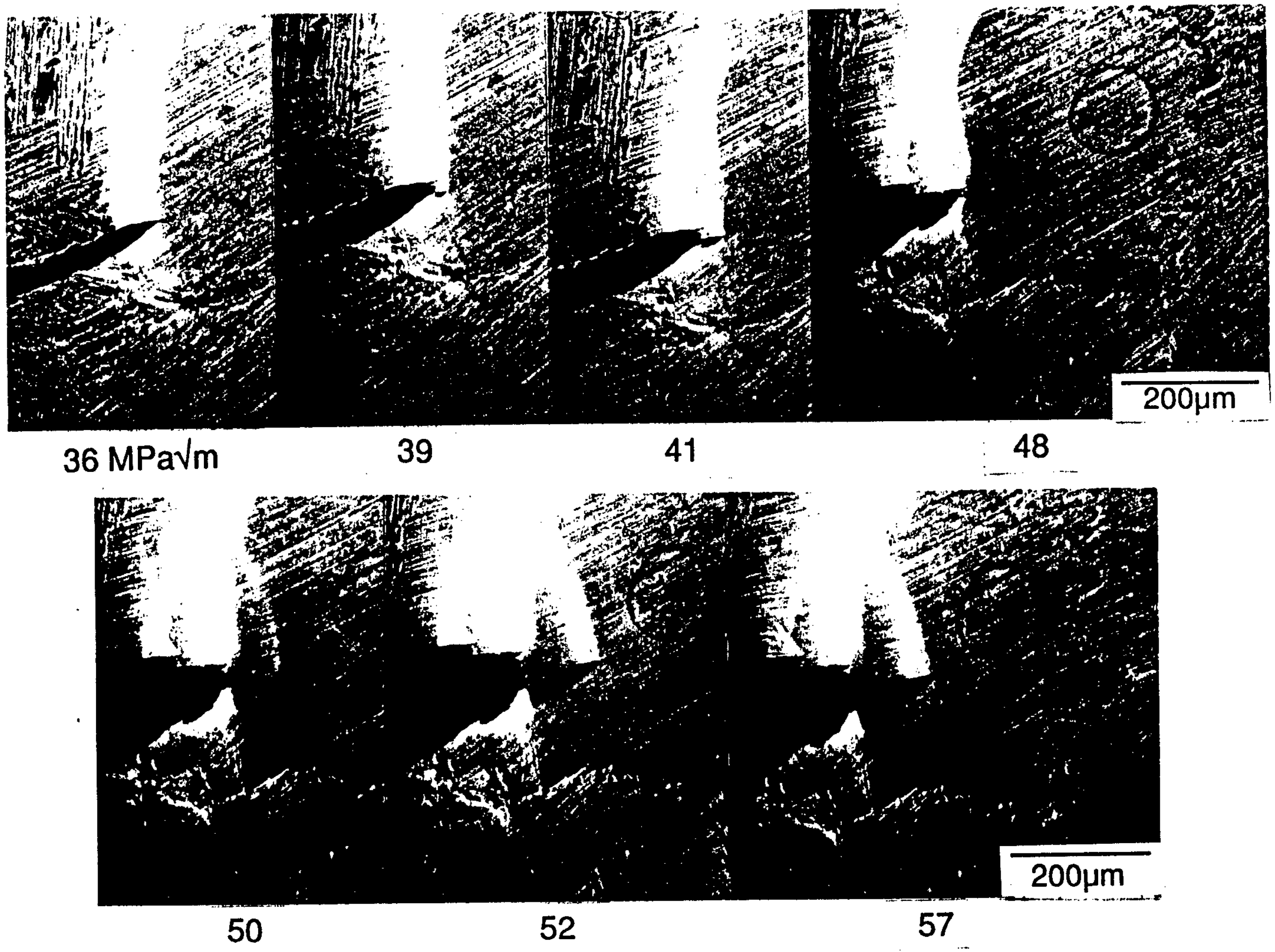




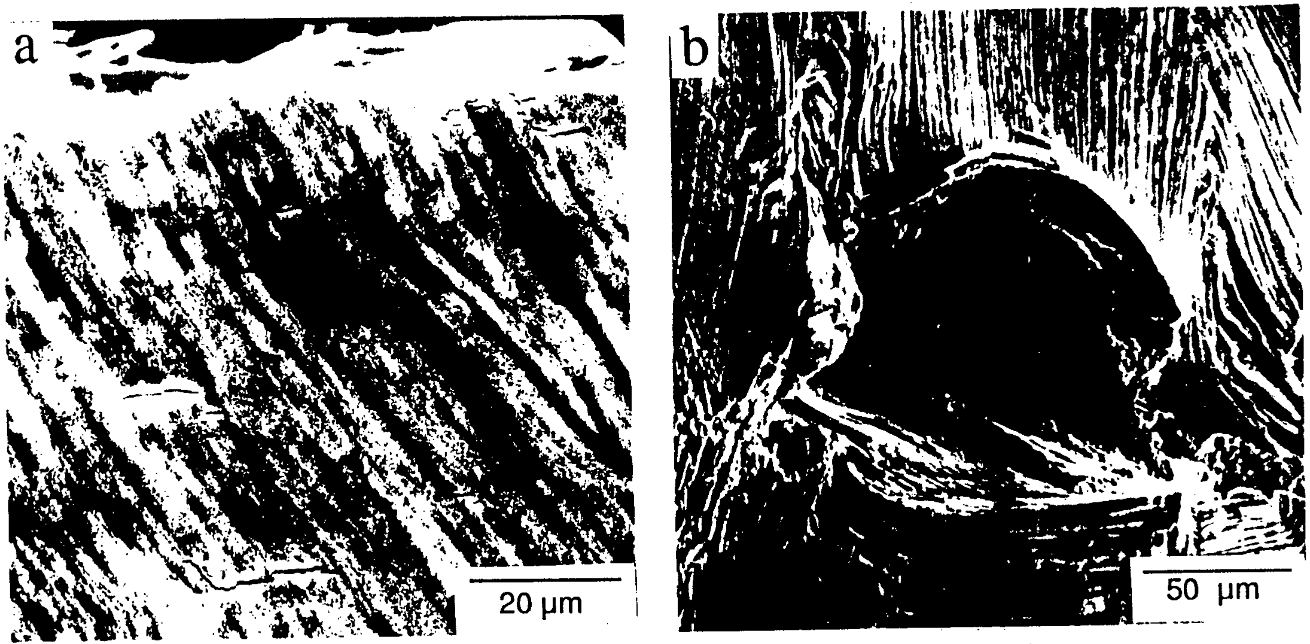
T-Cracks Involving Delamination, and Both Inter- and Trans-lamellar Slip/Twinning



Effect of displacement rate on the K-resistance curves of the G1L alloy at 800°C.



Fracture Process in Lamellar TiAl Alloys at 800°C



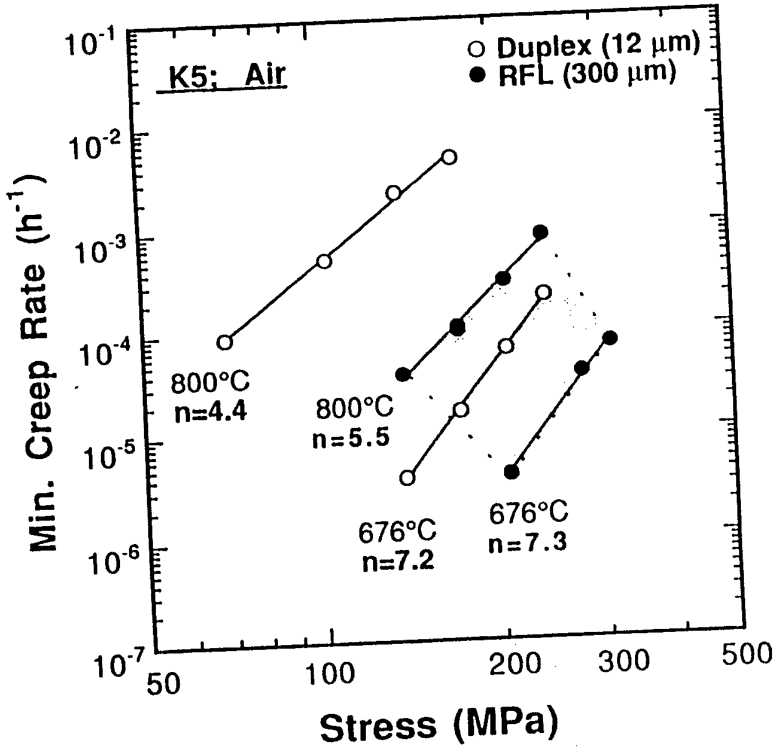
RT

800°C

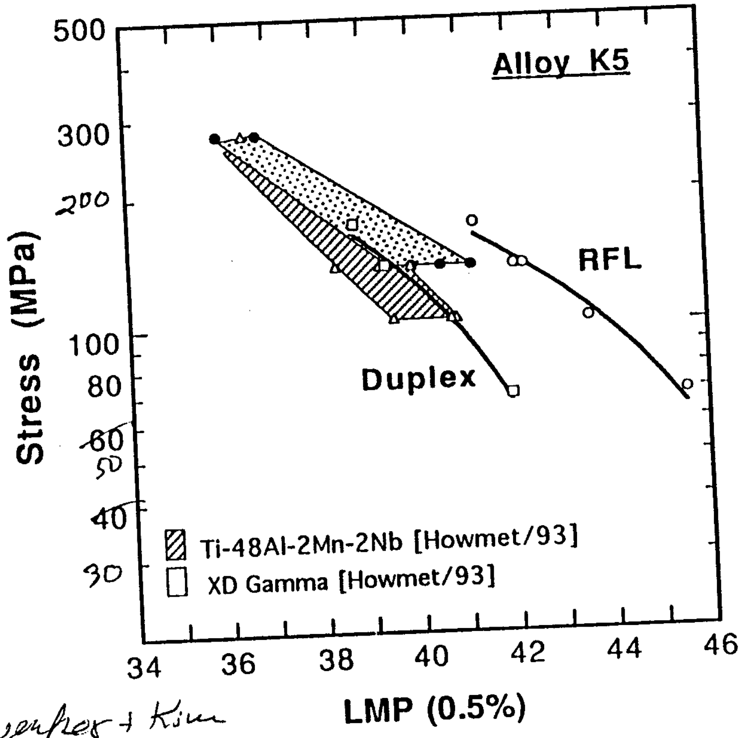
Crack-Tip Regions of Lamellar TiAl Fracture Specimens

Creep Resistance of Alloy K5

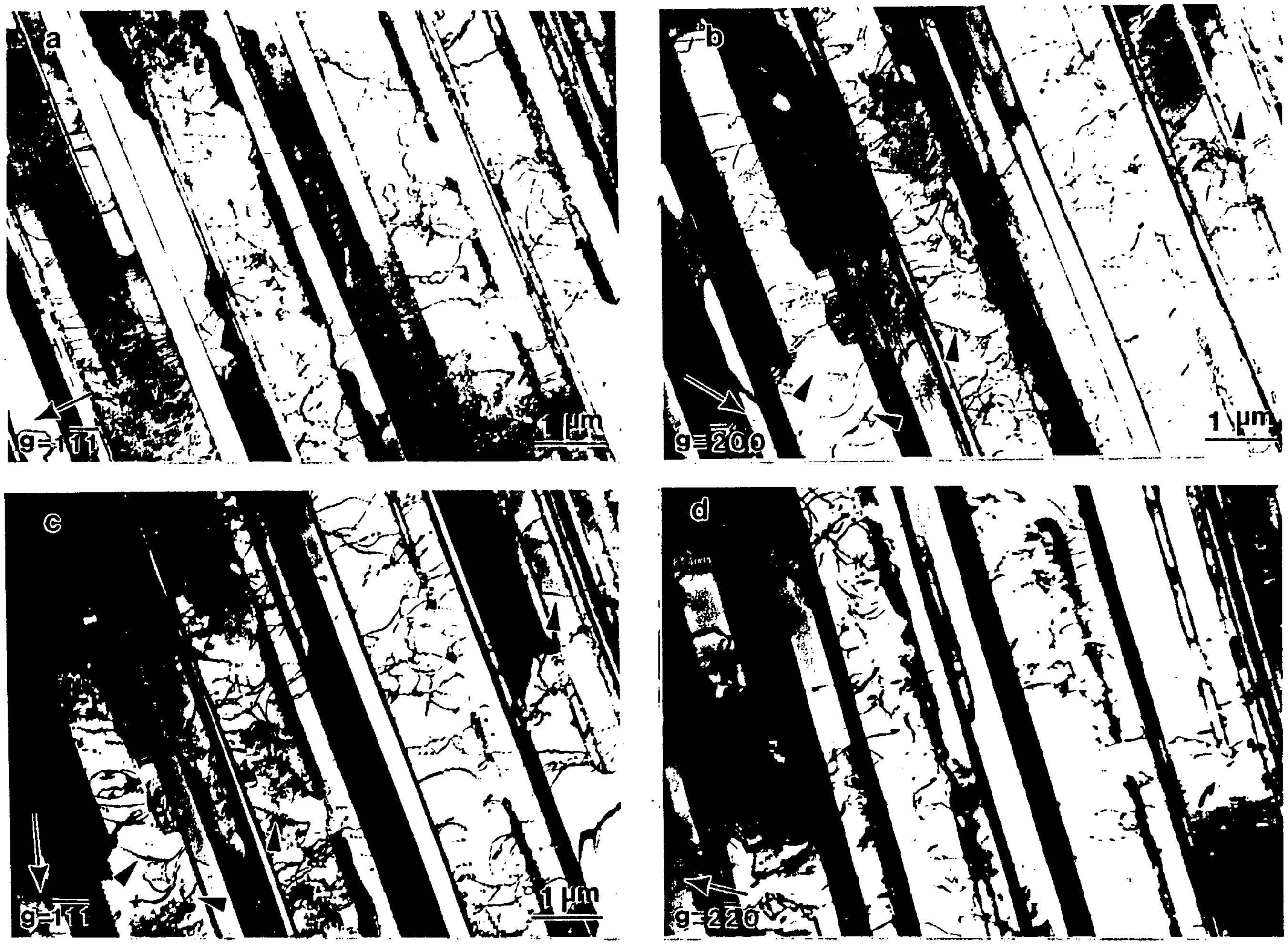
Stress Exponents



Larsen-Miller Plot

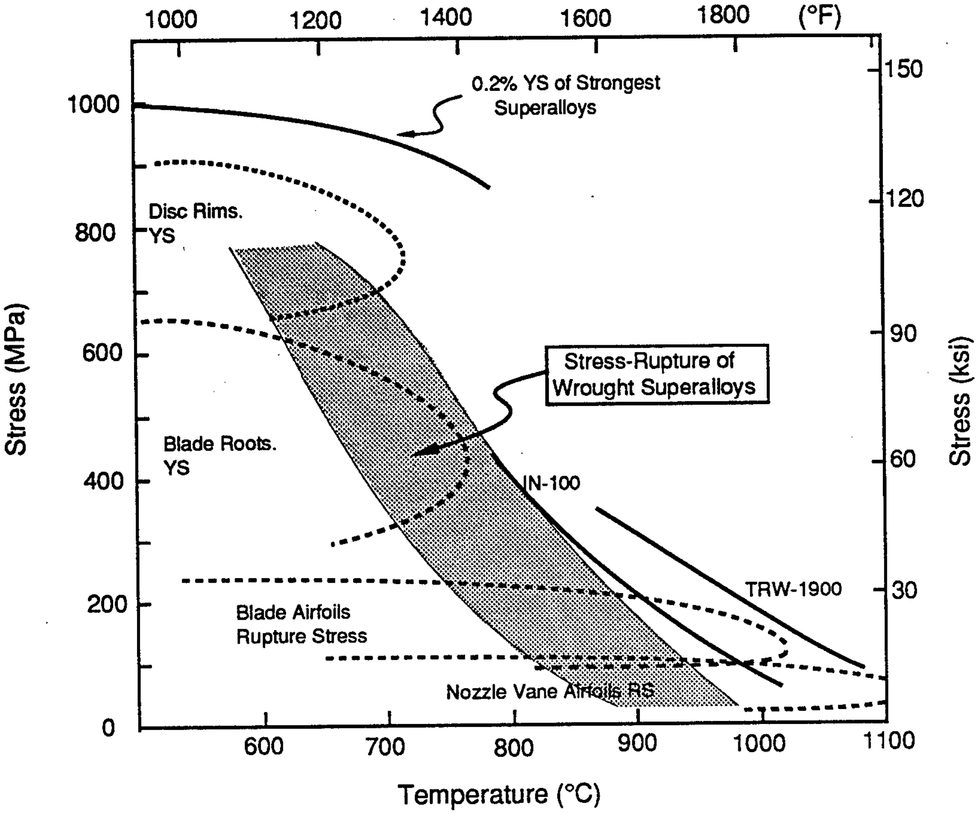


schwenker + Kim
(94)



Alloy G1 : Lamellar structure near the fracture surface of the specimen crept in vacuum at 207 MPa

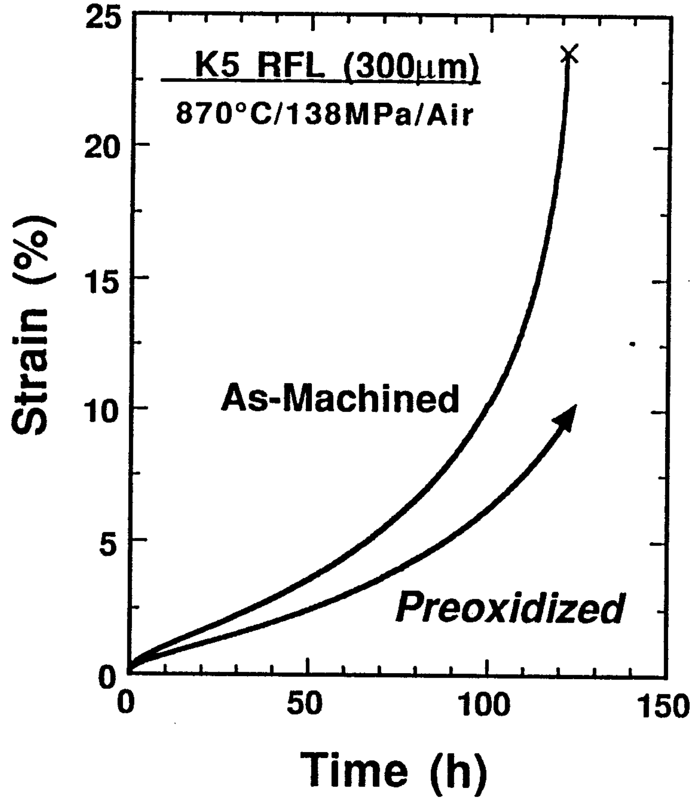
Alloy K5 RFL Specimen Crept at 800°C to 18.7% in Air Under (138-173-207-242-285 MPa) Step Stress Conditions

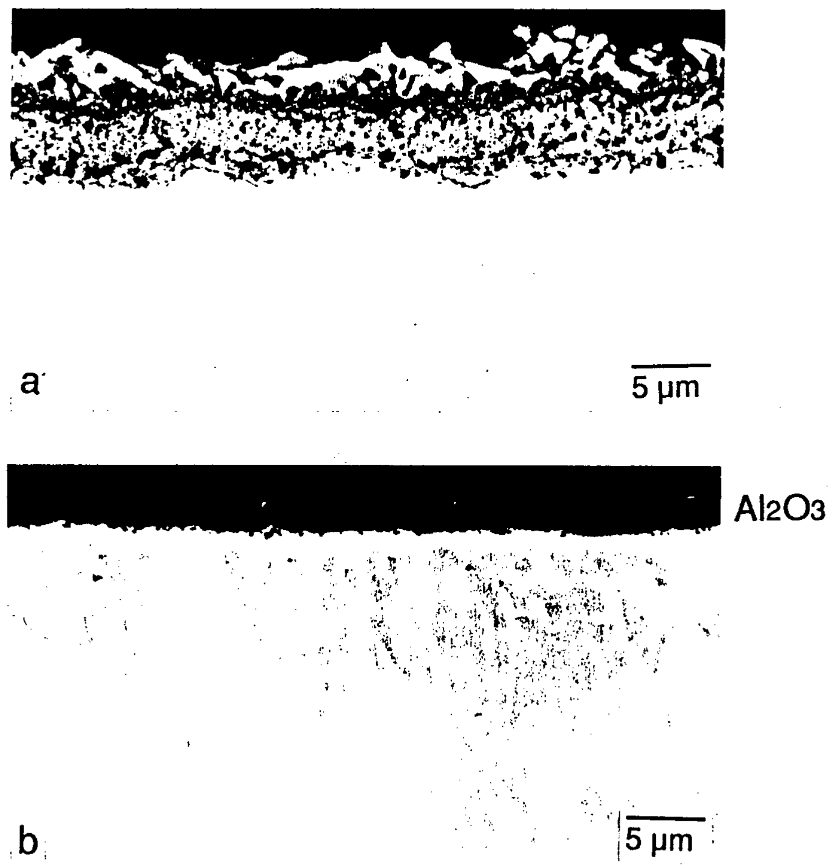


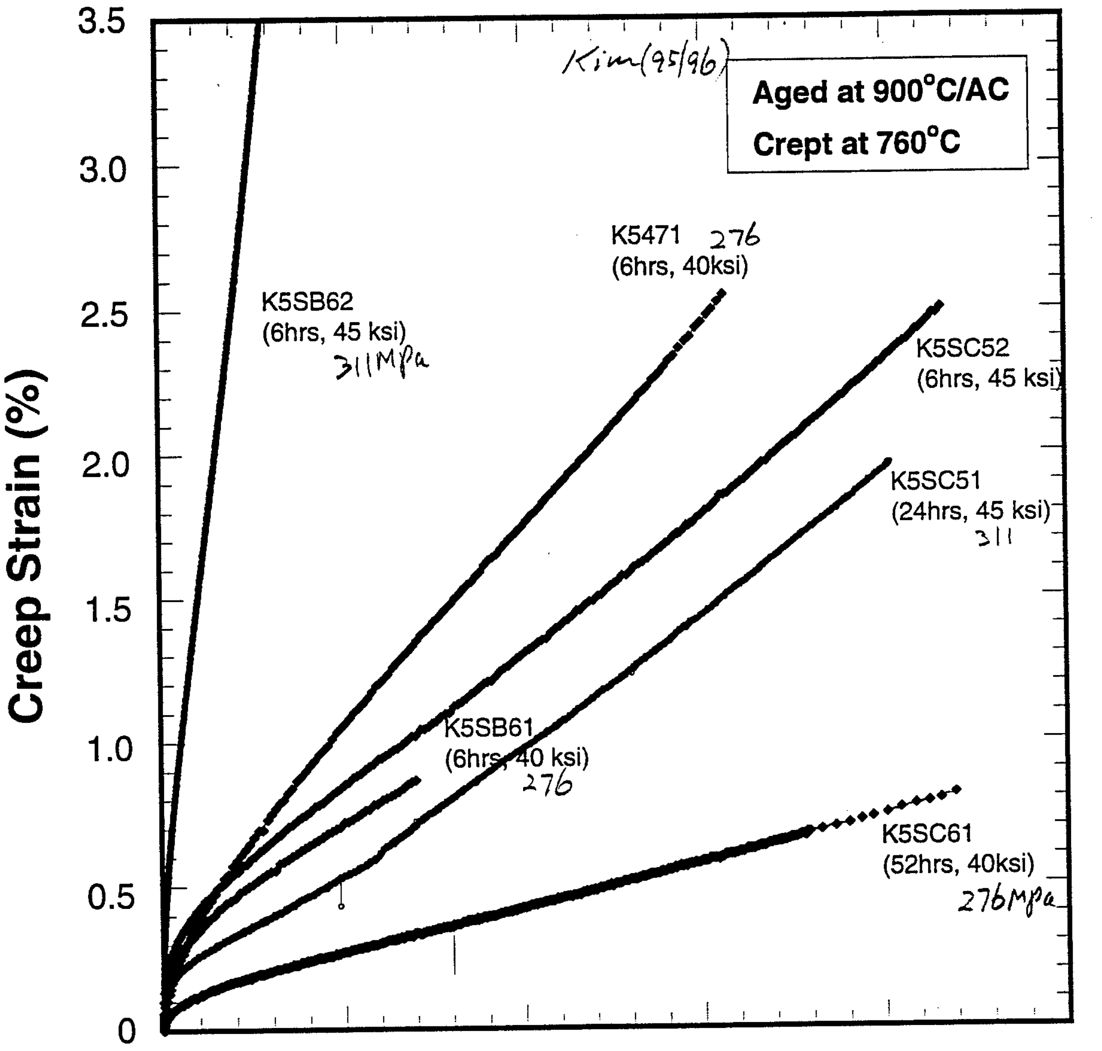
Turbine Blade and Vane Operating Temperatures,Yield Stresses (YS), 1000-h RuptureStresses (RS) for Superalloys

