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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**Title and Subtitle**

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**Abstract**

The Final Proceedings for International Workshop on Gamma Titanium Aluminide Alloy Technology, 1 May 1996 - 3 May 1996  
The Topics covered include: Fundamental research issues for understanding the emerging class of Gamma Titanium Aluminide Alloy Technologies

**Subject Terms**

UNCLASSIFIED

**Security Classification of Report**

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**Security Classification of This Page**

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**Limitation of Abstract**

UL
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 $\alpha_2$ Phase
Ti-43Al: Homogenized and DTA Cooled
Cooling Rate vs Lamellar Spacing
(Ti-47Al)

0.2 °C/min

50 °C/min
Cooling Rate (R) vs Lamellar Spacing (λ)

\[ \lambda = C \cdot R^{-1/2} \]
**Ti-43Al**: Cooled at 5°C/min

**Ti-47Al**: Cooled at 30°C/min

DTA specimens of homogenized alloys
Processing Routes for Gamma Alloys

IM
Alloy Ingot
    ▼
    HIP
    ▼
    Homogenize
    ▼
    Hot Work
    ▼
    Forge/Extrude
    ▼
    Machine to NNS

PM
Alloy Powder
    ▼
    (Elemental Powder)
    ▼
    Consolidate
    ▼
    HP/HP
    ▼
    Billet
    ▼
    Roll
    ▼
    Form to NNS
    ▼
    Heat Treatments
    (Component-Specific)
    ▼
    Casting
Alloy Casting
    ▼
    Strip
    ▼
    Casting
    ▼
    NNS
    ▼
    HIP
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
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
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

200 μm
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
Alloy K5's: Isothermally-Forged (1150°C/70/70)
Isothermally forged (85%) microstructures
Alloy K5: Isothermally-Forged and Duplex-Treated
Lamellar Structures: Light-to-Gray Areas

Alloy G1: Forged + (α+γ) Treated + Air Cooled
Microstructures of Gamma Alloys

Duplex

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 13: Ti-46.4Al-2.1Cr-3Nb-0.7W
Wrought Alloy K5 after High Temperature Treatments
RT Tensile Curves in Duplex/NL Microstructures

IA: Indirect Aging
DA: Direct Aging
RT: Lab Air

300 μm
1200 μm

FL
RT; Lab Air
4x10^4 s^-1
Flow Stress Constant, \( C \) (MPa)

- \( \sigma = C \dot{\varepsilon}^m \)
- \( \dot{\varepsilon} = 1.0 \)
- \( \varepsilon = 0.60 \)

Temperature (°C)

- TiAl (G2)
- SS 304
- CP-211
- Ti-6Al-4V
- IN 718

Diagram:

1. CAN
2. TAIL CAP
3. NOSE CAP
4. EVACUATION TUBE
5. BILLET OR CORE (SI, TEMP)
6. SILICA FABRIC (SI, TEMP)
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

$1270^\circ\text{C}/4\text{h}/\text{AC}/\text{RT}$

$1270^\circ\text{C}/4\text{h}/\text{FC}/900^\circ\text{C}/\text{AC}$

$+900^\circ\text{C}/48\text{h}/\text{AC}$

Weak Yield Point

Pronounced Yield Point
K5 Duplex: $\varepsilon_t = 0.5\%$

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
Tensile Fracture Surfaces of Alloy G1 in Various Microstructural Conditions

Near Gamma

a Duplex with direct aging

a Duplex with indirect aging

A Nearly-Lamellar with indirect aging
Tensile Curves of Fully-Lamellar Gamma Materials
\( \varepsilon_1/\sigma_1 = 0.3 \% / 427 \text{ MPa} \)  \( \varepsilon_3/\sigma_3 = 0.55 \% / 493 \text{ MPa} \)

