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1MOrD1-04

Effect of stress ratio on high-cycle fatigue properties of Ti-6Al-4V ELI alloy forging at low temperature

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OUTLINE

1. Background

2. Experimental procedures

3. Fatigue tests at various stress ratios *R* at 293 & 77 K

   R = ratio of min. stress to max. stress

4. Evaluation using the modified Goodman diagram

5. Summary

➢Background

Japan Aerospace Exploration Agency (JAXA) – NIMS (2000~)

Evaluate the mechanical properties of metallic materials used in liquid-fuel engines for Japan's H-IIA and H-IIB launch vehicles

- to increase the reliability of the Japanese launch vehicles
- to accumulate fundamental data for developing a future launch vehicle engine

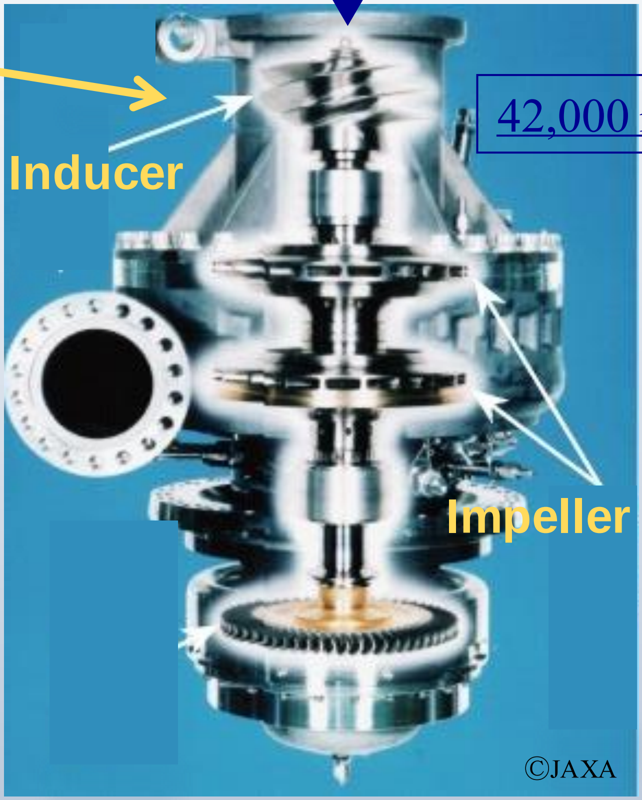
Liquid hydrogen turbo pump

LE-7A engine
©JAXA

Liquid hydrogen（20 K）

529L/sec

42,000 rpm



Ti-6Al-4V ELI alloy

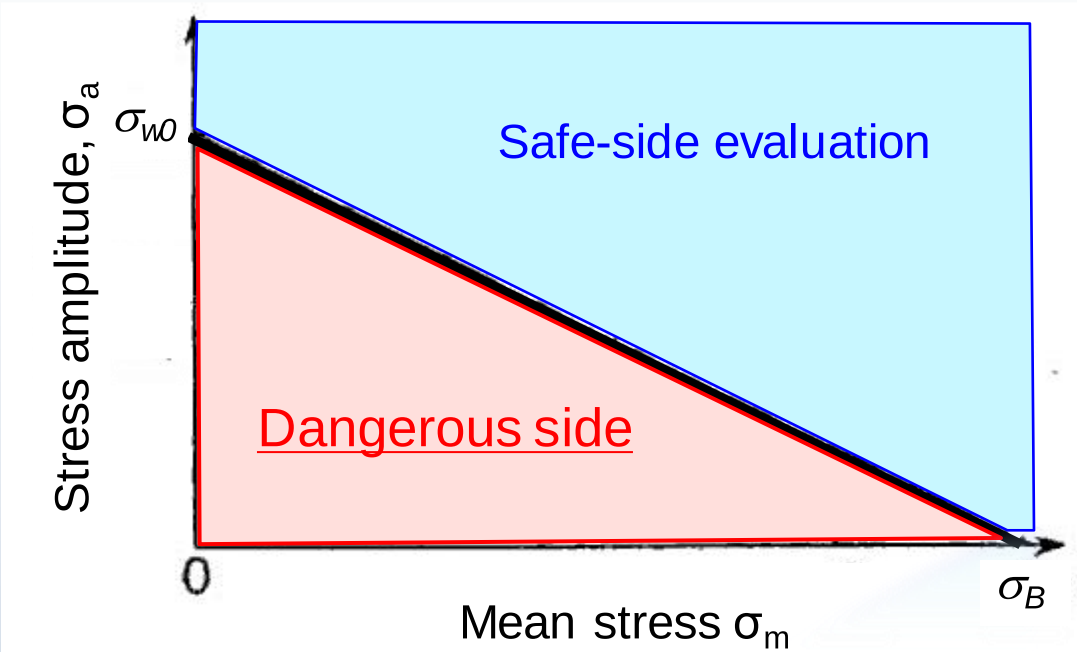
- typical ($\alpha+\beta$) type titanium alloy
- high specific strength
- popular (low cost)
- high strength @cryogenic temp.