Effect of Al_2O_3 Layer on Creep

Creep of Alloy K5

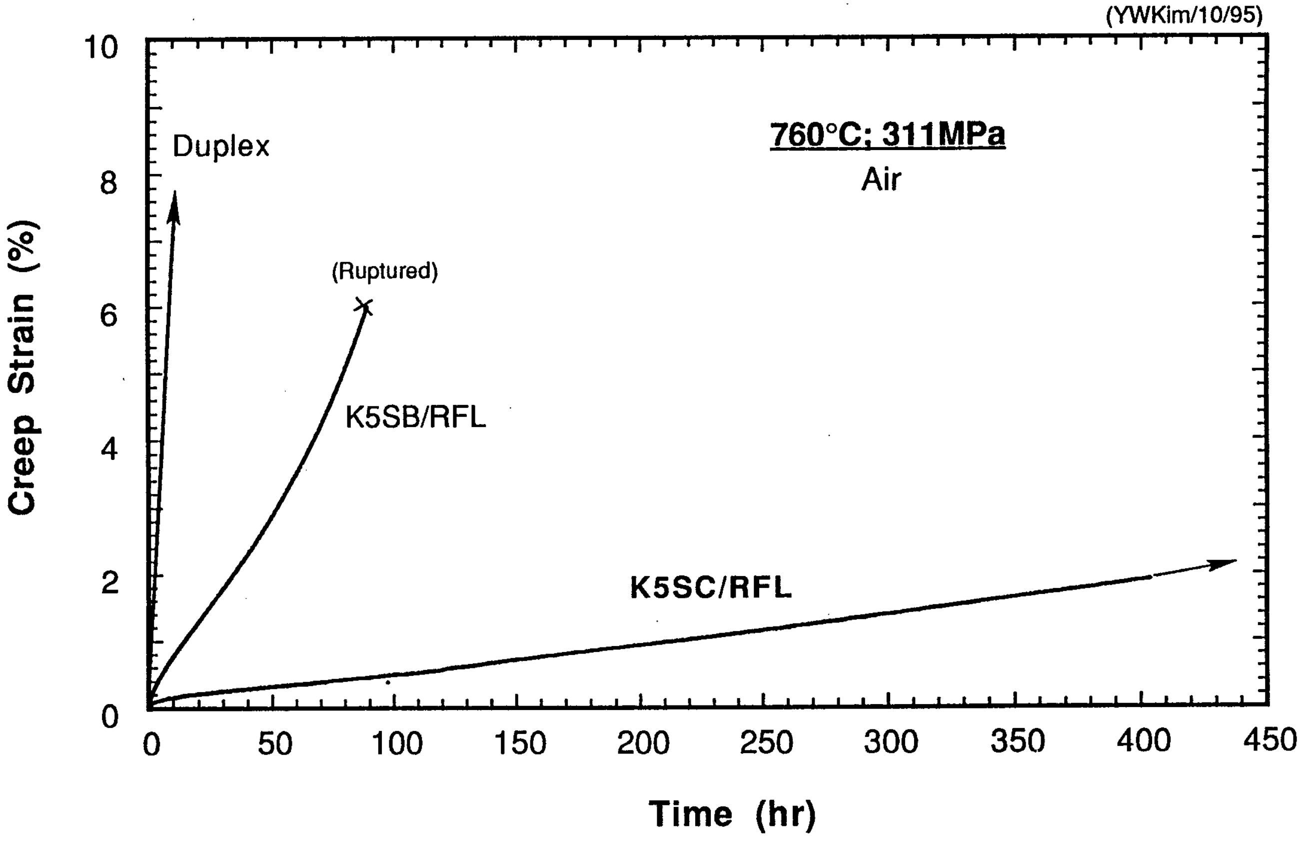


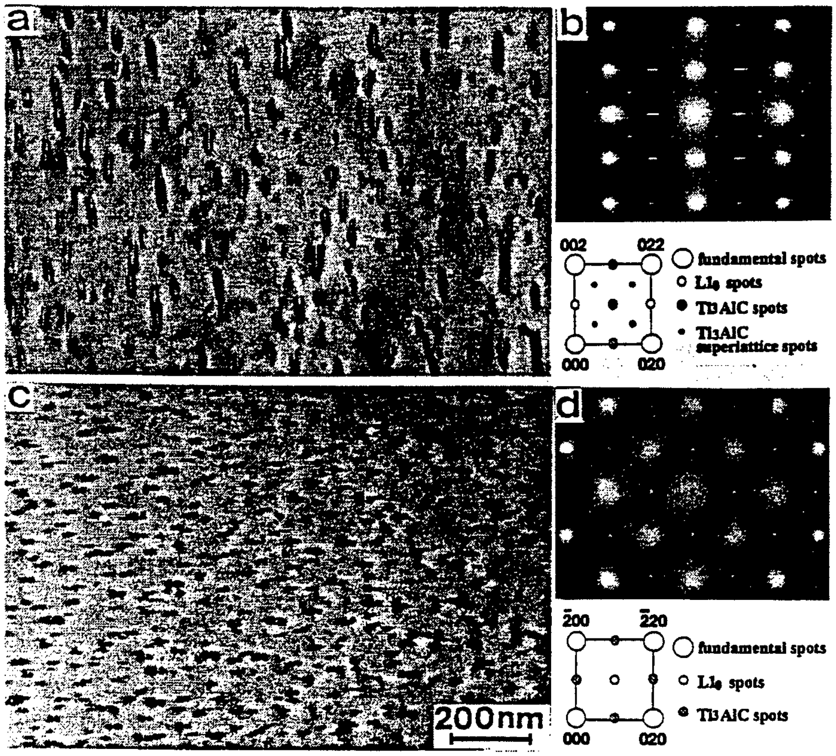



Kim(95/96)
Aged at 900°C/AC
Crept at 760°C
K5SB62
(6hrs, 45 ksi)
311MPa
K5471 276
(6hrs, 40ksi)
K5SC52
(6hrs, 45 ksi)
K5SC51
(24hrs, 45 ksi)
311
K5SB61
(6hrs, 40 ksi)
276
K5SC61
(52hrs, 40ksi)
276MPa
Creep Strain (%)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
100
200
300
400
500
Time (h)

Creep of Alloy K5 Series

(under severe conditions)





Nemoto (94)

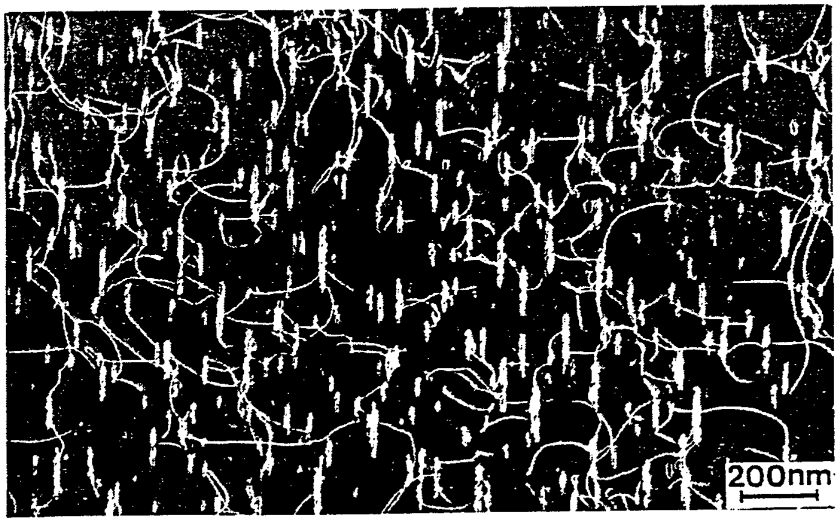


Figure 8 Dark field electron micrograph showing the bypassing dislocations in $(Ti_{0.49}Al_{0.51})_{99.5}$ $C_{0.5}$ aged at 1073 K for $3.6x10^5$ s (100h/over aged) and deformed to 3% at 873 K. The dislocation loops surrounding needles can be seen.

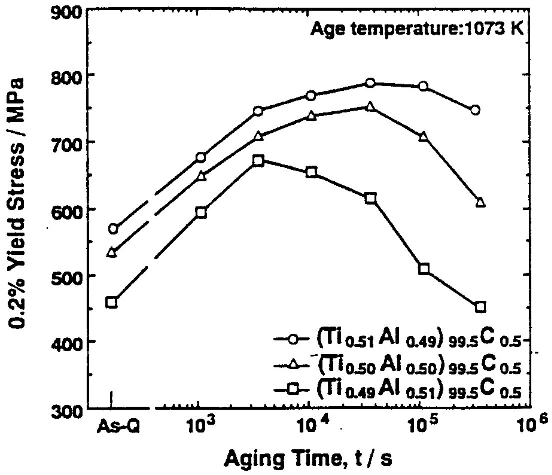


Figure 2 Effects of the deviation from the stoichiometry on the variation of compressive yield strength of $(Ti_{0.51}Al_{0.49})_{99.5}C_{0.5}$, $(Ti_{0.50}Al_{0.50})_{99.5}C_{0.5}$ and $(Ti_{0.49}Al_{0.51})_{99.5}C_{0.5}$ during aging at 1073 K.

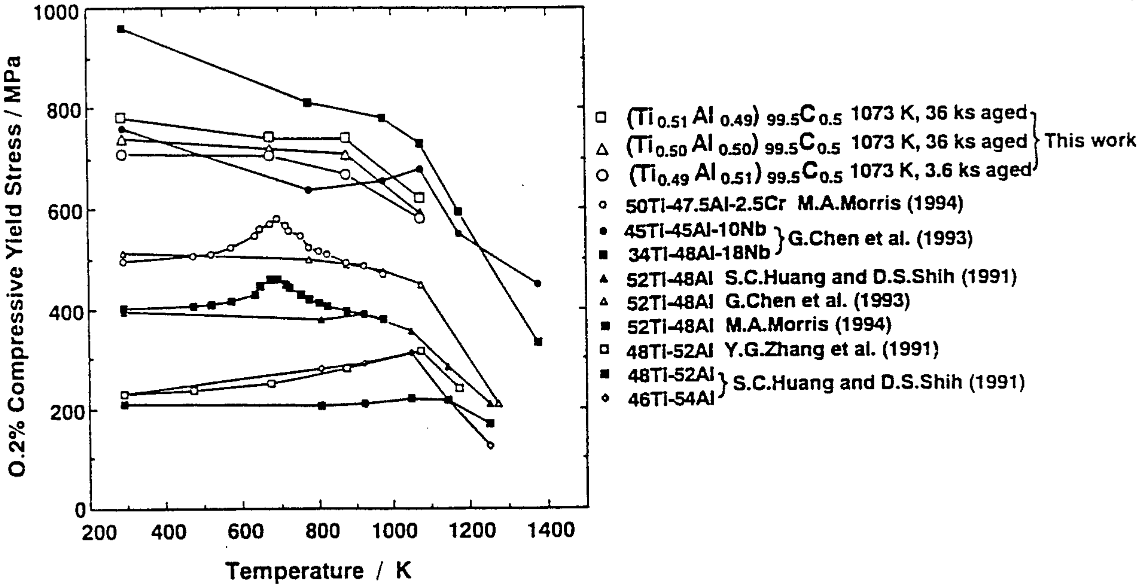
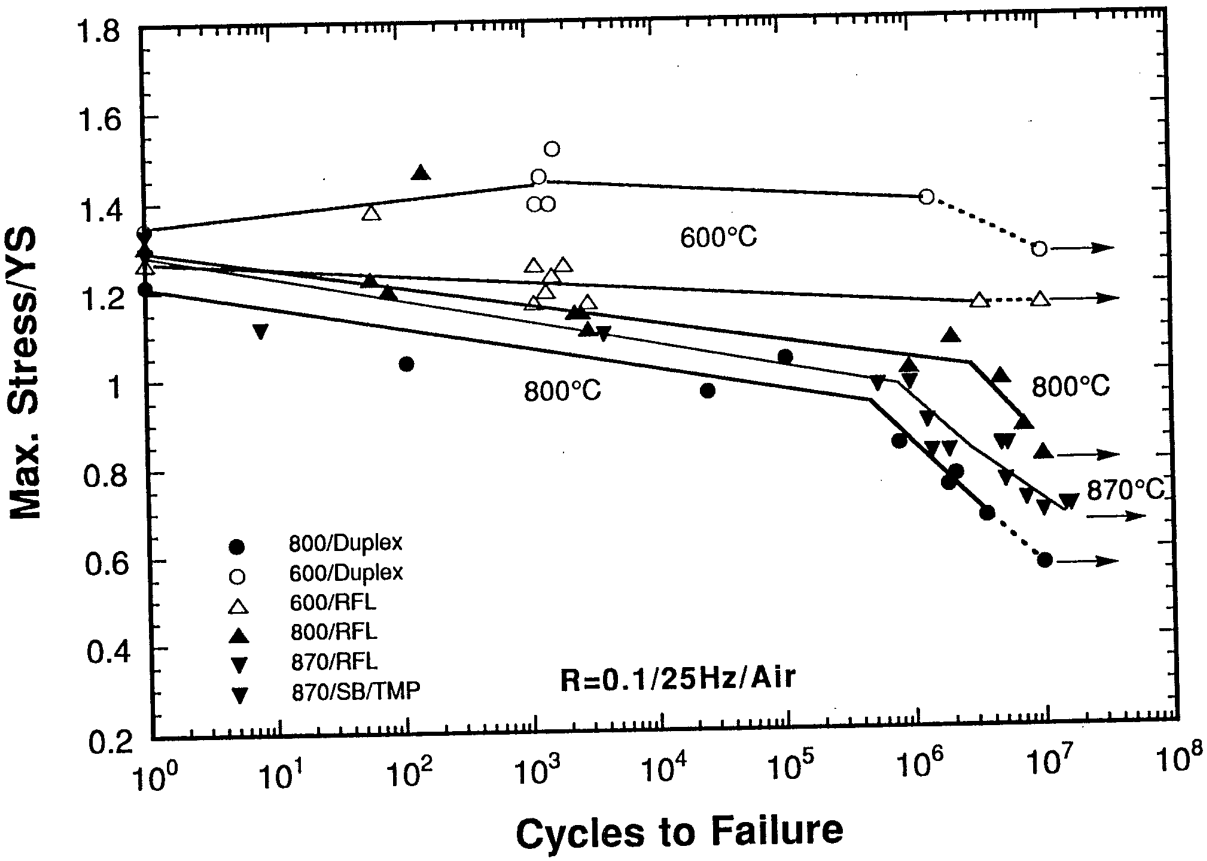
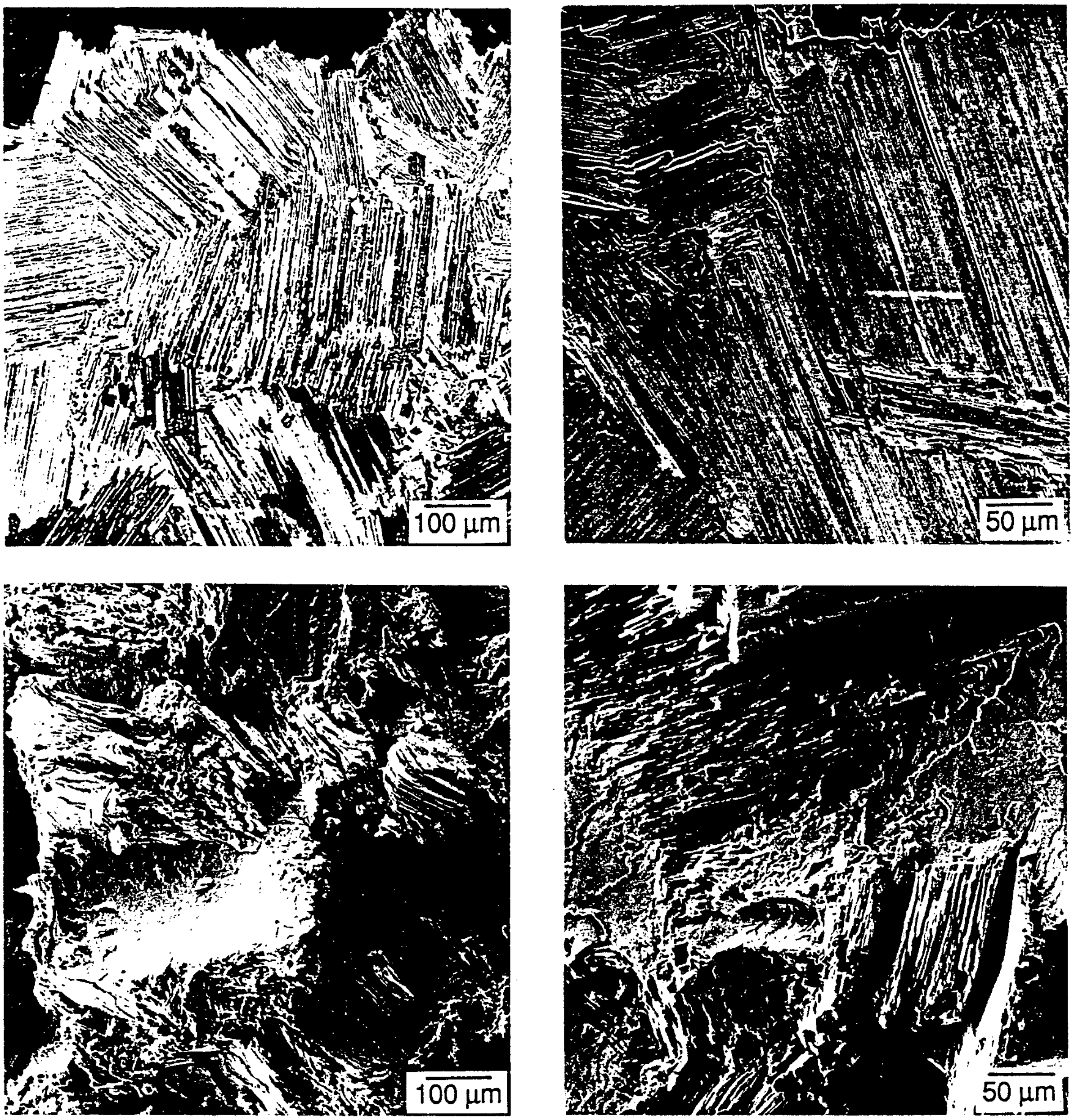


Figure 3 Temperature dependence of compressive yield strength of $(Ti_{0.51}Al_{0.49})_{99.5}C_{0.5}$ and $(Ti_{0.50}Al_{0.50})_{99.5}C_{0.5}$ aged at 1073 k for $3.6x10^4$ s (10 h), and $(Ti_{0.49}Al_{0.51})_{99.5}C_{0.5}$ aged at 1073 k for $3.6x10^3$ s (1 h). Data for binary and ternary TiAl are also included.