Alloy K5 RFL Flat Gage Tensile Specimen Surface Deformed at RT

(\( \sigma_0/\sigma_y = 328/474 \text{ MPa} \); \( \lambda_L = 0.3 \mu \text{m} \))
RT Tensile Deformation/Strain-Accomodation Observed on Electropolished Surfaces of Alloy K5 RFL Specimens at $\sigma/\varepsilon=528$ MPa/1.21% ($\sigma_0/\varepsilon_0=328/0.19$)
BSE Image of RT Tensile Deformation/Strain-Accomodation near GB's on Surfaces of Alloy K5 RFL Specimens at $\sigma/\varepsilon=528$ MPa/1.21% ($\varepsilon_0=0.19$)
Deformed Microstructure of Alloy G1 at 1.9% Tensile Strain
Alloy K5 RFL Tensile Specimen Flat Gage Surface Deformed at RT

\( \sigma_x^0 = 524 \text{ MPa}, \varepsilon_x^0 = 0.78\% \) (\( \sigma_x^0 = 328, \varepsilon_x^0 = 0.19 \))
RT Tensile Transgranular Fracture of FL Gamma Alloys:
(a) Overall, (b) Interlamellar and Translamellar, (c, d) Translamellar Cleavage with Interlamellar Deformation
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

![Graph showing corrected Hall-Petch relation in FL TiAl](image)

Hall-Petch Relations in TiAl Alloys

![Graph showing Hall-Petch relations in TiAl alloys](image)
Hall-Petch Relations in TiAl Alloys

**Duplex Material**

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

- \( k_d \approx 1 \text{ MPa}\sqrt{\text{m}} \)
- Relatively isotropic

**Fully-Lamellar Material**

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

- \( k_{d\lambda} = 2.5 \text{ MPa}\sqrt{\text{m}} \) (for \( \lambda = 1 \mu\text{m} \))
- Combined Effect of \( d \) and \( \lambda \)

\[ k_{dy} = k_d \left( \tau^*_{\text{avg}} / \tau^*_{s} \right) = \text{ftn} (\lambda) \]
Orientation vs. Yield-Stress in the (\(\chi + \phi_2\)) Lath Structure

\[ \sigma_{90}; \sigma_0 = f(\lambda, \phi_2/\chi, C) \]

\[ \sigma_{90} = \sigma_0 + k^{-1/2} \]

(k = 0.5 MPa m)
Yielding of the \((r+\alpha')\) Lath Structure

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

\[
\phi \text{ (degree)}
\]

\[
\begin{align*}
(111) &< 1-10] \\
Yield Stress (MPa) &
\end{align*}
\]

\[
\gamma_y \\
\gamma_{90} \\
\gamma_0 \\
\gamma_s \\
\gamma_{avg} = \frac{\gamma_{90} + \gamma_0 + 2\gamma_s}{4} \quad (~2.5 \gamma_s~)
\]

\[
\gamma_{avg} \text{ : Stress required to activate and move dislocations across lath boundaries}
\]

\[
k_d = k_d \left( \frac{\gamma_{avg}}{\gamma_s} \right) \quad (~2.5k_d~)
\]
Tensile Fracture of FL Alloy G5 at 750°C
Tensile Properties of Alloy K5

(Dependence on Microstructure, Temperature and Strain Rate)

Strain Rate: $5 \times 10^{-2}$ s$^{-1}$

Temperature (°C)

Stress (MPa)

Alloy K5

RFL: 300μm
Duplex: 15μm

Strain Rate: $1 \times 10^{-4}$ s$^{-1}$
Tensile Fracture of Alloy K5 (Duplex) in Air at 600°C

[YS/UTS/E: 396/545/3.6]
Far Below Fracture Surface

Just Below Fracture Surface

Near CI site

Away From CI

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

Stress (MPa)

Strain Rate (s⁻¹)

600°C

800°C

YS/600

UTS/600

YS/800

UTS/800

UTS

YS

0

10⁻⁵

10⁻⁴

10⁻³

10⁻²

10⁻¹

0

10⁻⁵

10⁻⁴

10⁻³

10⁻²

10⁻¹
Effect of Strain Rate on BDT in Alloy K5

![Graphs showing the effect of strain rate on BDT in Alloy K5.](image)
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)
      $\alpha_2/\gamma$ Ratio ($\alpha_2$ vol%)
   Uniformity