Important !

Understand the effect of stress ratio (mean stress) on high-cycle fatigue properties at cryo. temp.

➢Endurance limit diagram

Endurance limit diagram → Relationship betwee fatigue limit σ_w and mean stress σ_m



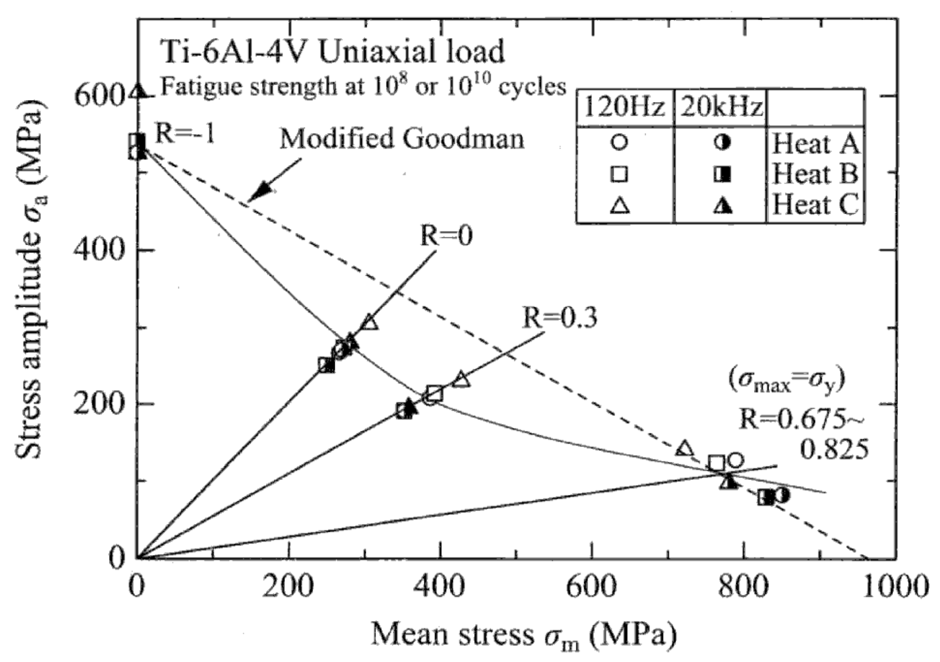
Modified Goodman line

$$\sigma_w = \sigma_{w0}\left(1 - \frac{\sigma_m}{\sigma_B}\right)$$

σ_{w0} : Fatigue limit at $R = -1$ (zero mean stress)

σ_B : Tensile strength

The modified Goodman line for Ti-6Al-4V alloy enters the dangerous side near *R* = 0 at RT !!