HCF of Alloy K5

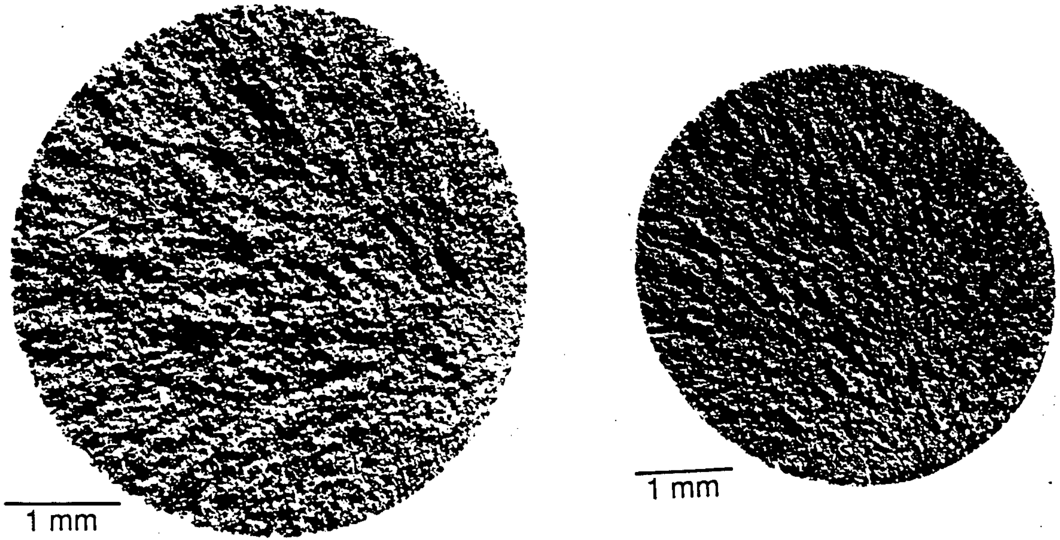




$\sigma_m = 430$ MPa ; $C_f = 2{,}310$

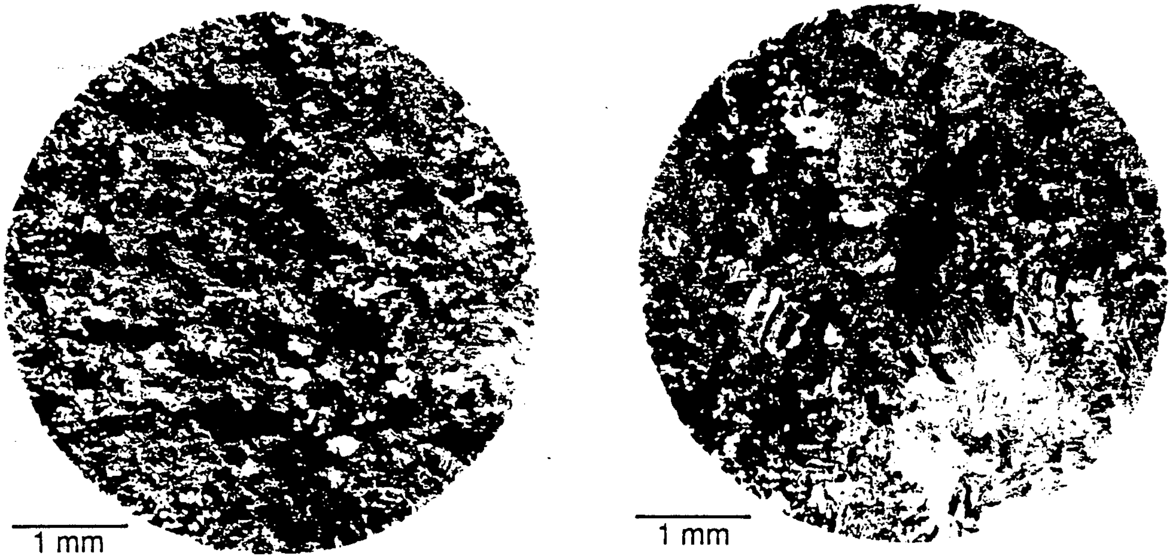
$\sigma_m = 330$ MPa ; $Cf = 7.2x\,10^6$

Fatigue Deformation and Fracture of FL Alloy K5 at 800°C and R=0.1 in Air (UTS = 500 MPa)



σ_m/UTS=430/505 MPa ; C_f=10,700

σ_m/UTS=280/505 MPa ; C_f =3.6x10^6



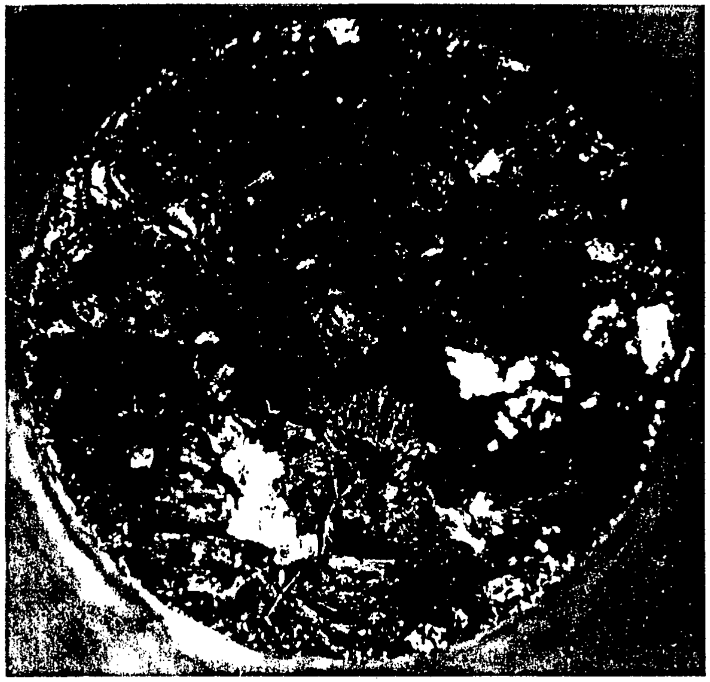
σ_m/UTS=430/500 MPa ; C_f =2,310

σ_m/UTS=330/500 MPa ; C_f =7.2x10^6

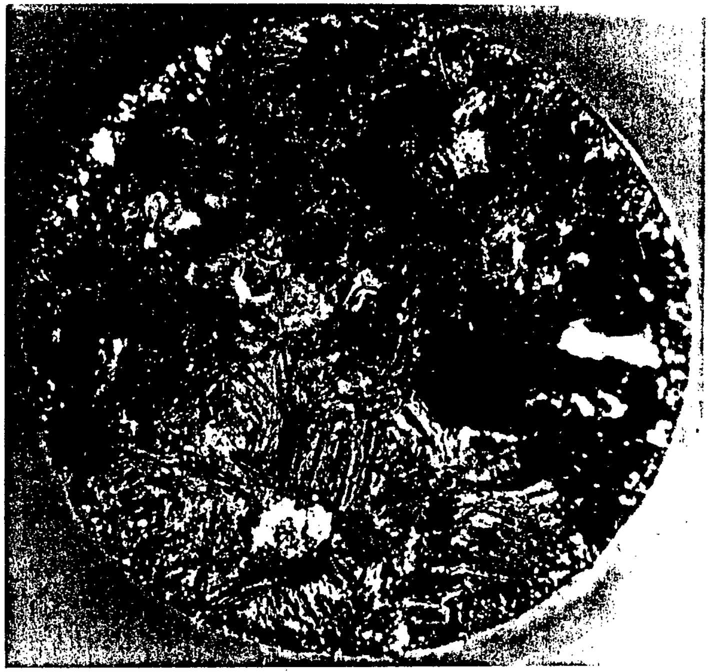
Fatigue Fracture of Alloy K5 in Various Conditions at 800°C and R = 0.1 in Air

Load-Controlled Fatigue Failure of FL Alloy K5

(R=0.1 / 870°C / Air)



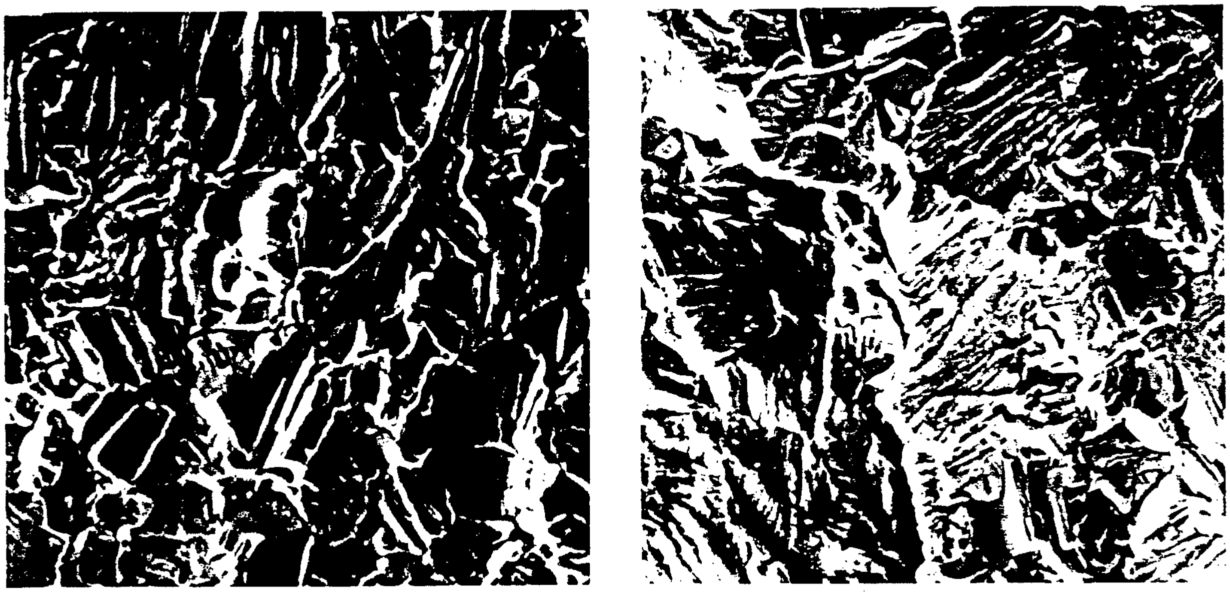
3



$\sigma_{max}=350$ MPa / $N_f=9.6\times10^5$

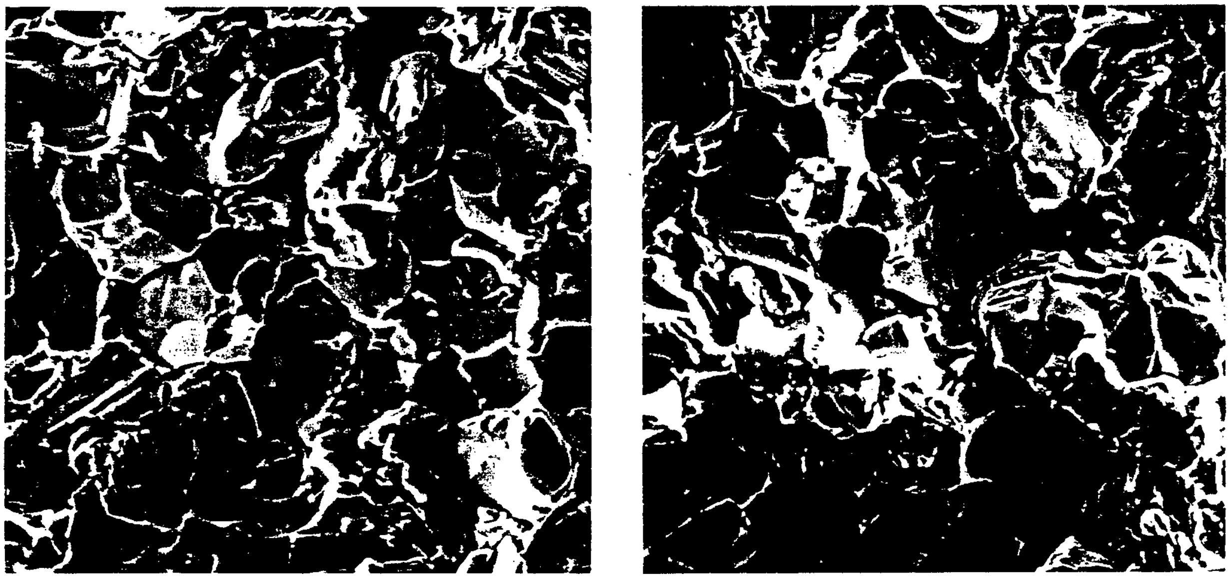
$\sigma_{max}=250$ MPa / $N_f=1.63\times10^7$

<——>



Near CI Site

Near CI



Away from CI

Away from CI

$\sigma_m = 625$ MPa / $c_f = 1629$

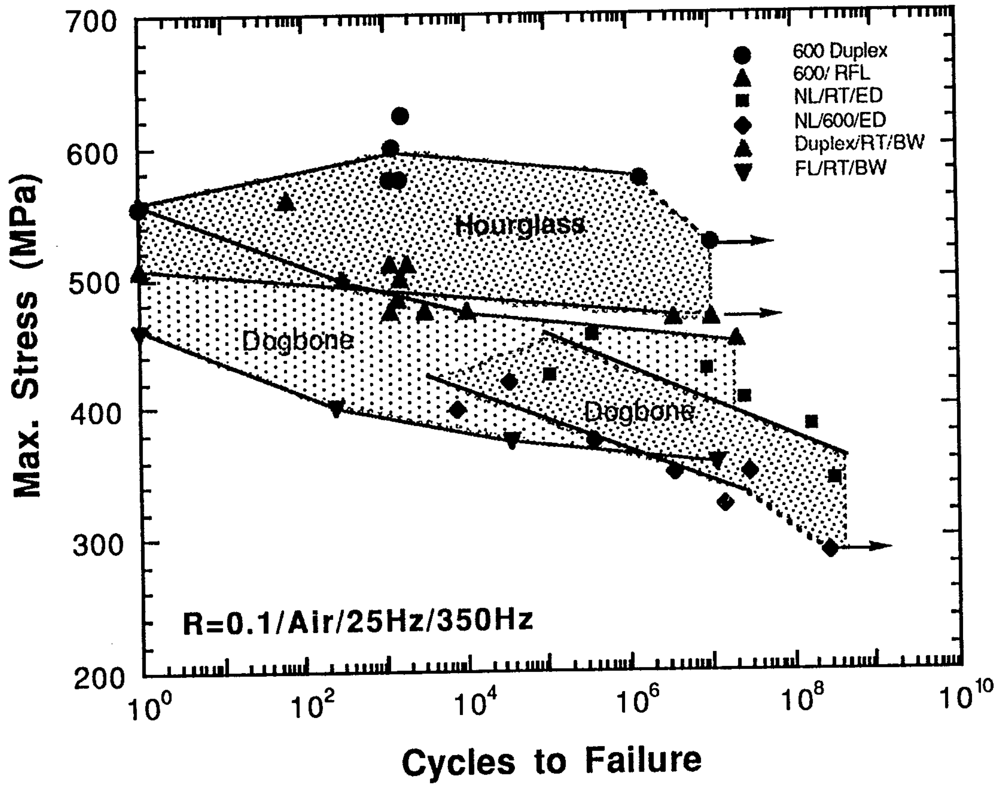
$\sigma_m = 575$ MPa / $c_f = 1.36 \times 10^6$

Fatigue Fracture of a Duplex Alloy K5 at 600°C in Air

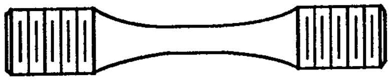
(R = 0.1; UTS = 583 MPa)

√

Specimen Geometry Effect at <BDTT



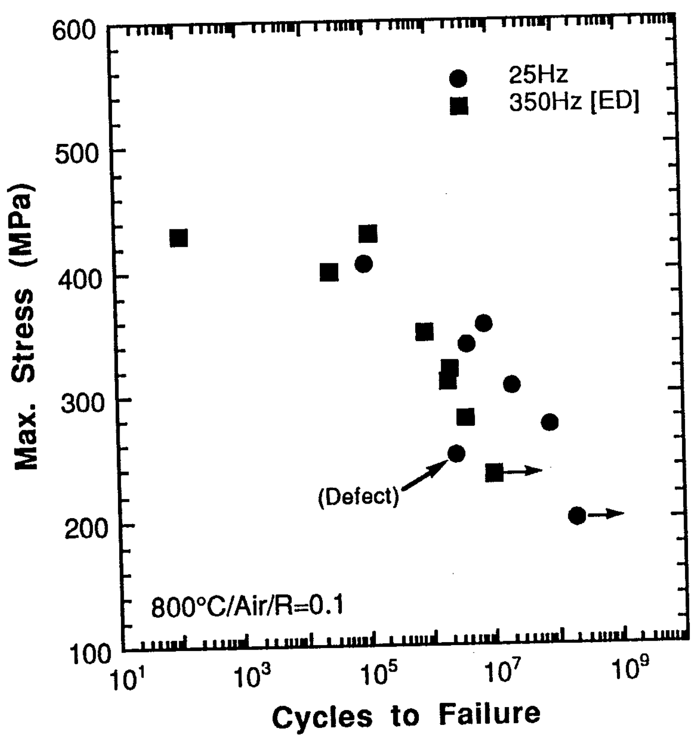
(Hourglass)



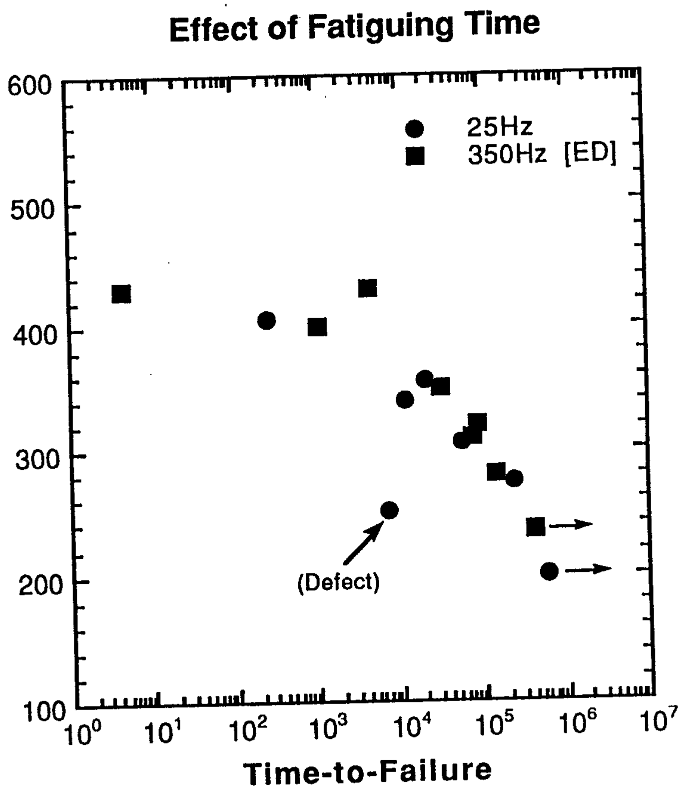
(Dogbone)

HCF of Alloy K5 in Duplex at 800°C

(Effect of Frequency and Fatiguing Time)



Frequency Effect



Effect of Fatiguing Time

Effect of Frequency on HCF

(at 800°C)

High Stress Regime ($\sigma_{max} > \sigma_y$)

Frequency-dependent (need investigation)

High-rate deformation

Low Stress Regime ($\sigma_{max} > \sigma_y$)