Composition
   $\alpha_2/\gamma$ Ratio; LS

Cleavage Strength

Interfacial Bond Strength
Grain Size Effects on Tensile and Toughness

Ductility and Strength

Ductility and Toughness
Fracture Resistance and Near-Tip Plasticity at RT
General Tensile Yielding vs. Near-Crack-Tip Plasticity at K\textsubscript{lc}
Plastic Deformation and Microcracking Around the Advancing Crack Tip in a 7178 Al Alloy CT Specimen under a Monotonic Tension Loading at RT
Interlamellar and Translamellar Deformation in Crack-Tip and Ligament Regions
Fracture Toughness

Grain Size Effect

Lamellar Spacing Effect

\[ K \propto \lambda^{1/2} \]

LS, \( \lambda^{1/2} (\mu m^{-1/2}) \)

Elongation (%) vs. Grain Size (\( \mu m \))

Toughness (MPa\( \sqrt{m} \)) vs. Lamellar Spacing, LS (\( \mu m \))

- Duplex/NL
- \( K_q \)
- Ductility
- \( K_{1c} \)
- \( K_q \)

Alloys: G1, K5, K7
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.
Crack-Tip Regions of Lamellar TiAl Fracture Specimens

800°C

50 μm

20 μm
Creep Resistance of Alloy K5

Stress Exponents

Larsen-Miller Plot

- Ti-48Al-2Mn-2Nb [Howmet/93]
- XD Gamma [Howmet/93]
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 Rupture Stresses (RS) for Superalloys
Effect of $\text{Al}_2\text{O}_3$ Layer on Creep

Creep of Alloy K5

- **K5 RFL (300μm)**
- **870°C/138MPa/Air**

Strain (%) vs. Time (h)

- **As-Machined**
- **Preoxidized**

Images:
- **a:** Micrograph showing the layers of Al$_2$O$_3$
- **b:** Cross-section image with scale bar of 5 μm
Creep of Alloy K5 Series
(under severe conditions)

760°C; 311MPa
Air

Creep Strain (%)

Time (hr)

Duplex
(Ruptured)
K5SB/RFL
K5SC/RFL
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$^3$ 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<sub>0.51</sub>Al<sub>0.49</sub>)<sub>99.5</sub>C<sub>0.5</sub>, (Ti<sub>0.50</sub>Al<sub>0.50</sub>)<sub>99.5</sub>C<sub>0.5</sub> and (Ti<sub>0.49</sub>Al<sub>0.51</sub>)<sub>99.5</sub>C<sub>0.5</sub> during aging at 1073 K.

Figure 3 Temperature dependence of compressive yield strength of (Ti<sub>0.51</sub>Al<sub>0.49</sub>)<sub>99.5</sub>C<sub>0.5</sub> and (Ti<sub>0.50</sub>Al<sub>0.50</sub>)<sub>99.5</sub>C<sub>0.5</sub> aged at 1073 K for 3.6x10<sup>4</sup> s (10 h), and (Ti<sub>0.49</sub>Al<sub>0.51</sub>)<sub>99.5</sub>C<sub>0.5</sub> aged at 1073 K for 3.6x10<sup>5</sup> s (1 h). Data for binary and ternary TiAl are also included.
HCF of Alloy K5

Max. Stress/YS vs. Cycles to Failure

- 800/Duplex
- 600/Duplex
- 600/RFL
- 800/RFL
- 870/RFL
- 870/SB/TMP

R=0.1/25Hz/Air
Fatigue Deformation and Fracture of FL Alloy K5 at 800°C and $R=0.1$ in Air (UTS = 500 MPa)
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)

\[ \sigma_{\text{max}} = 350 \text{ MPa} / N_f = 9.6 \times 10^5 \]

\[ \sigma_{\text{max}} = 250 \text{ MPa} / N_f = 1.63 \times 10^7 \]
Fatigue Fracture of a Duplex Alloy K5 at 600°C in Air

( R = 0.1;  UTS = 583 MPa)

Near CI Site

Away from CI

Near CI

Away from CI

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

$\sigma_m = 575$ MPa / $c_f = 1.36 \times 10^6$
Specimen Geometry Effect at <BDTT

![Graph showing the effect of specimen geometry on stress and cycles to failure.](image)

- **Max. Stress (MPa)**
- **Cycles to Failure**

- **600 Duplex**
- **600/ RFL**
- **NL/RT/ED**
- **NL/600/ED**
- **Duplex/RT/BW**
- **FL/RT/BW**