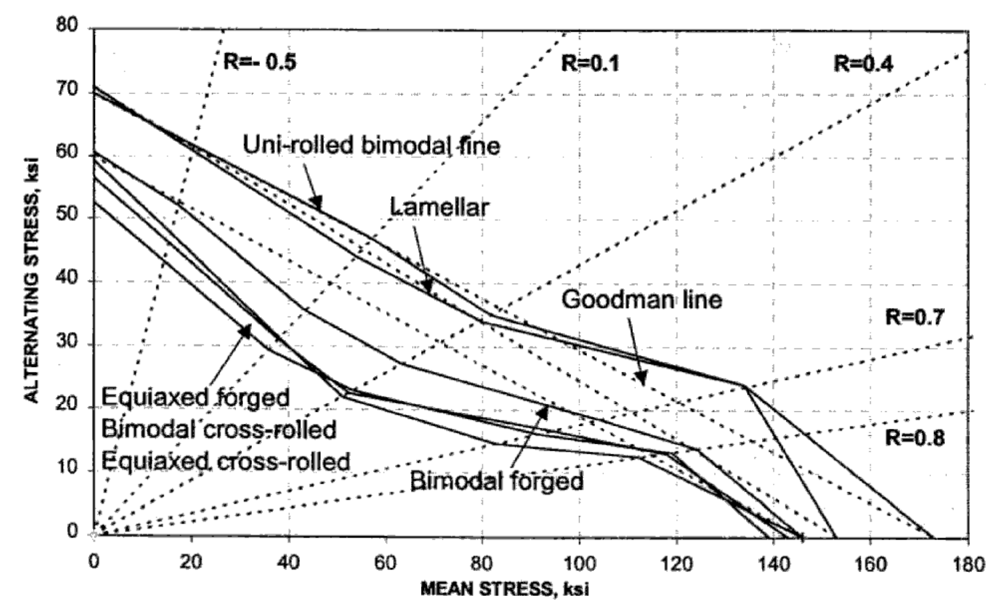


Fig.3. Constant life diagrams (10^7 cycles).

E. Takeuchi et al. Tetsu to Hagane, vol.96, (2010), p.36-41, Ti-6Al-4V Normal, bar, RT, Fatigue Strength at 10^7, 10^8 and 10^{10} cycles

Frederic S. Cohen et al., Fatigue Behavior of Titanium Alloys, (2007), p.39-46, Ti-6Al-4V Normal, bar or rod, RT, Fatigue Strength at 10^7 cycles

What we did in this research

① Fatigue tests under various stress ratios at 293 and 77 K for Ti-6Al-4V ELI alloy forging

② Evaluation of the effect of the stress ratio on the high-cycle fatigue properties using the modified Goodman diagram