Frequency-independent

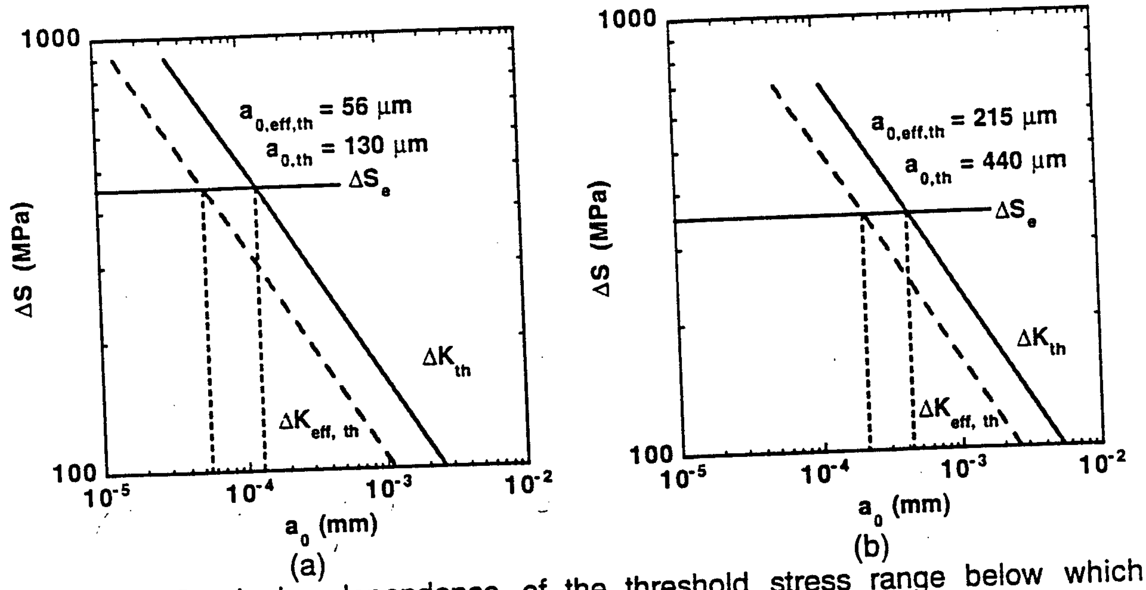
Time-dependent

Creep deformation important

Creep Fatigue

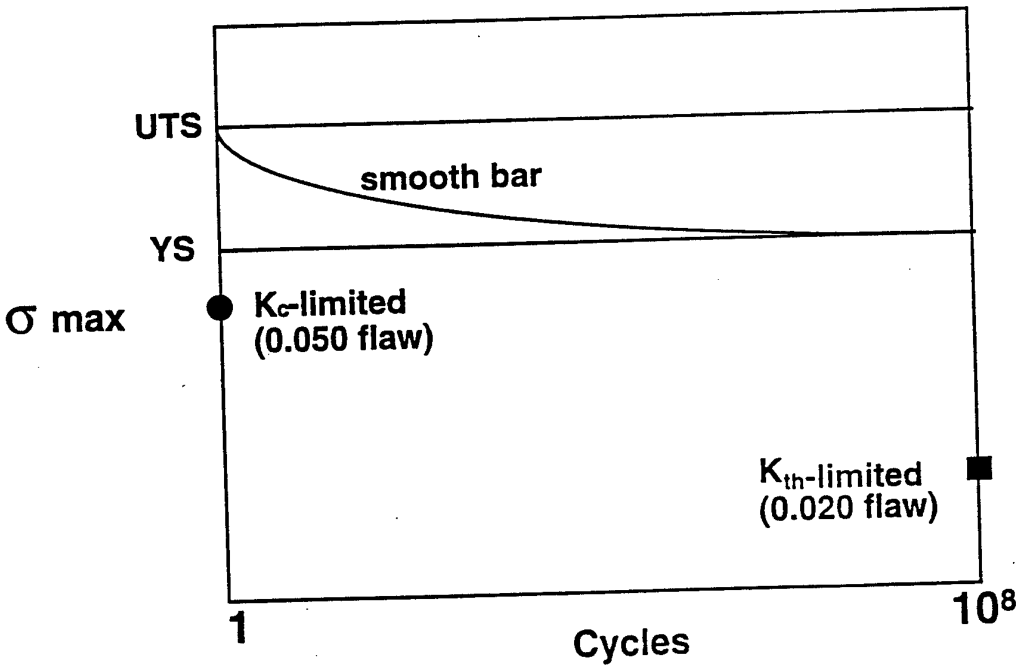
Suggested at Low Stresses

Mean Stress: $\sigma_{avg} = (\sigma_{max} + \sigma_{min})/2$

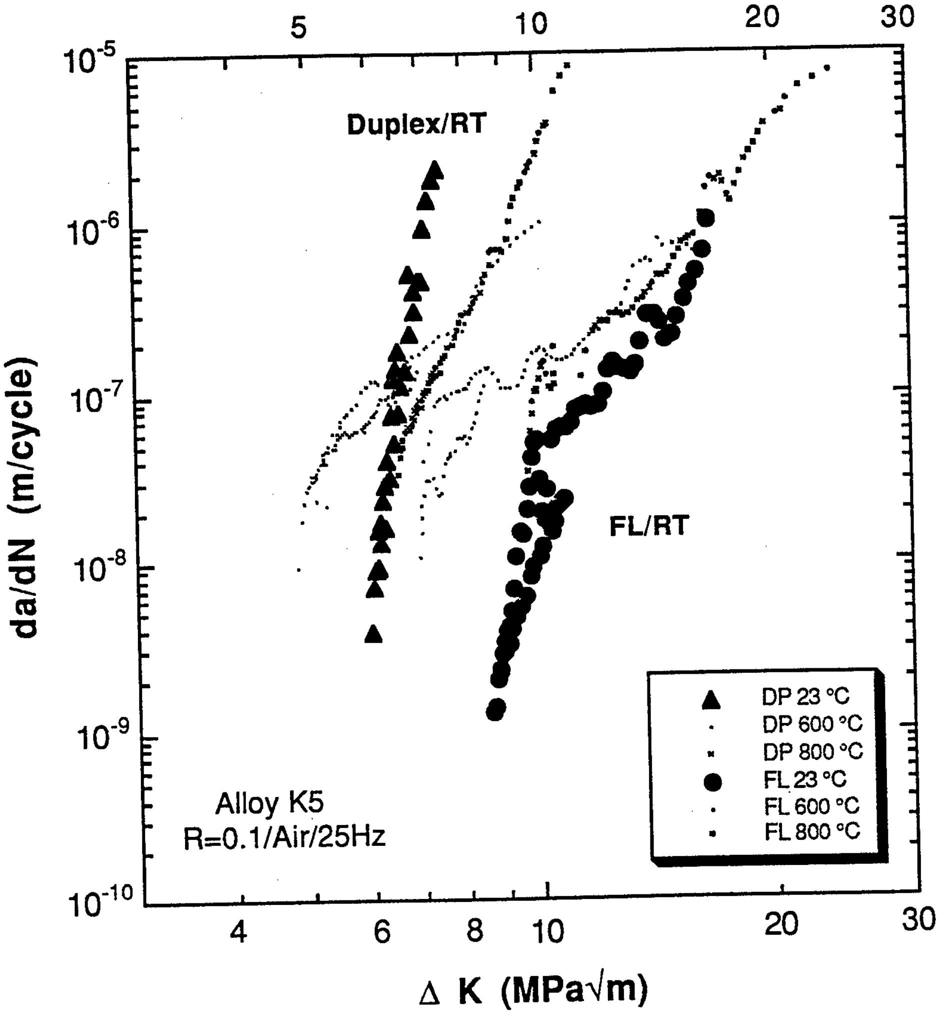


(a) (b)

Figure 10. Crack-size dependence of the threshold stress range below which specimen failure will not occur in the alloy K5 in the (a) duplex and (b) lamellar conditions.



FCG of Alloy K5



Fatigue Deformation and Failure

- Fatigue behavior in gamma alloys consists of:

  Deformation period (remarkably long),
  Crack initiation and growth (to a critical size)
  Rapid crack propagation (to failure)

- Below BDTT, flat SN curves are observed. The fatigue strength is controlled by tensile properties.

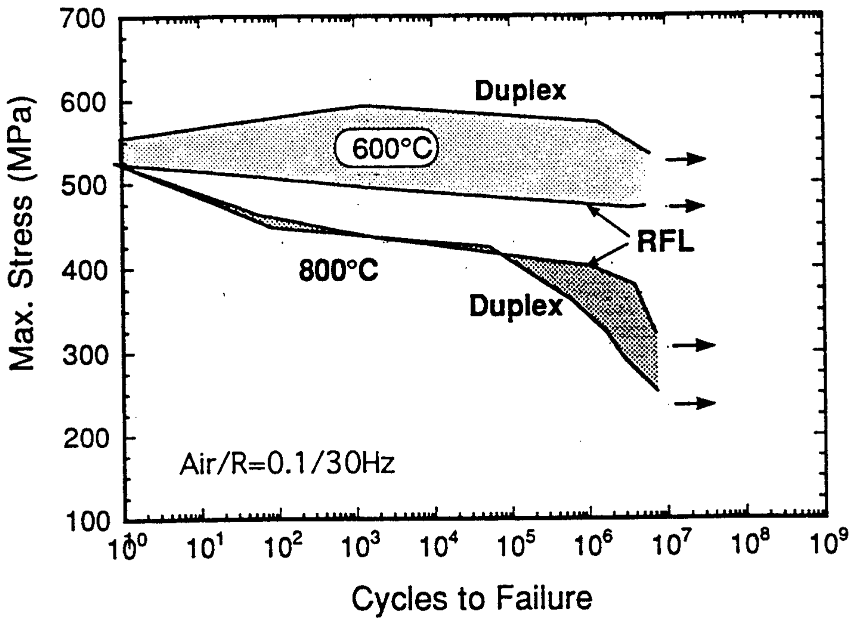
  Duplex microstructure (preferred)

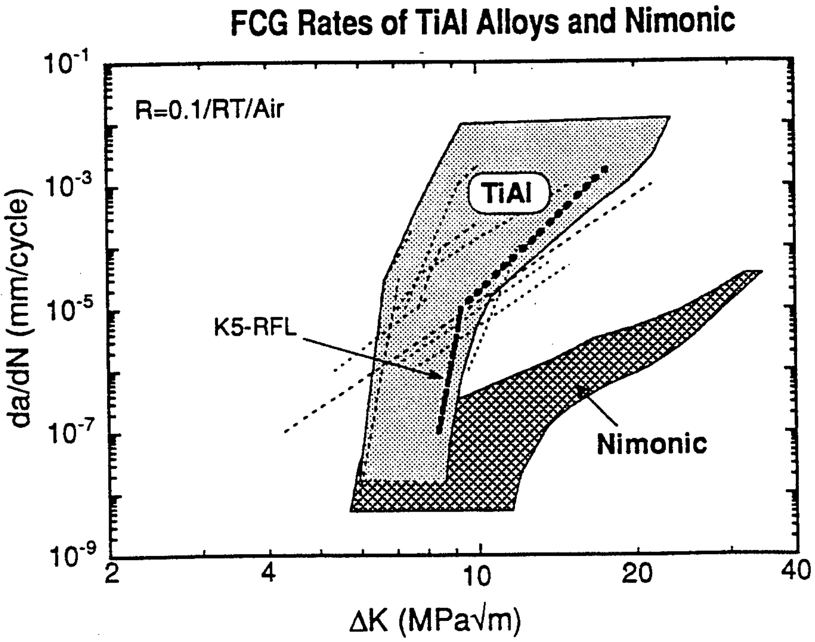
  Above BDTT, fatigue life depends on tensile deformation behavior under high applied stress (>YS). Under low stresses (<YS), fatigue strength appears related to creep resistance.

  Fully-lamellar microstructure (preferred)

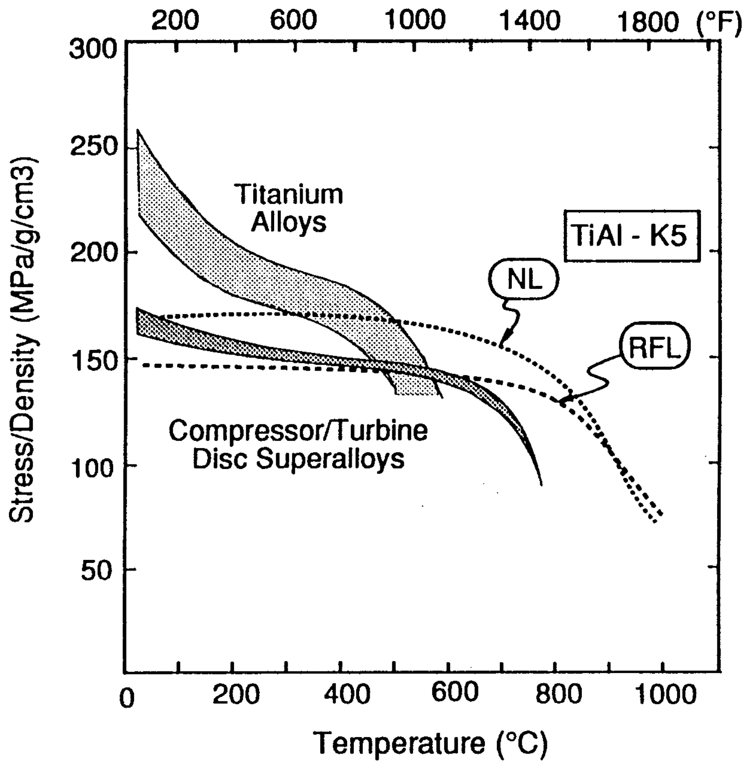
- Fracture takes place transgranularly below BDTT and boundary fracture becomes predominant at higher temperatures.

Fatigue Behavior

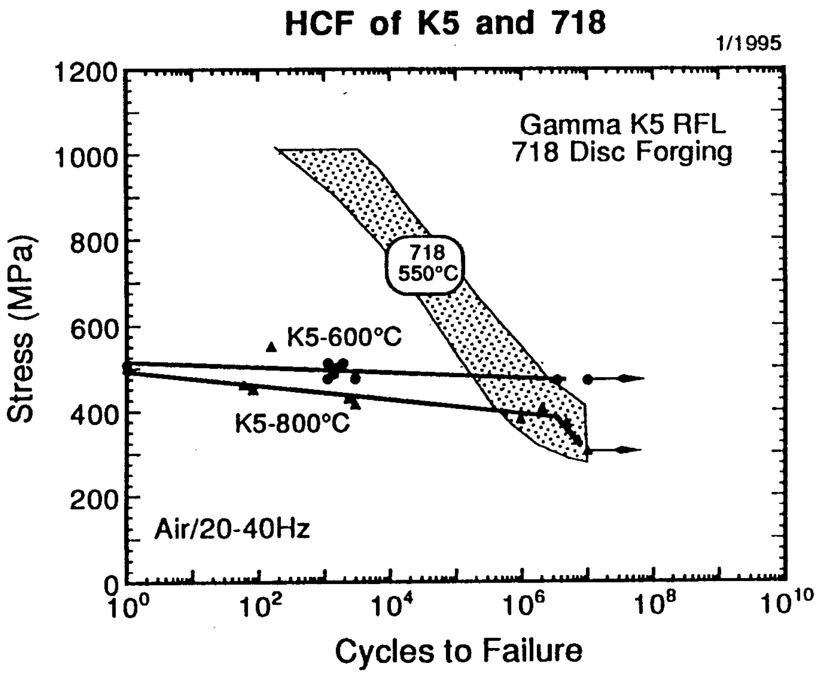




Alloy K5 vs. Disk Superalloys



HCF of K5 and 718



Alloy Design

Alloy Selection

Microstructural Optimization

- Considerations
    - Mechanical Data and Behavior
    - Damage-Tolerance & Life-Prediction
    - Microstructural Controllability
- Derive Optimum Microstructures
- Devise Process & Treatment Schemes

Chemistry Modification

- Promote Desired Microstructures
- Improve Mechanical Behavior
- Enhance Environmental Resistance

Design of Microstructures

- Property Requirements
- Dimensional Considerations
- Component-Specific Microstructures
- Scaled-up Process Development

Designed Microstructures

Refined FL (RFL)
- Alloy Modification
- Innovative Heat Treatments

TMT Lamellar (TMTL)
- Boron Addition
- Heat Treatments

TMP Lamellar (TMPL)
- Extrusion
- Forging
- Aging

****Aligned Lamellar****
- Directionally Solidified (DS)
- Directionally Worked : DELM; DFLM

Other Types: Under Exploration

Chemistry Modification

(Standard: NG, DP, NL and FL)

Optimized Microstructural Features

(Wrought Alloys)

Lamellar Structure Base

Grain Size: 50-400 μm

GB Morphology

- Slip Transmission
- Bond Strength

Lamellar Spacing < 2μm

- Strength; Strain-to-Failure
- Toughness; Creep

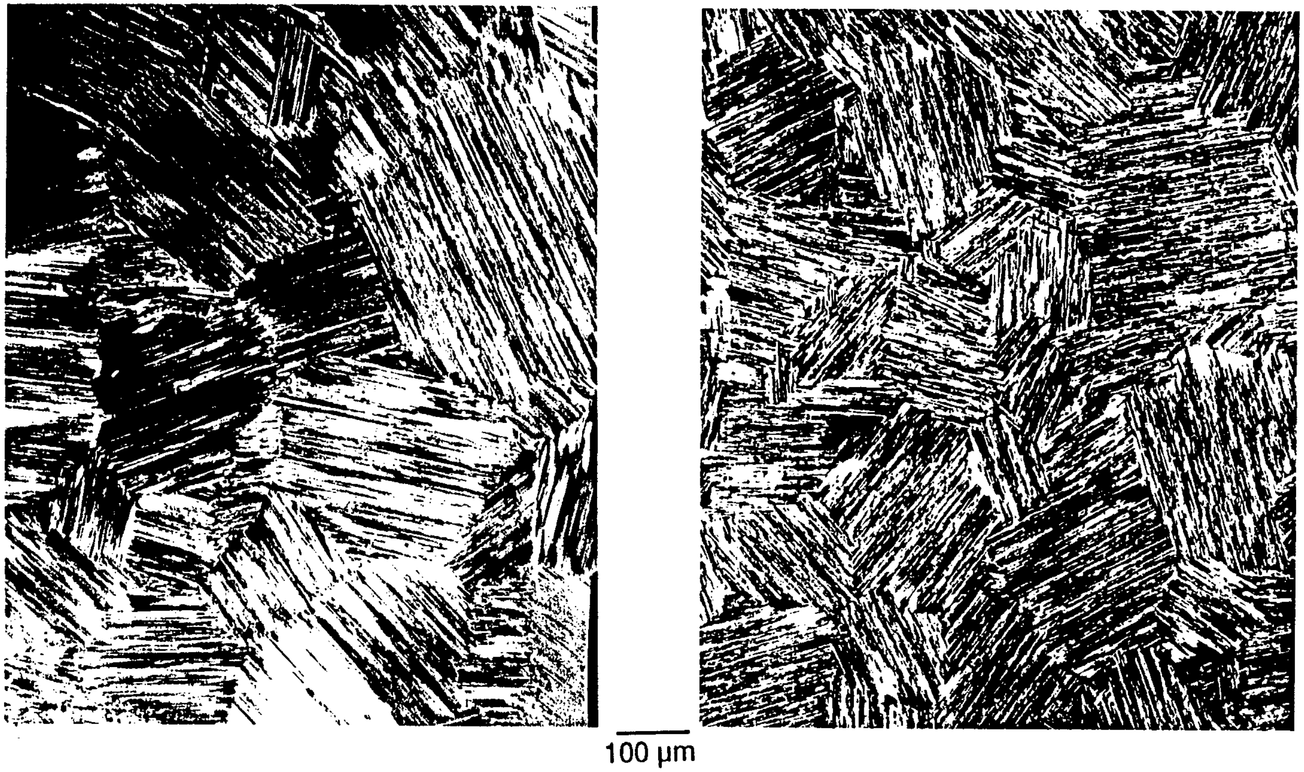
α_2 **Volume Fraction:** 5-30 %

- Strength; Ductility; Toughness
- Anisotropy

Texture Consideration

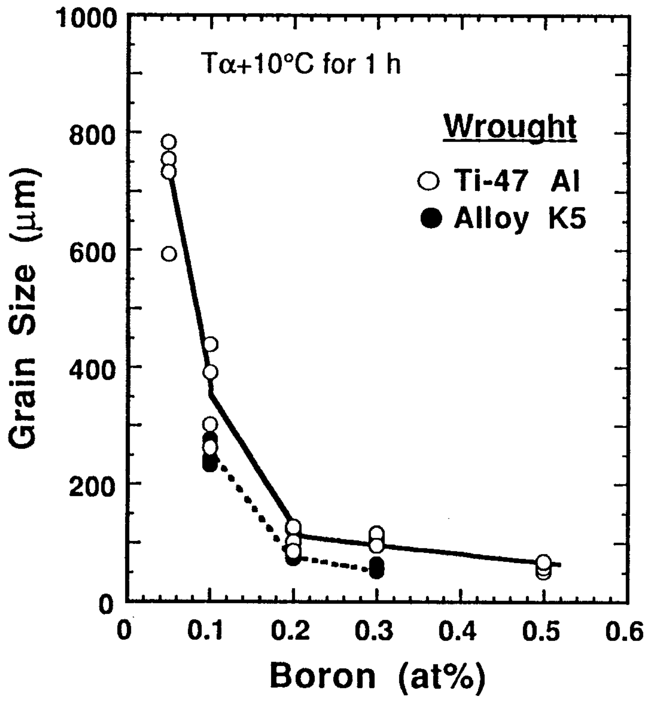
Duplex Microstructures (?)

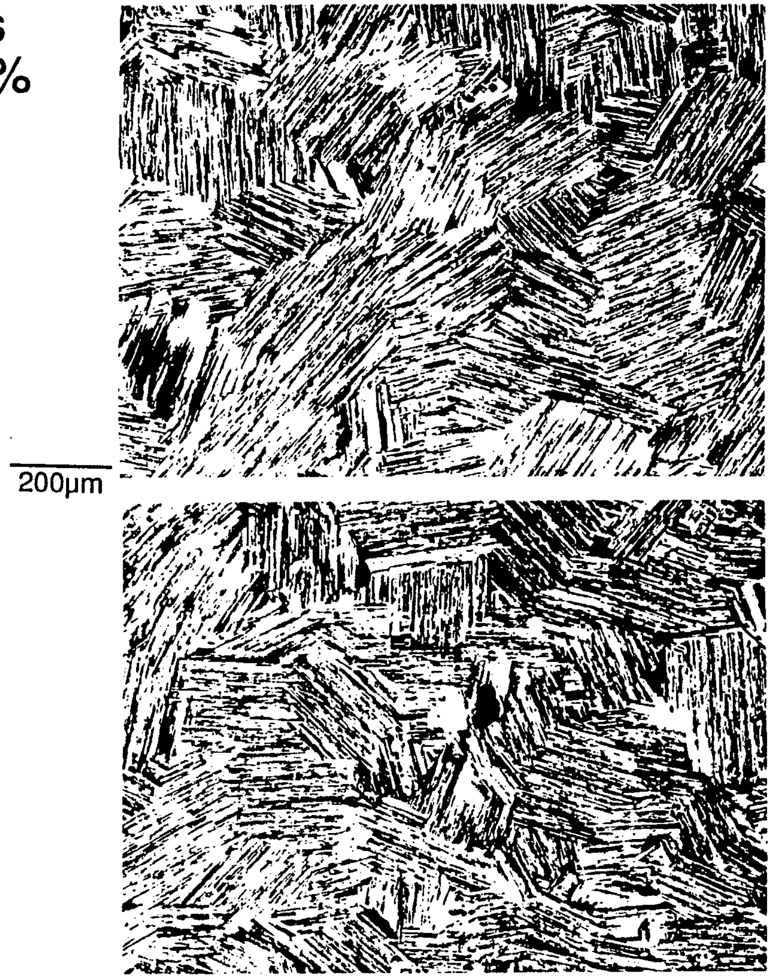
RFL vs. TMTL Microstructures

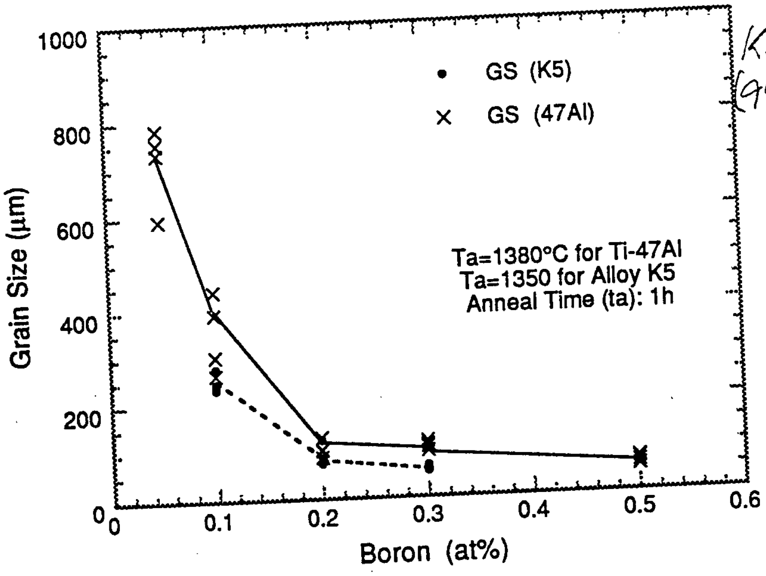


TMT Lamellar Microstructures

Wrought Processed Alloys
Boron Additions: 0.05-0.5 %
HW plus Alpha Treatment
Advantages/Disadvantages