*R=0.1/Air/25Hz/350Hz*

(Hourglass)

(Dogbone)
HCF of Alloy K5 in Duplex at 800°C
(Effect of Frequency and Fatiguing Time)

**Frequency Effect**

- **Max. Stress (MPa)** vs. **Cycles to Failure**
  - 25Hz
  - 350Hz [ED]

**Effect of Fatiguing Time**

- **Time-to-Failure** vs. **Max. Stress (MPa)**
  - 25Hz
  - 350Hz [ED]

800°C/Air/R=0.1
Effect of Frequency on HCF
(at 800°C)

High Stress Regime \((\sigma_{\text{max}} > \sigma_y)\)
Frequency-dependent (need investigation)
High-rate deformation

Low Stress Regime \((\sigma_{\text{max}} > \sigma_y)\)
Frequency-independent
Time-dependent
Creep deformation important

Creep Fatigue
Suggested at Low Stresses
Mean Stress: \(\sigma_{\text{avg}} = (\sigma_{\text{max}} + \sigma_{\text{min}})/2\)
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

![Graph showing FCG of Alloy K5 with various markers representing different conditions such as DP 23 °C, DP 600 °C, DP 800 °C, FL 23 °C, FL 600 °C, and FL 800 °C. The graph plots ΔK (MPa√m) on the x-axis and dā/dN (m/cycle) on the y-axis.]
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.
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

**α₂ Volume Fraction:** 5-30 %
- Strength; Ductility; Toughness
- Anisotropy

**Texture Consideration**

*Duplex Microstructures (?)*
TMT Lamellar Microstructures

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

Graph: Grain Size (µm) vs. Boron (at%) for Ti-47 Al and Alloy K5 after Tα+10°C for 1 h.

Micrographs show lamellar microstructure with a scale bar of 200µm.
Grain Size (μm)

GS vs Boron Content in Gamma Alloys

Ta=1380°C for Ti-47Al
Ta=1350 for Alloy K5
Anneal Time (t_a): 1h

Temperature (°C)

Cooling-Rate and Boron Content on Alpha Decomposition
Alloy K1: As-Forged; Near Gamma; Duplex; and TMTL microstructures
Forged and TMT-Lamellar Treated (1370°C/1hr/FC/1000°C/AC)

Ti-47Al-0.05B

Ti-47Al-0.10B

Ti-47Al-0.24B
Alloy K7: **Alpha-Treated (1390°C/30min) and Cooled Differently**
Alloy K6: **Alpha-Treated (1370°C/1h) and Cooled Differently**
Alloy K7: **TMT-Treated** (1390°C/1.5h/AC) and **Annealed** (1300°C/24h/AC)
TMP Lamellar Microstructures

AS-EXTRUDED

<table>
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<th>COMPRESSION $\sigma_y$</th>
<th>K5SC-6 ($\alpha$HT)</th>
<th>K5SC-5</th>
<th>K5WSB-4</th>
<th>KG1-4</th>
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900°C/24Hr/AC

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Kim (95)

50 μm

L

T
K5SC Alloy TMPL Extrusion LT-Section
A TMP Microstructure in a 4822 Extrusion
Thermal Stability of TMP Lamellar Extrusions

![Graph showing yield stress versus aging time for different conditions and materials.](image-url)

- **RT LT-Compression**
- **Fine TMP-NL**
- **Coarse TMPL**
- **Fine TMPL**

Materials:
- **K8:** Ti-46.4Al-1.1Cr-4.0Nb-0.2W-0.09C-0.16Ox
- **K5N:** Ti-45.8Al-1.6Cr-3.0Nb-0.3W-0.07C-0.17Ox
Flow Curves of Lamellar Alloys

- K5SC6-TMPL (~100 μm)
- K5SC5-TMPL (~100 μm)
- G8-RFL (350 μm)
- K5-RFL (300 μm)
- G8-FL (1200 μm)
- G8-FL (2500 μm)

RT/Air/5x10^{-4}s^{-1}
Strengths of RFL/TMPL Gamma Alloys

YS

UTS

Temperature (°C)