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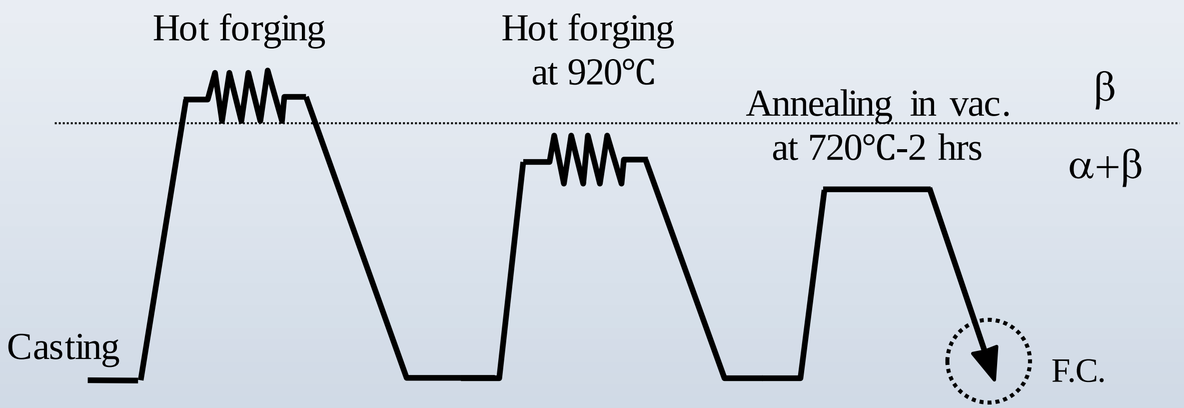
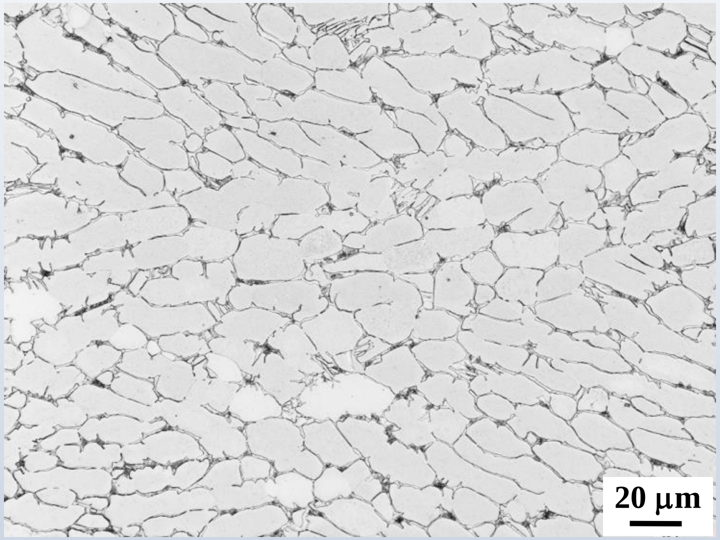
➢Experimental procedures

Chemical compositions（mass%） Aerospace Material Specification 4930E
Titanium Alloy Bars, Wire, Forgings, and Rings, 6Al - 4V , Extra Low Interstitial, Annealed

		Al	V	Fe	H	O	N	C	Ti
Top		6.16	4.18	0.22	0.0042	0.09	0.006	0.01	bal.
Bottom		6.18	3.93	0.17	0.0067	0.11	0.007	0.01	bal.
Requirement	Max	6.50	4.50	0.25	0.0125	0.13	0.05	0.08	bal.
	Min	5.50	3.50	—	—	—	—	—	

Forging and Heat Treatment Process

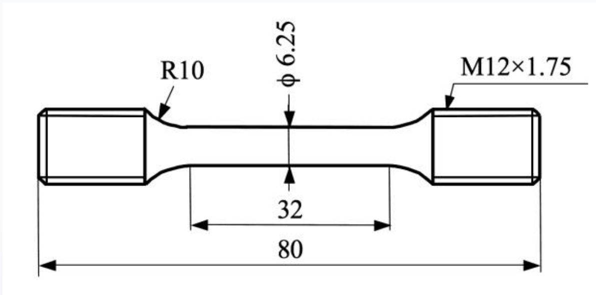




Constituents: α and β phases
- Equiaxed α grains
- β exists along the α grain boundaries.

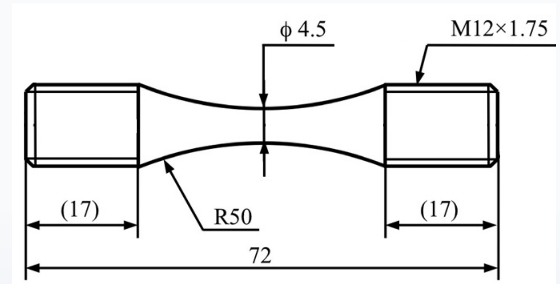
➢Experimental procedures

Tensile test



- Temperature: 77 and 293K
- Crosshead speed: 0.5 mm / min
- Initial strain rate: 2.2×10^{-4} /s