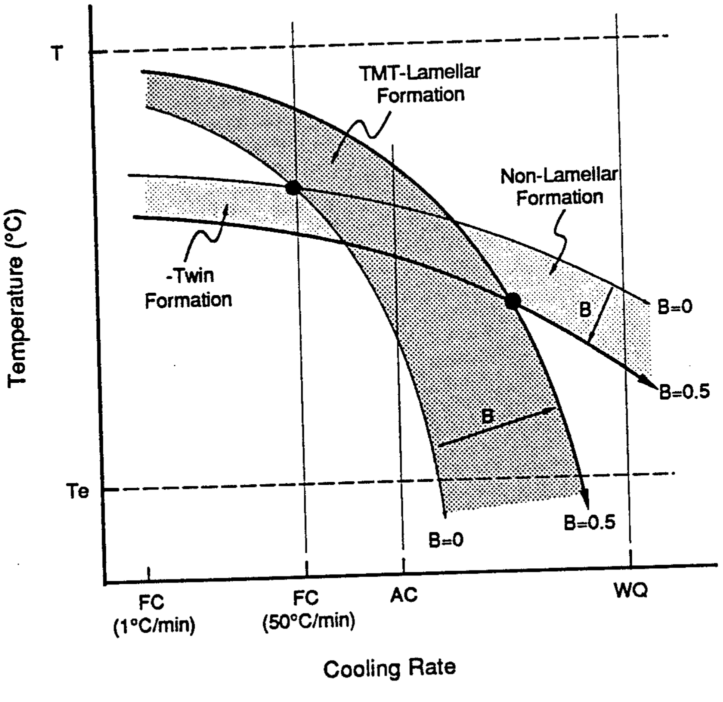




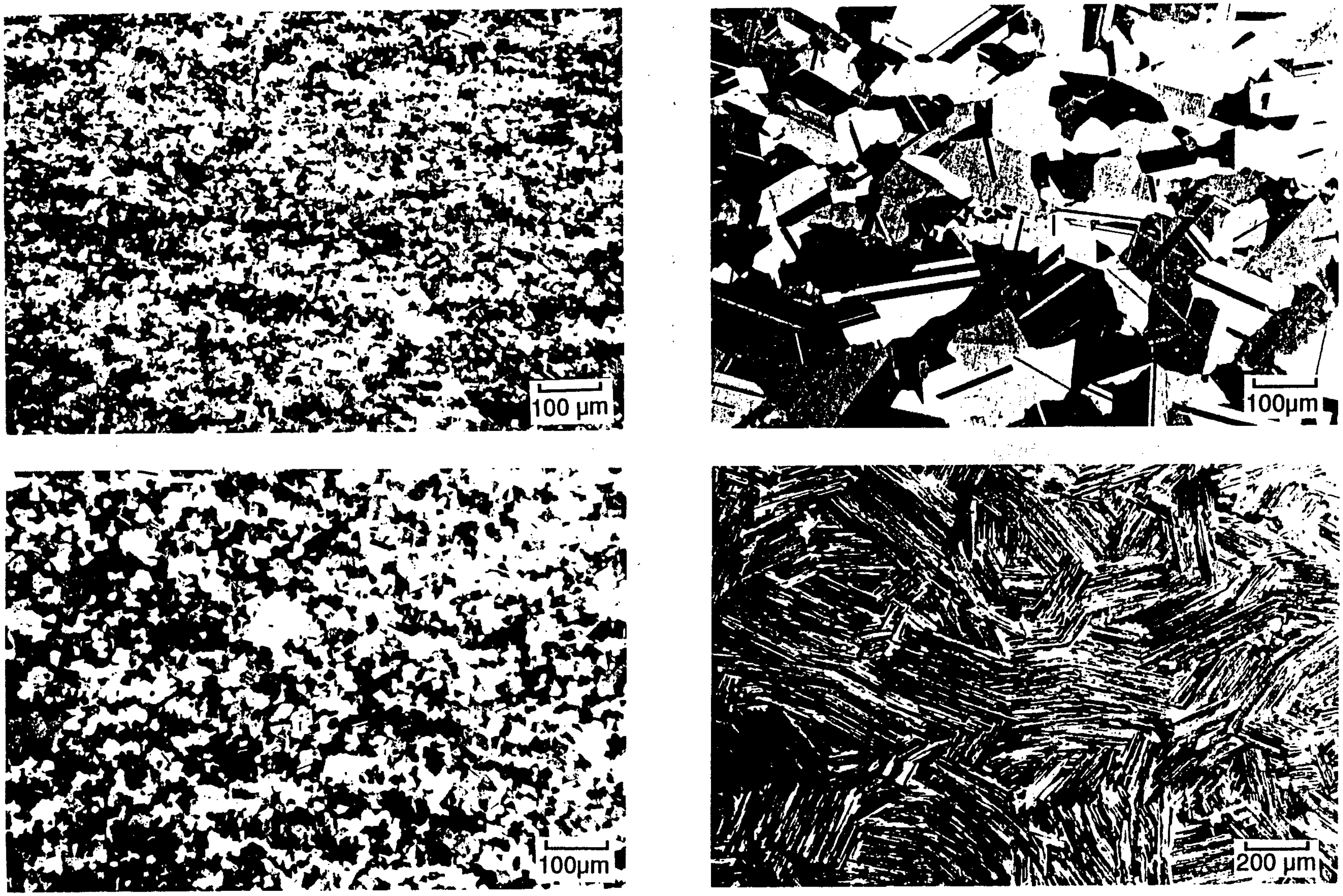


Kim (94/95)

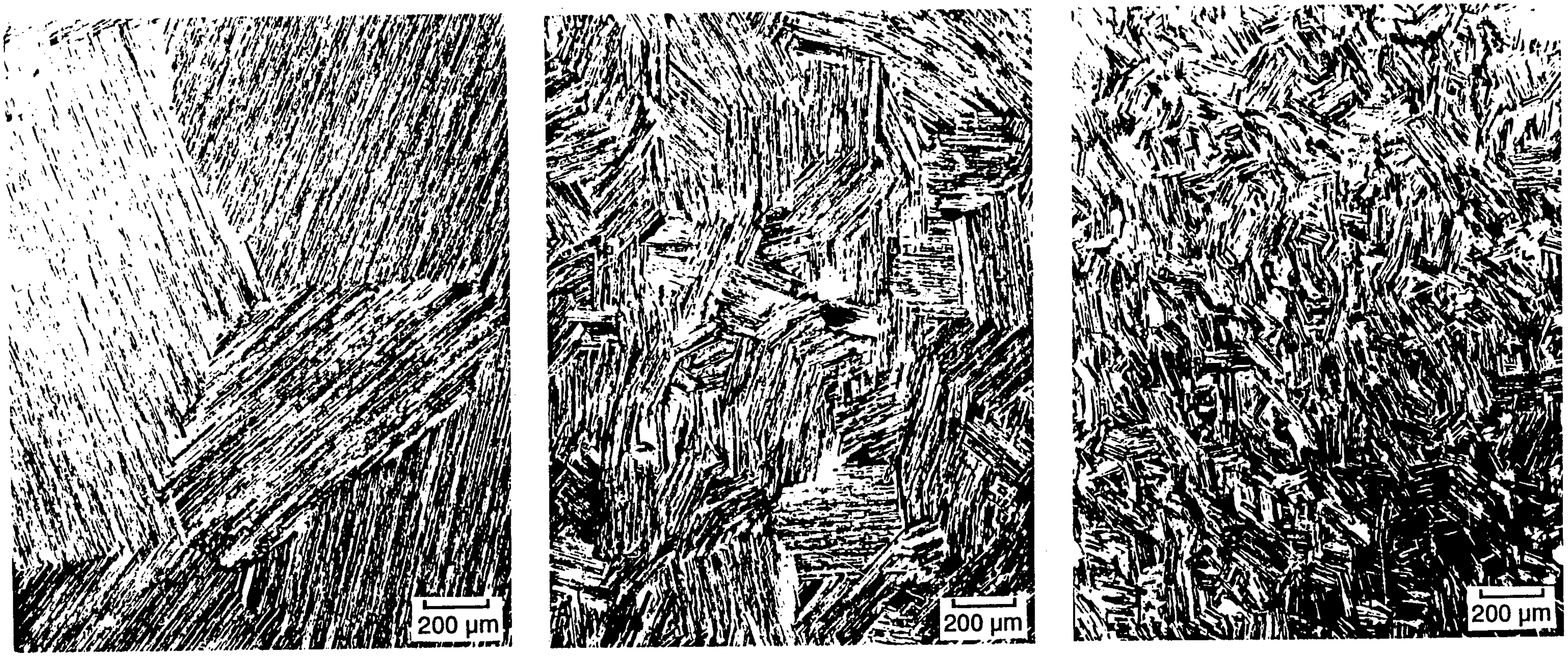
GS vs Boron Content in Gamma Alloys



Cooling-Rate and Boron -Content on Alpha Decomposition

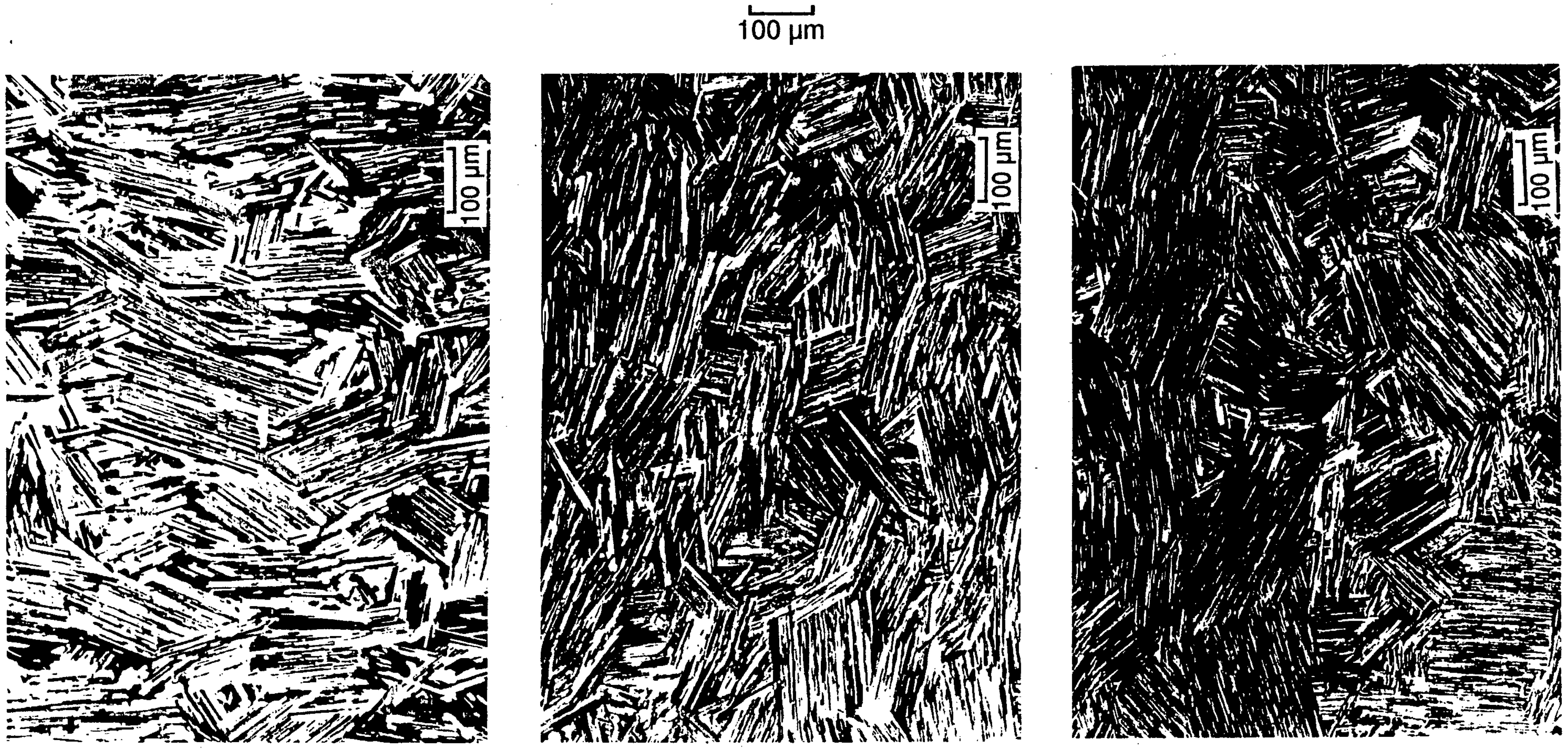


Alloy K1: **As-Forged; Near Gamma; Duplex; and TMTL microstructures**



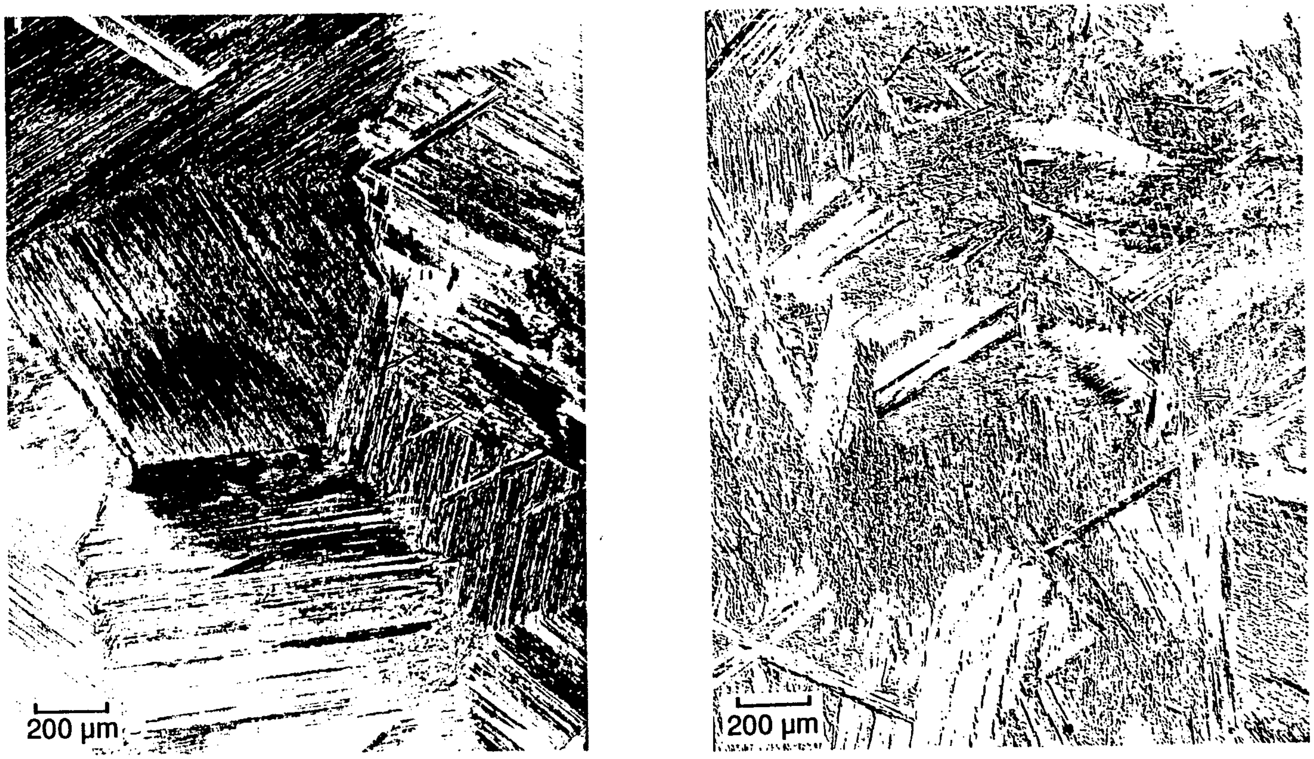
Ti-47Al-0.05B Ti-47Al-0.10B Ti-47Al-0.24B

Forged and **TMT-Lamellar Treated** (1370°C/1h/FC/1000°C/AC)



FC/900°C/AC FC/1300°C/AC AC

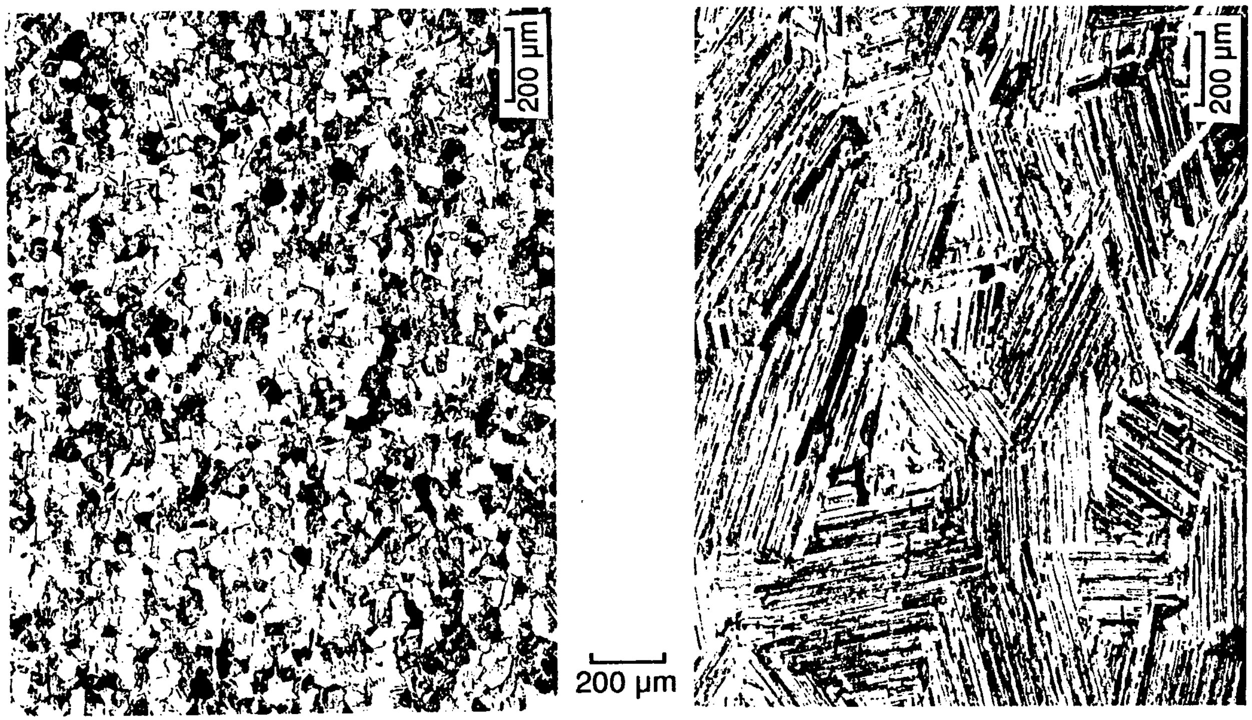
Alloy K7: **Alpha-Treated** (1390°C/30min) **and Cooled Differently**



FC/1200°C/AC

AC

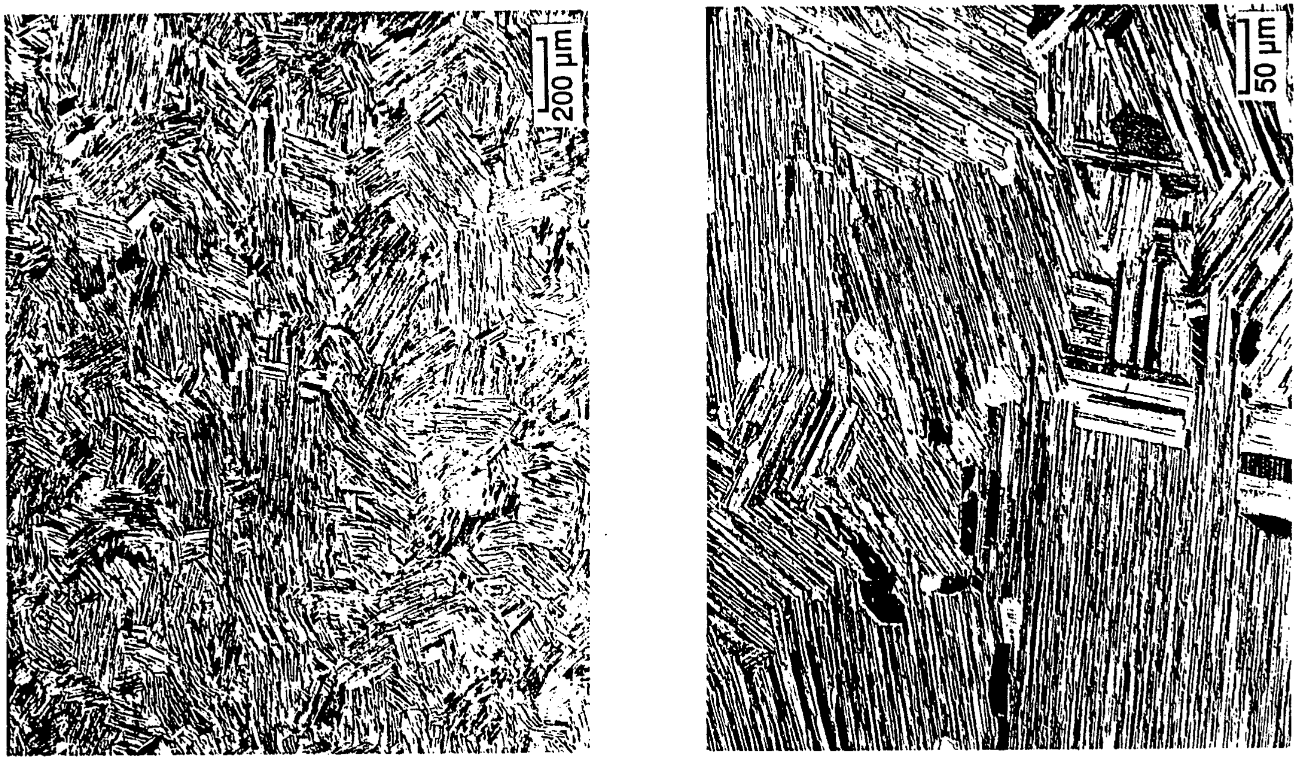
Alloy K6: **Alpha-Treated** (1370°C/1h) **and Cooled Differently**