Stress (MPa)

Temperature (°C)

Stress (MPa)
Microstructure on RT Tensile Properties
GS/LS/YS Relations in TiAl FL Alloys

![Graph showing yield stress vs grain size with lines and annotations for IM/TML, IM/TMPL, FL, and IM/FL with equations for the relationships.](image)
Longitudinal (L)  Long-Transverse (LT)

Alloy K8 TMP-Lamellar Extrusion
Alloy K5S: Effect of Ram Speed on the Alpha-Forged Microstructure
K5S (Ti-46.2Al-2Cr-3Nb-0.2W-0.2Si): Directionally Alpha-Forged
Cooling Rate vs Microstructure/Tensile-Properties in $\alpha$-Trended Alloy G8
Gamma Microstructure/Property Relationships:

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

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

**TMP LAMELLAR STRUCTURE HAS BEST BALANCE OF PROPERTIES**
## Properties of Titanium-Base Alloys and Superalloys

<table>
<thead>
<tr>
<th>Property</th>
<th>Ti-Base</th>
<th>Ti₃Al-Base</th>
<th>TiAl-Base</th>
<th>Superalloys</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>hcp/bcc</td>
<td>DO19</td>
<td>L10</td>
<td>fcc/L12</td>
</tr>
<tr>
<td><strong>Density (g/cm³)</strong></td>
<td>4.5</td>
<td>4.1-4.7</td>
<td>3.7-3.9</td>
<td>7.9-8.5</td>
</tr>
<tr>
<td><strong>Modulus (GPa)</strong></td>
<td>95-115</td>
<td>110-145</td>
<td>160-180</td>
<td>206</td>
</tr>
<tr>
<td><strong>Yield Strength (MPa)</strong></td>
<td>380-1150</td>
<td>700-990</td>
<td>350-600</td>
<td>800-1200</td>
</tr>
<tr>
<td><strong>Tensile Strength (MPa)</strong></td>
<td>480-1200</td>
<td>800-1140</td>
<td>440-700</td>
<td>1250-1450</td>
</tr>
<tr>
<td><strong>Ductility (%) at RT</strong></td>
<td>10-25</td>
<td>2-10</td>
<td>1-4</td>
<td>10-25</td>
</tr>
<tr>
<td><strong>Ductility (%) at HT(°C)</strong></td>
<td>12-50 (550)</td>
<td>10-20 (660)</td>
<td>10-60 (870)</td>
<td>20-80 (870)</td>
</tr>
<tr>
<td><strong>Fracture Toughness (MPa/m) at RT</strong></td>
<td>30-60</td>
<td>13-30</td>
<td>12-35</td>
<td>30-90</td>
</tr>
<tr>
<td><strong>Creep Limit (°C)</strong></td>
<td>600</td>
<td>750</td>
<td>750⁺⁻⁹⁵¹⁺</td>
<td>800-1090</td>
</tr>
<tr>
<td><strong>Oxidation Limit (°C)</strong></td>
<td>600</td>
<td>650</td>
<td>800⁺⁻⁹⁵¹⁺</td>
<td>870⁺⁻¹⁰⁹⁰**</td>
</tr>
</tbody>
</table>

* Duplex; ¹ Fully-lamellar microstructures; ² Uncoated; ³ ** Coated; ⁴ 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
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
G10 Valve Extrusion: Transverse Sections
Wrought Gamma Exhaust Valves

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

Valve Extrusion
Head Coining

Commercial Steel Valve
Production Press (TRW)
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
Gamma Titanium HPC 6th Stage Blades

Participants:
- P&W: Cast "XD" Ti-47Al-2Nb-2Mn-0.8%TiB₂
- Rolls Royce: Cast "XD" Ti-45Al-2Nb-2Mn-0.8%TiB₂
- Allison ADC: Wrought Alloy 7
- GE: Wrought Ti-48Al-2Cr-2Nb

Schedule:
- Design and fabrication: 96
- Delivery to P&W: 96
- Proof spin (P&W): 96
- F119 Core test - 100 hrs (AEBC): 96
- Engine tests - 2000 TAG cycles (P&W): 97
- Spin pit test to failure (P&W, UK): 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