Duplex

TMTL

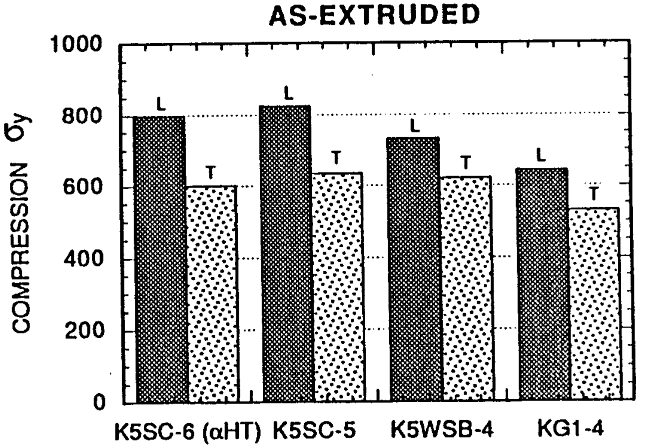
Alloy K2 (Ti-46.8Al-2Cr-4.0Nb-0.3B): **Boride Distribution**



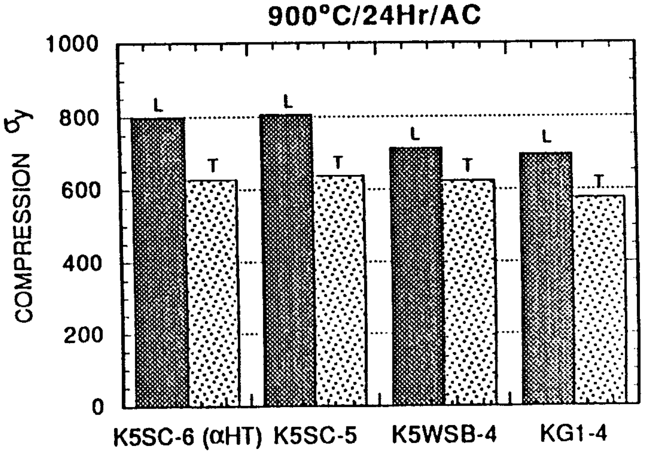
Alloy K7: **TMT-Treated** (1390°C/1.5h/AC) **and Annealed** (1300°C/24h/AC)

TMP Lamellar Microstructures

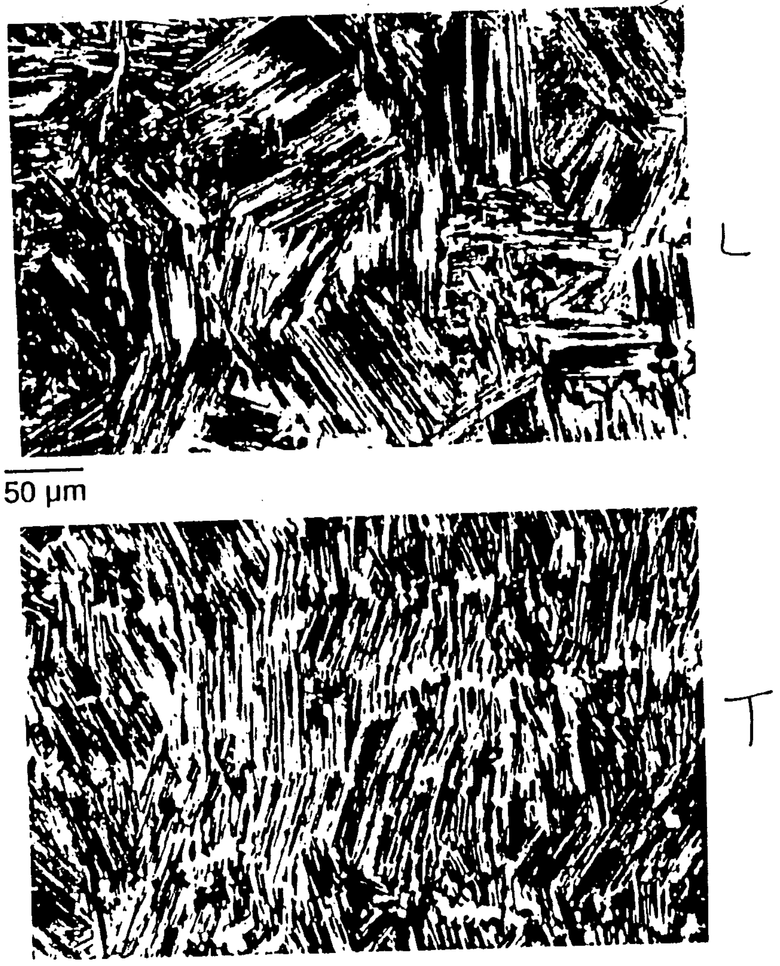
Kim (95)

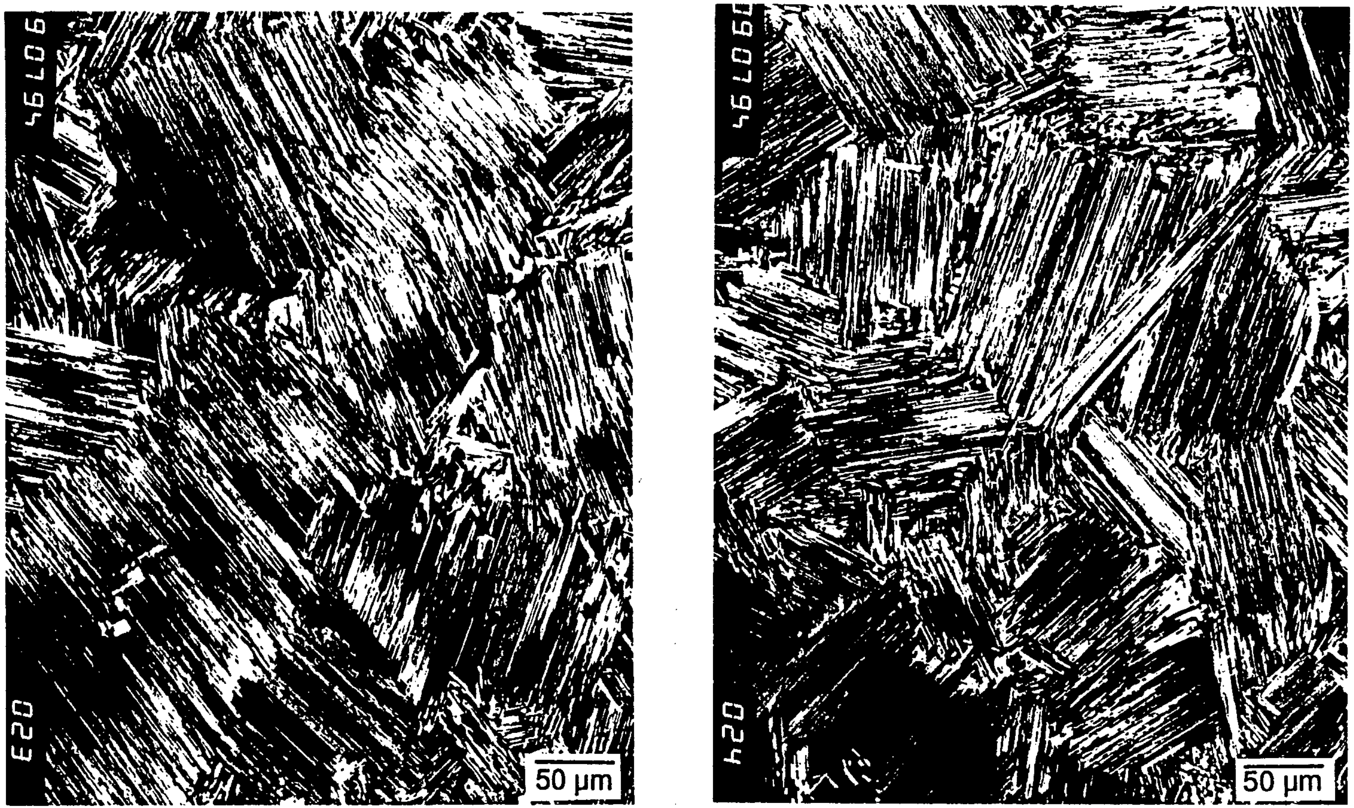


AS-EXTRUDED

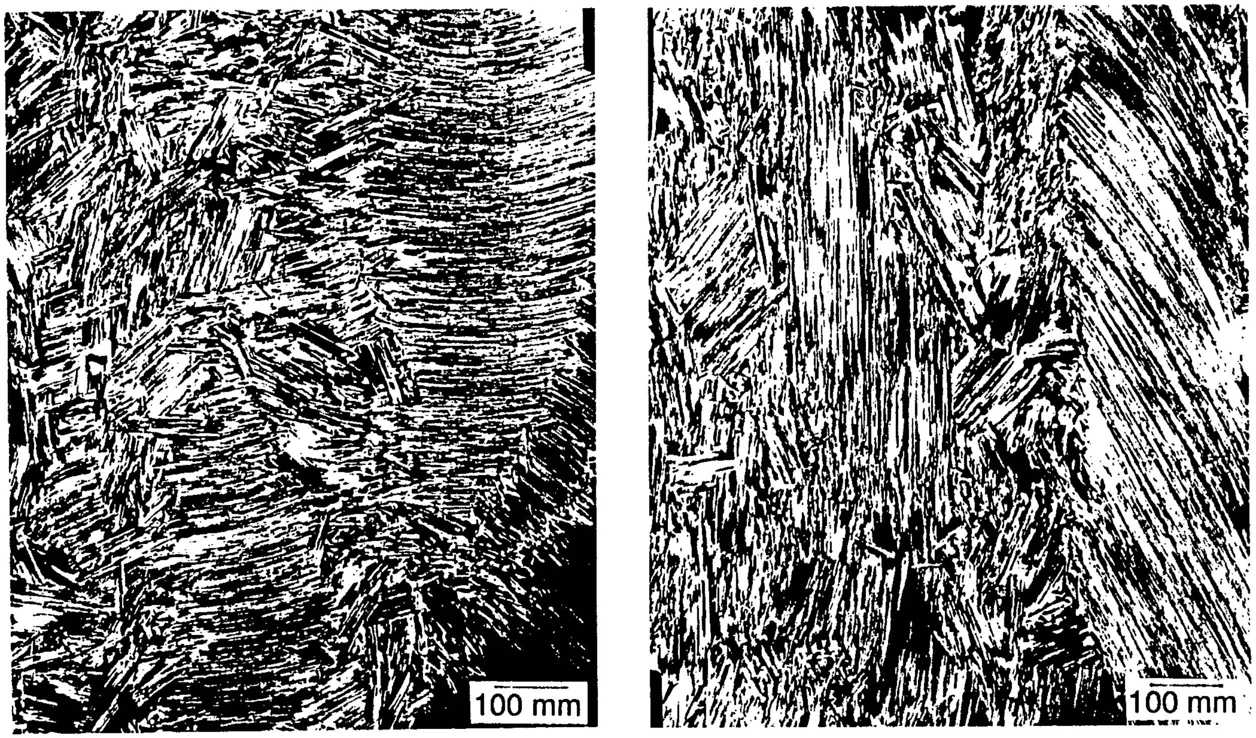


900°C/24Hr/AC





K5SC Alloy TMPL Extrusion LT-Section

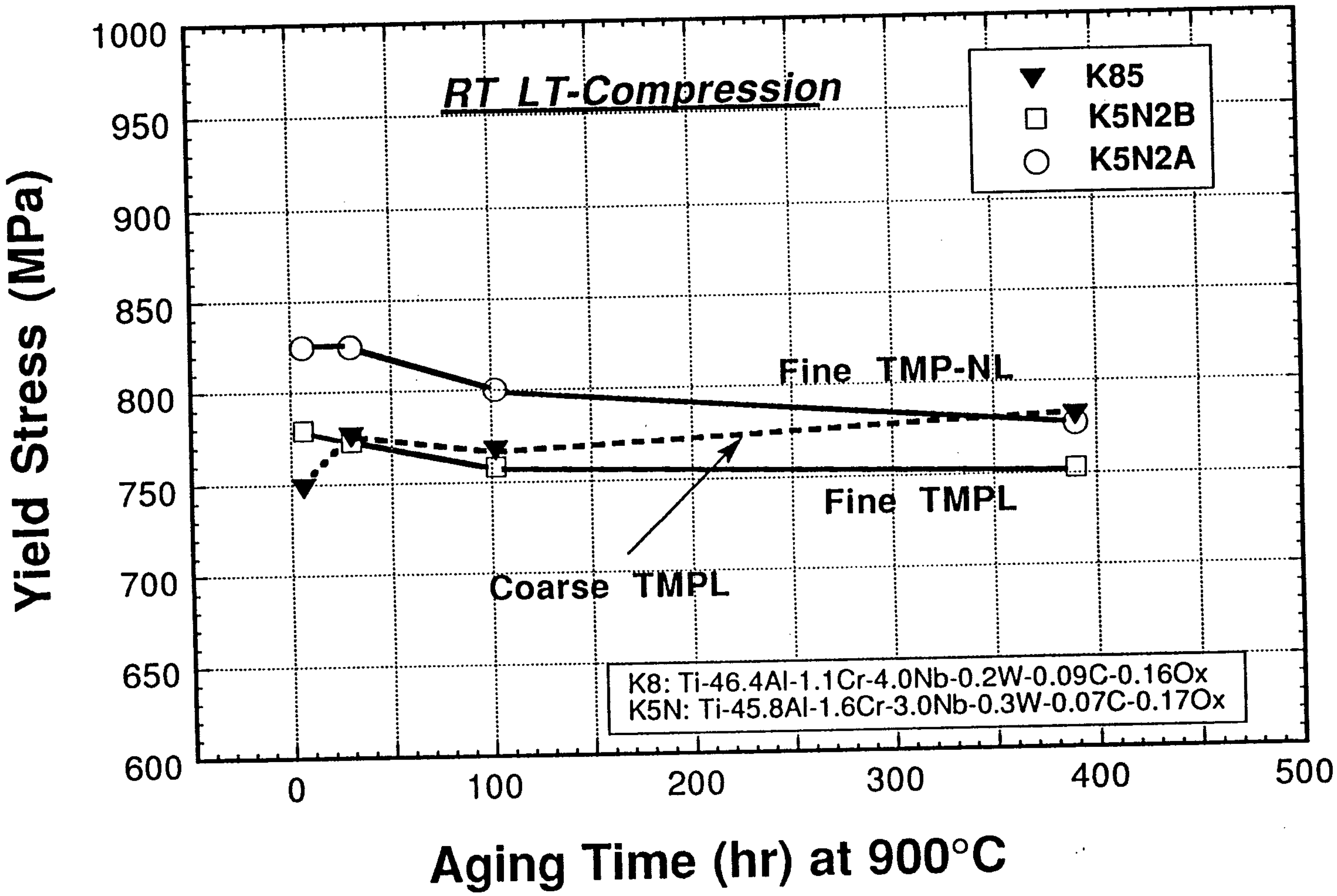


Transverse

Longitudinal

A TMP Microstructure in a 4822 Extrusion

Thermal Stability of TMP Lamellar Extrusions



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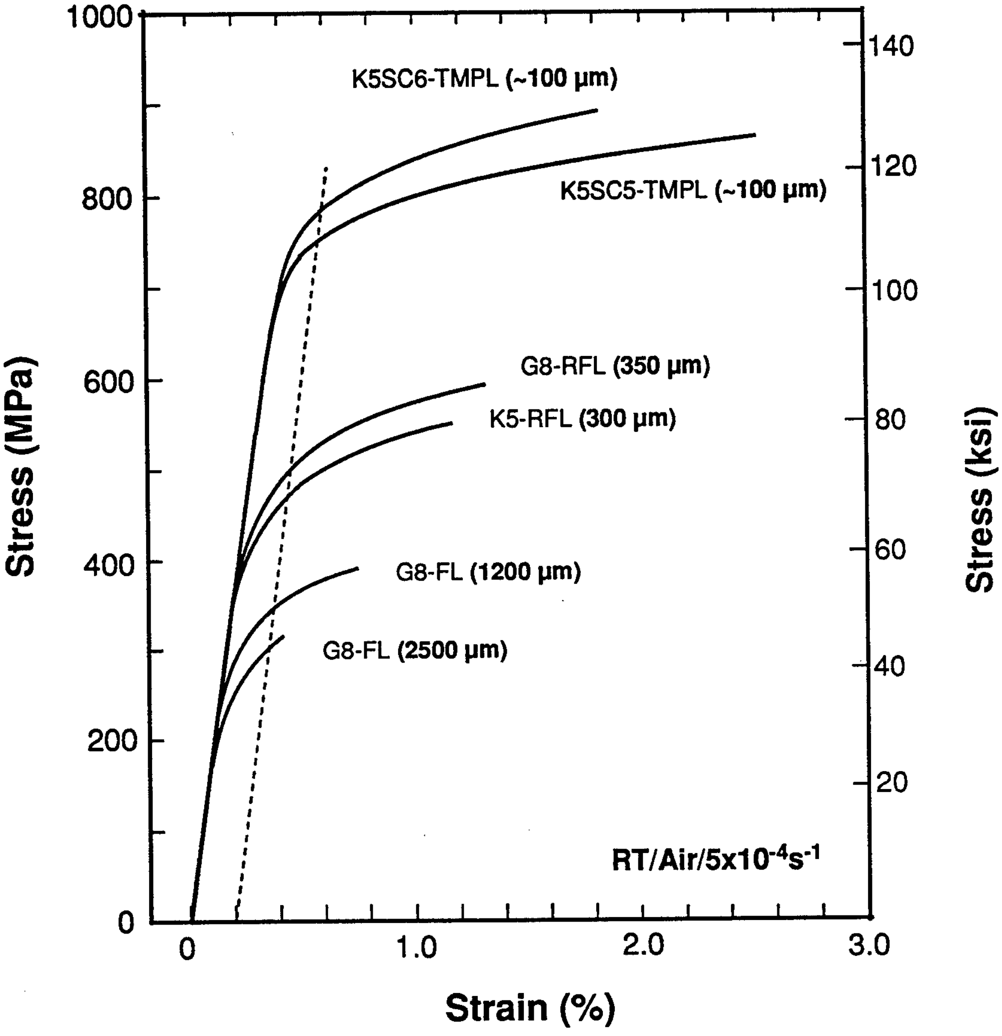
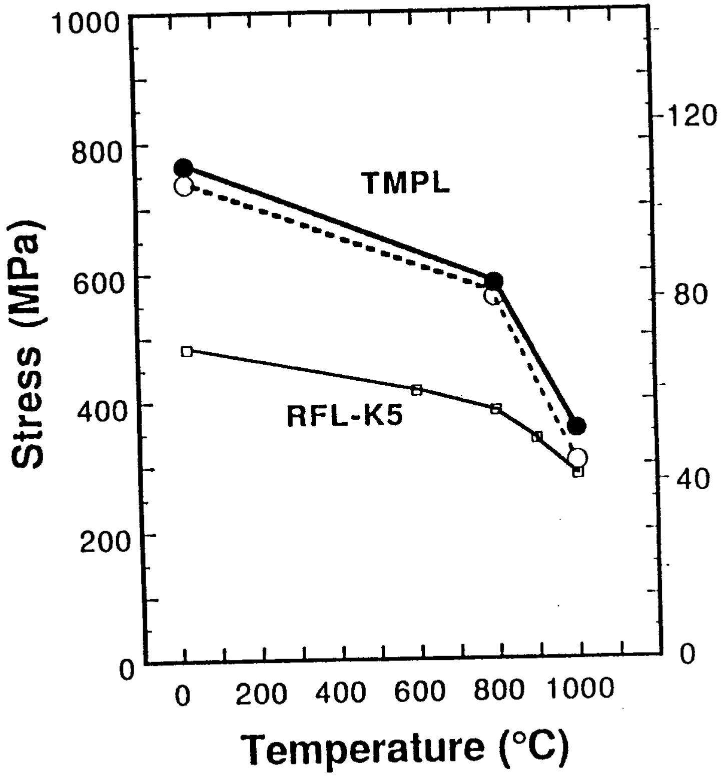
Flow Curves of Lamellar Alloys



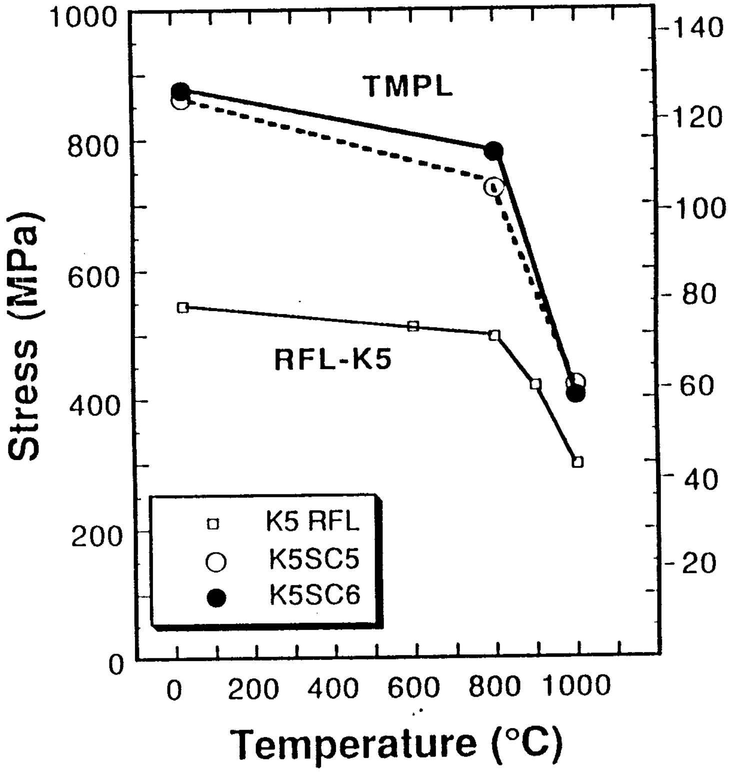
Strengths of RFL/TMPL Gamma Alloys

YS

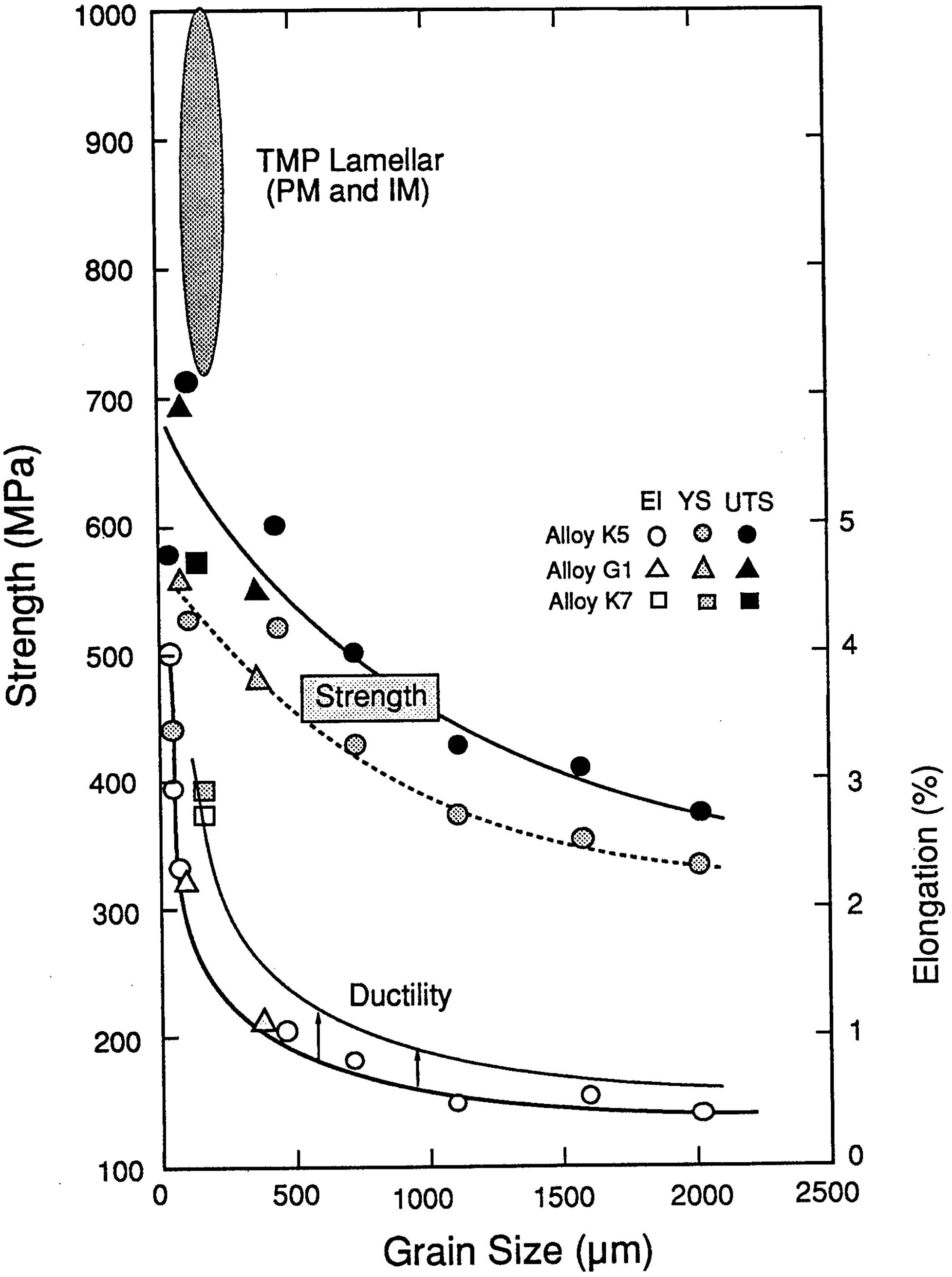


Kim (95)

UTS

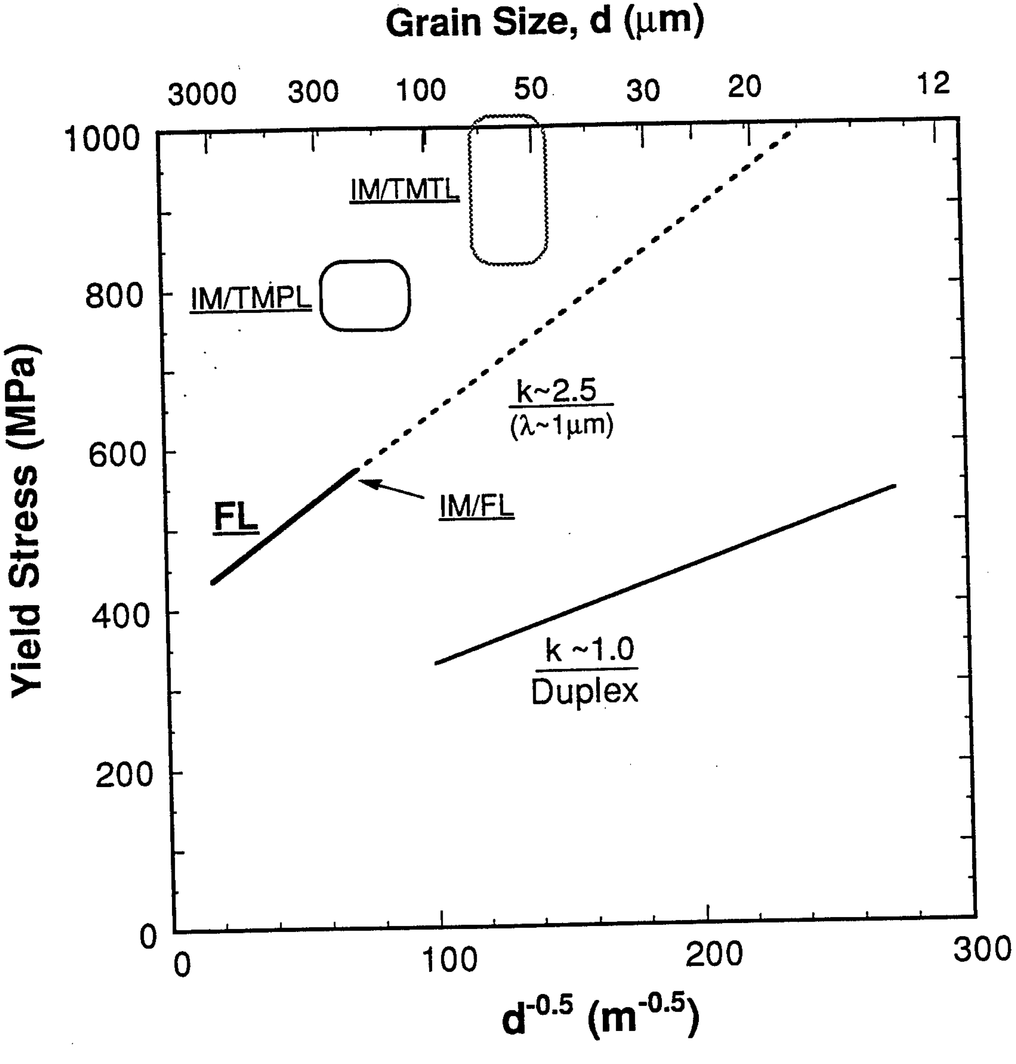


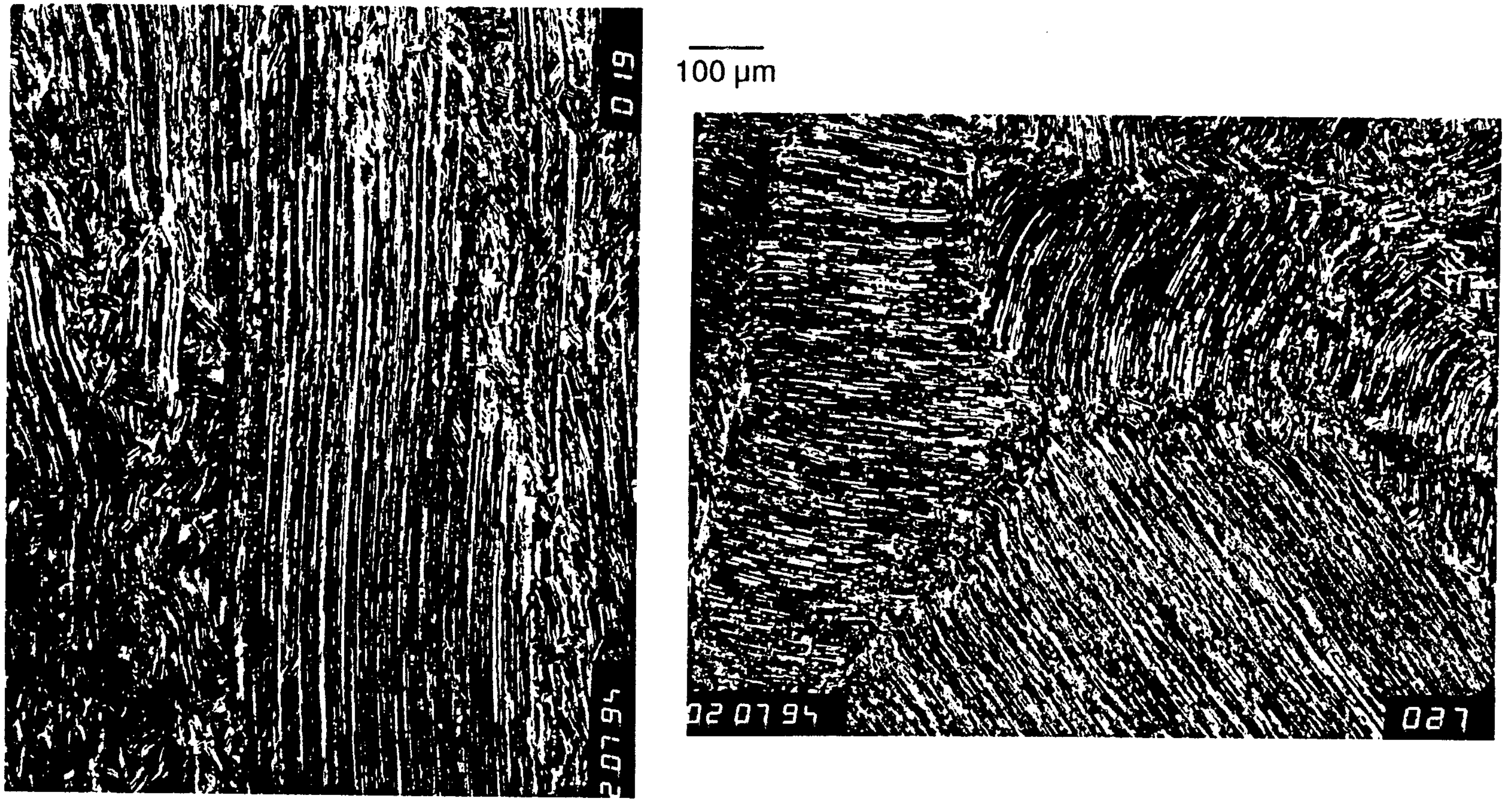
√



MIcrostructure on RT Tensile Properties

GS/LS/YS Relations in TiAl FL Alloys





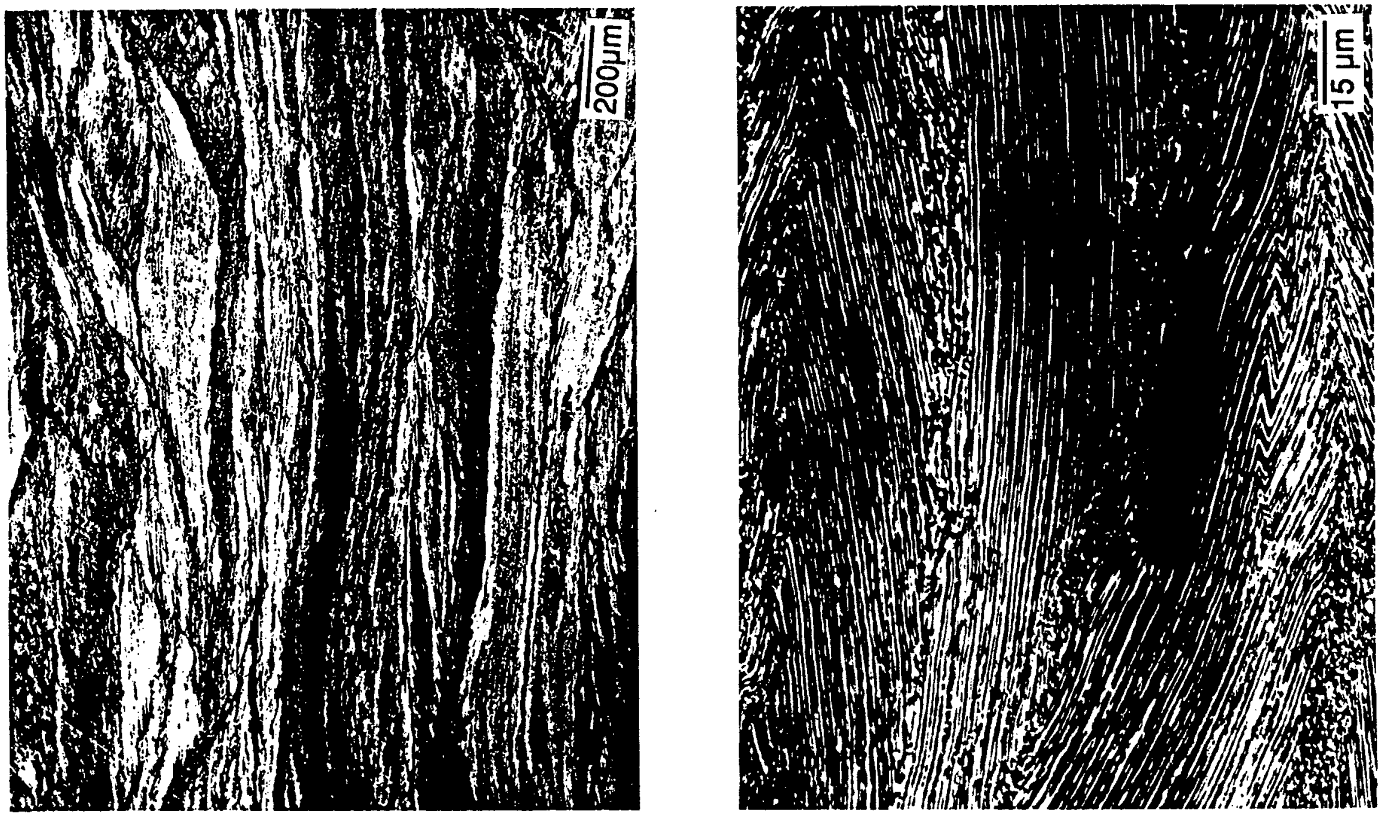
Longitudinal (L)

Long-Transverse (LT)

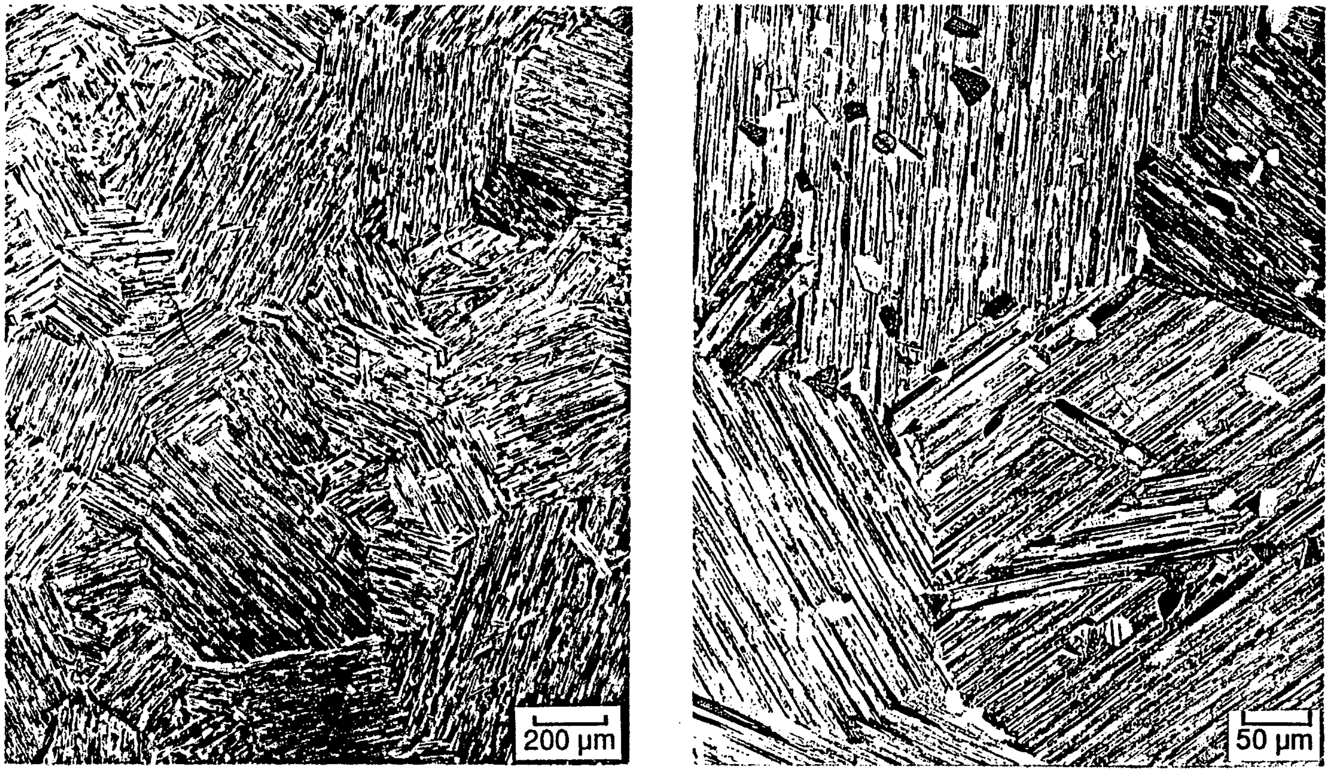
Alloy K8 TMP-Lamellar Extrusion

60 18 6

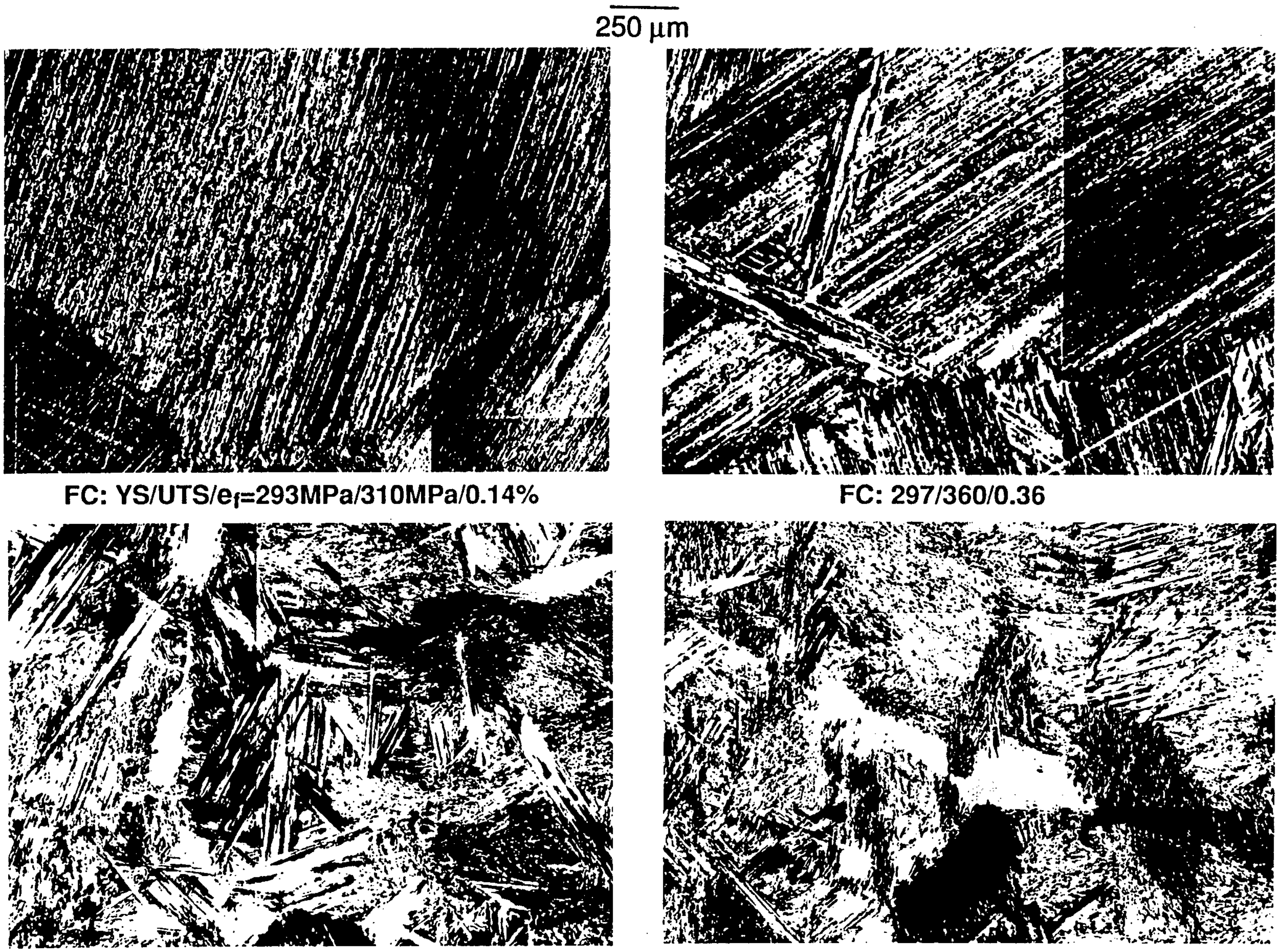
Alloy K5S: **Effect of Ram Speed on the Alpha-Forged Microstructure**



K5S (Ti-46.2Al-2Cr-3Nb-0.2W-0.2Si): **Directionally Alpha-Forged**



A Discrete Lamellar Structure in Alloy K5



FC: YS/UTS/e_f=293MPa/310MPa/0.14%

FC: 297/360/0.36

AC: 460/543/0.82

WQ: 516/579/0.5

Cooling Rate vs Microstructure/Tensile-Properties in α-Treasted Alloy G8

Advances in Microstructural Control

Gamma Microstructure/Property Relationships:

STRUCTURE	YEAR	YS (ksi)	UTS (ksi)	EL (%)	K (ksi√in)	CREEP (<950°C)
Duplex (G+L)	1988	65	80	**3-4**	12	Fair
Nearly Lamellar	1990	**90**	**105**	2-2.5	14	Fair
Fully Lamellar	1990	50	75	0.4-0.9	**22-30**	**Very Good**
Cast Nearly Lamellar*	1991	43	58	1.4-2.0	23-28	Good
TMP Lamellar	1991	**85**	**100**	**2-2.5**	**25-30**	Good

TMP LAMELLAR STRUCTURE HAS BEST BALANCE OF PROPERTIES

*Howment Co,
Cast Ti-48Al-2Mn-2Nb

Properties of Titanium-Base Alloys and Superalloys

Property	Ti-Base	Ti_3Al-Base	TiAl-Base	Superalloys
Structure	hcp/bcc	DO19	L1o	fcc/L12
Density (g/cm_3)	4.5	4.1-4.7	3.7-3.9	7.9-8.5
Modulus (GPa)	95-115	110-145	160-180	206
Yield Strength (MPa)	380-1150	700-990	350-600	800-1200
Tensile Strength (MPa)	480-1200	800-1140	440-700	1250-1450
Ductility (%) at RT	10-25	2-10	1-4	10-25
Ductility (%) at HT(°C)	12-50 (550)	10-20 (660)	10-60 (870)	20-80 (870)
Fracture Toughness (MPa/m) at RT	30-60	13-30	12-35	30-90
Creep Limit (°C)	600	750	750^a-950^b	800-1090
Oxidation Limit (°C)	600	650	800^*-950+	870^*-1090^{**}

^{a} Duplex; ^{b} Fully-lamellar microstructures; * Uncoated; + ** Coated; + Expected

Component Forming

(Wrought Processing)

Turbine Engine Components

Blades

- Alloy/Microstructures
- Mill product + Machining
- Impression Forging to NNS
  - Isothermal
  - Hot-Die Forming
- Heat Treatment

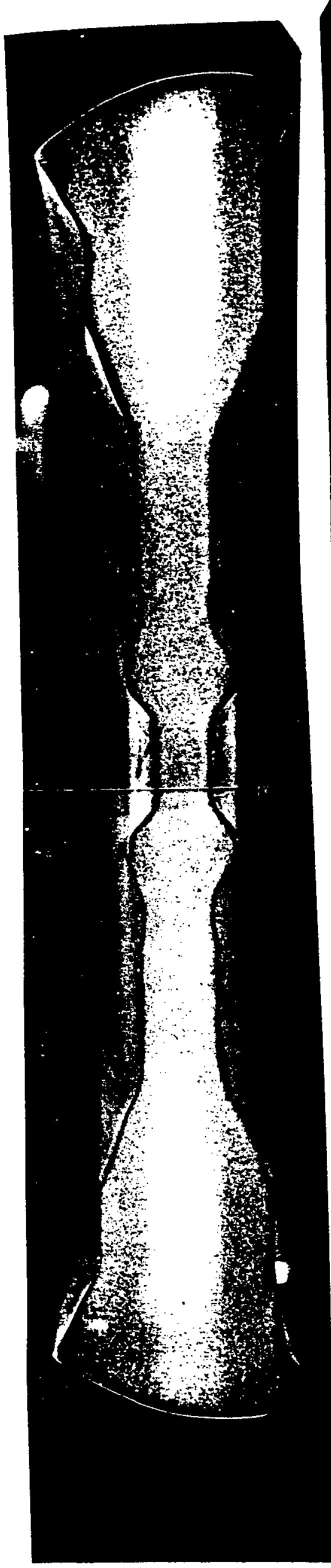
Disks

- Mill Product + Machining
- Impression Forging to NNS
  - Isothermal
  - Hot-Die Forming
- Heat Treatment

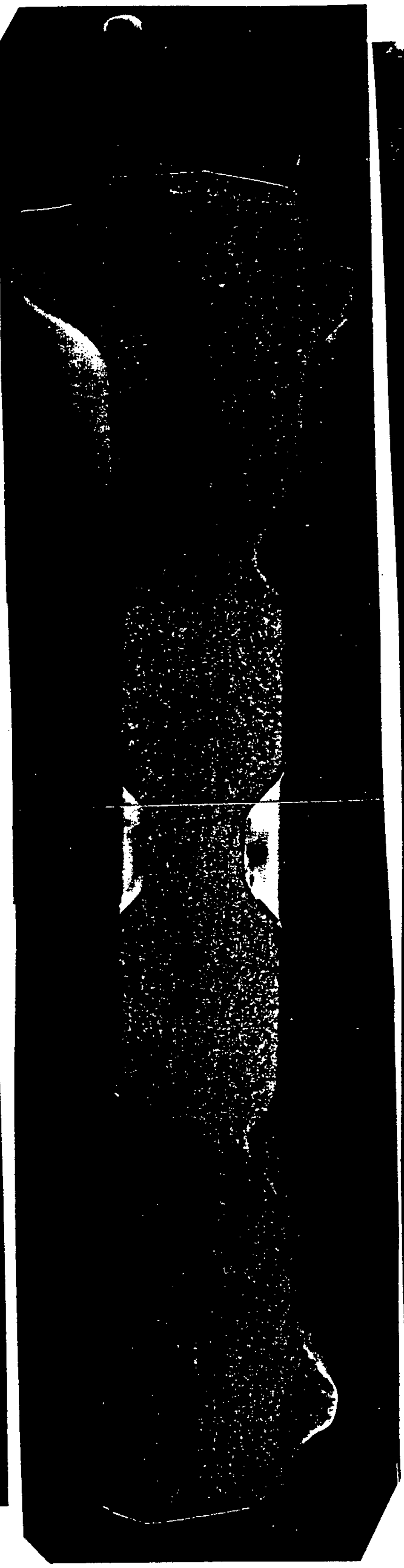
Engine Valves

Automotive Engines

Aircraft Engines



G87



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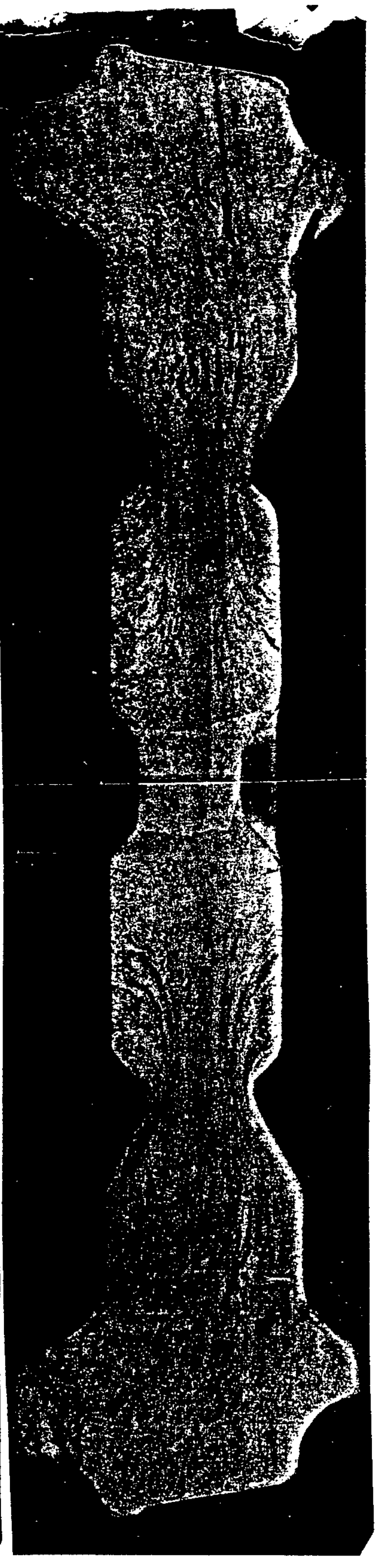

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W

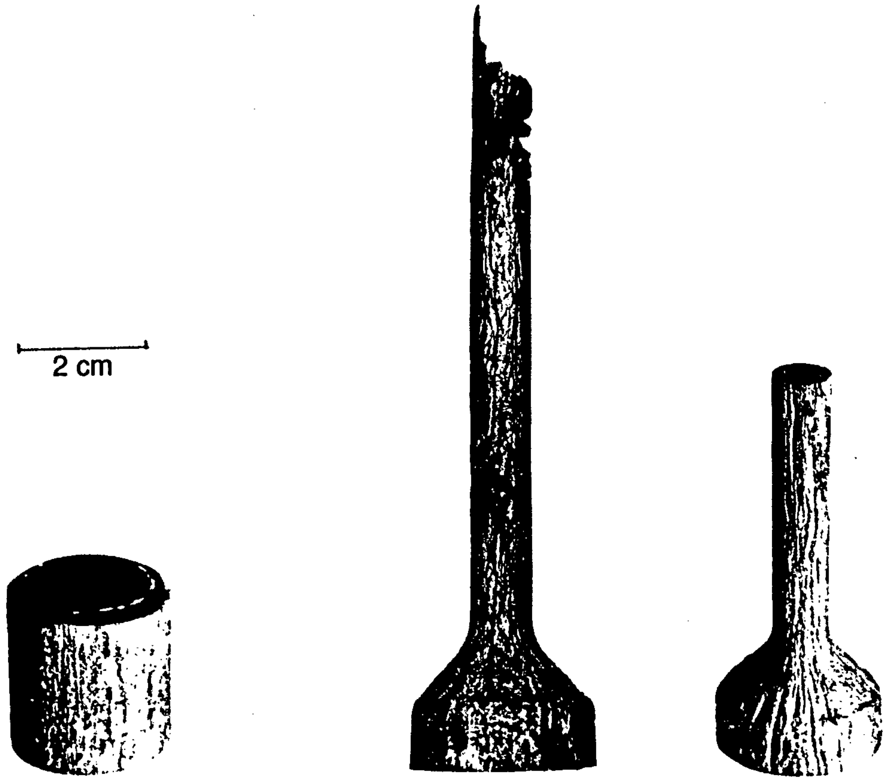
Automotive Valve Forming

Cast Valve

- Casting
- Hipping
- Passenger Car

Wrought Valve

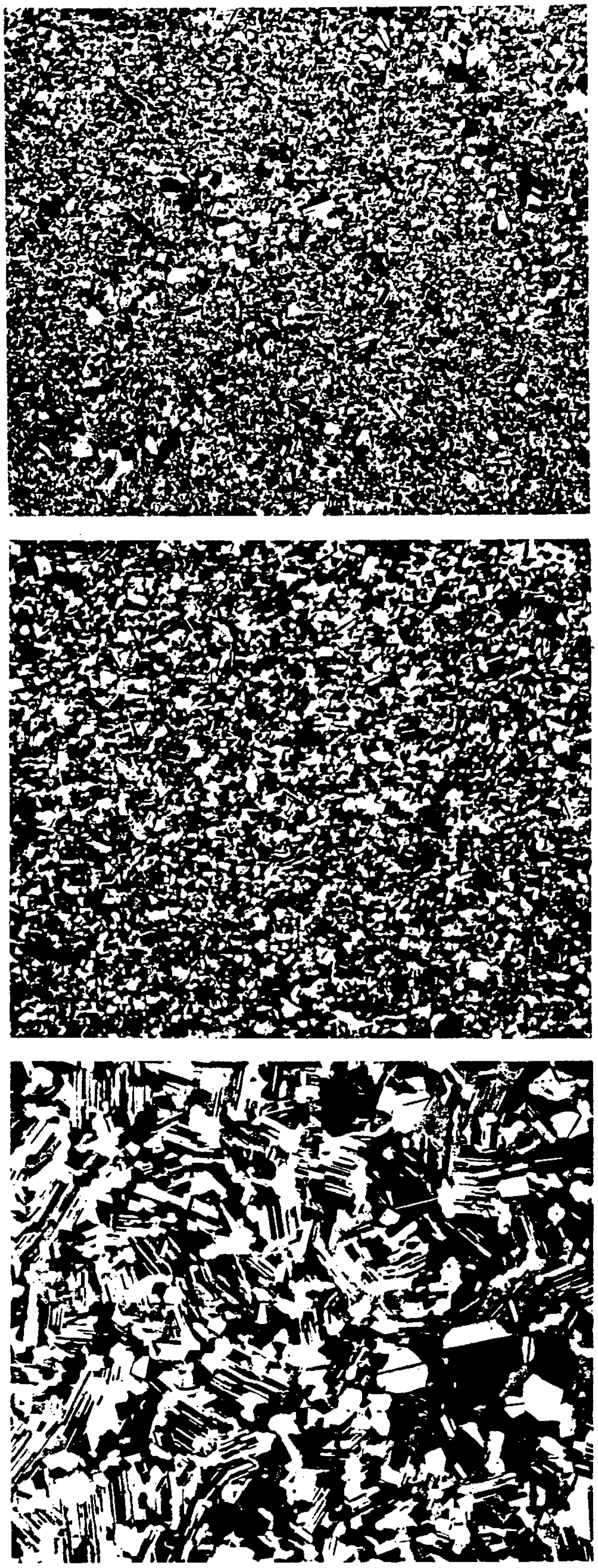
- Isothermal Forging
- Production Die Extrusion/Forging
  - Preconditioning: IM; PM
  - High Rate Extrusion of Preforms
  - High Rate Head Forging
  - Microstructure Control
- Head/Stem Joining
- High Performance

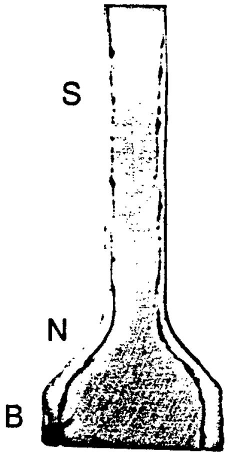


Preform

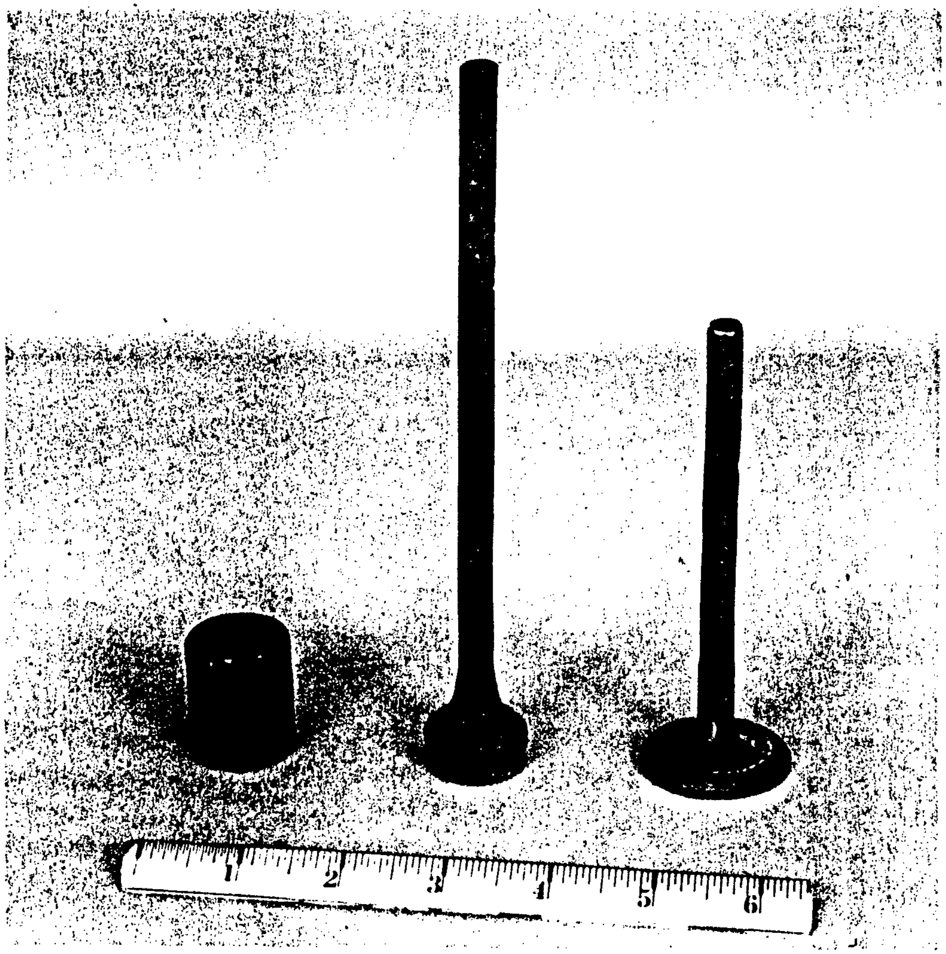
1st Step: Partial Extrusion

Wrought Gamma Engine Valve





G10 Valve Extrusion:
Transverse Sections



High-Rate (80 cm/sec)
Warm-Die (250°C)

Valve Extrusion
Head Coining

Commercial Steel Valve
Production Press (TRW)

Wrought Gamma Exhaust Valves

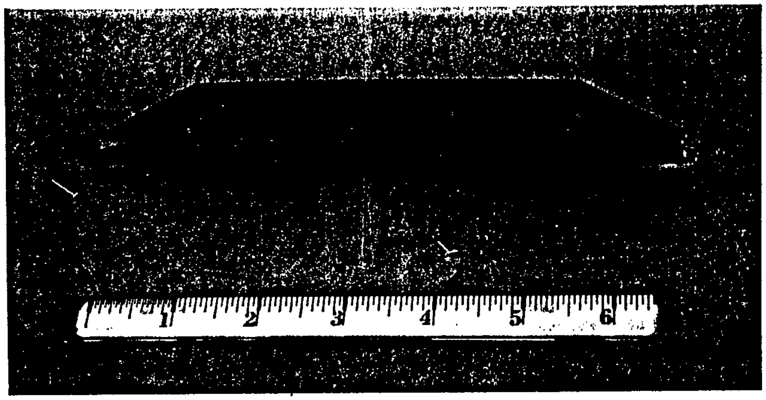
Applications

Aircraft Gas Turbine Engines

Automotive Engines

Land-Based Gas Turbine Engines

Others



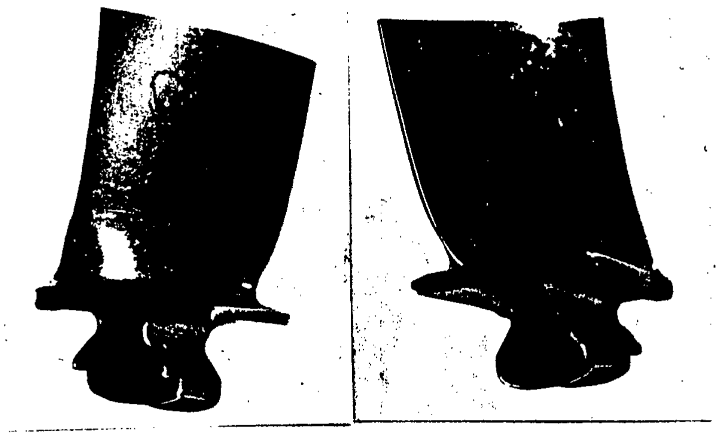
Cast 4822 Gamma Transition Duct Beam

GE-90 Engine for Boeing 777

CAESAR
Program

COMPONENT AND ENGINE
STRUCTURAL ASSESSMENT RESEARCH

Gamma Titanium HPC 6th Stage Blades



Participants:

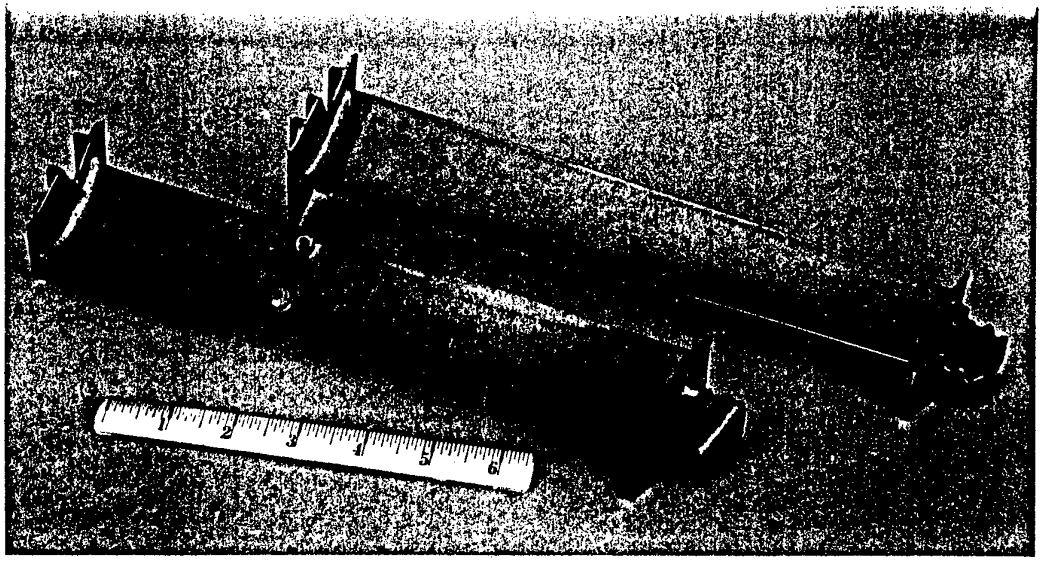
P&W	Cast "XD" Ti-47Al-2Nb-2Mn-0.8%TiB_2
Rolls Royce	Cast "XD" Ti-45Al-2Nb-2Mn-0.8%TiB_2
Allison ADC	Wrought Alloy 7
GE	Wrought Ti-48Al-2Cr-2Nb

Schedule:

Design and fabrication	[redacted] 96
Delivery to P&W	[redacted] 96
Proof spin (P&W)	[redacted] 96
~~F119 Core test - 100 hrs (AEDC)~~	[redacted] 96
~~Engine tests - 2000 TAC cycles (P&W)~~	[redacted] 97
~~Spin pit test to failure (P&W, UK)~~	[redacted] 97

Other gamma Ti components:

- ~~HPC inner shroud~~
- ~~combustor swirlers~~
- ~~nozzle tiles~~



4822 Cast Gamma LPT Blades for GE CF6-80C2

Cast and Chem-milled
Engine Tested for over 1000 cycles

Summary and Future

Continuous Alloy Exploration/Design

Casting vs Wrough Alloys

Continuous Search for Fundamentals

Process Development

Component-Specific Alloy Design

Search for Application Areas

Understand Practicality

Collaboration/Exchange