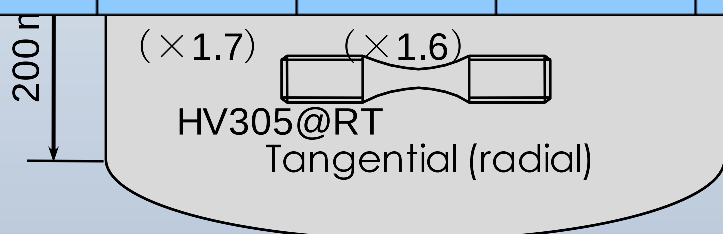
High-Cycle Fatigue test

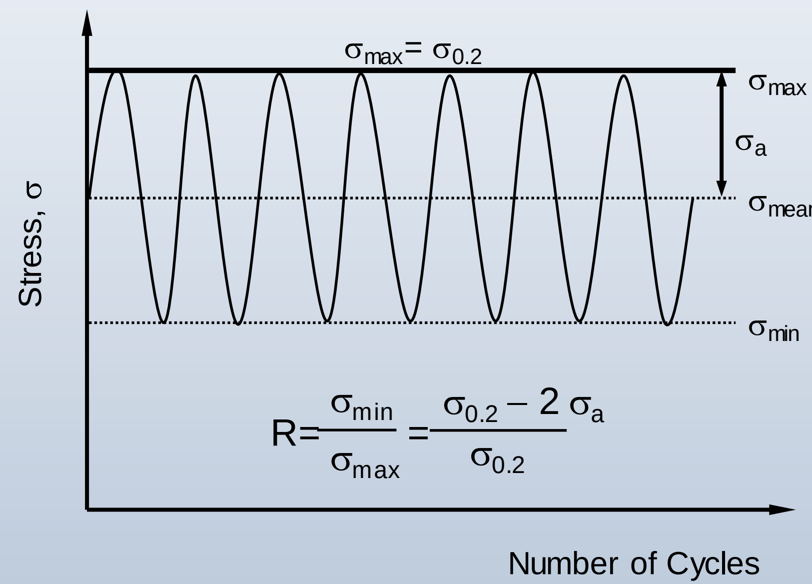


- Temperature: 77 and 293K
- Load control, Uni-axial loading, Sinusoidal waveform
- Stress ratio: R = -1, 0.01, 0.5 and $\sigma_{max}=\sigma_{0.2}$ test
- Frequency: 10 Hz

Tensile properties

Temp. / K	0.2% proof stress / MPa	Tensile strength / MPa	Elongation (%)	Reduction of area (%)
293	770	833	12	22
77	1,280	1,370	13	20





1. Background

2. Experimental procedures

3. **Fatigue tests at various stress ratios *R* at 293 & 77 K**

   ***R* = ratio of min. stress to max. stress**

4. Evaluation using the modified Goodman diagram

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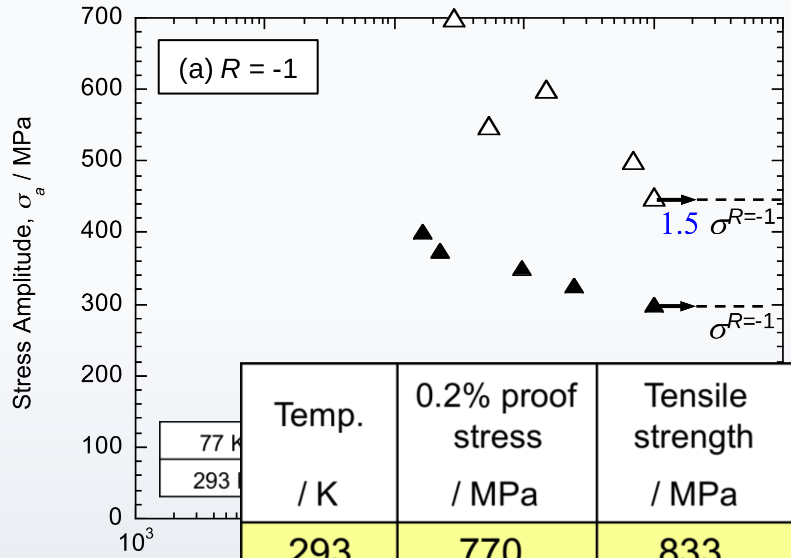
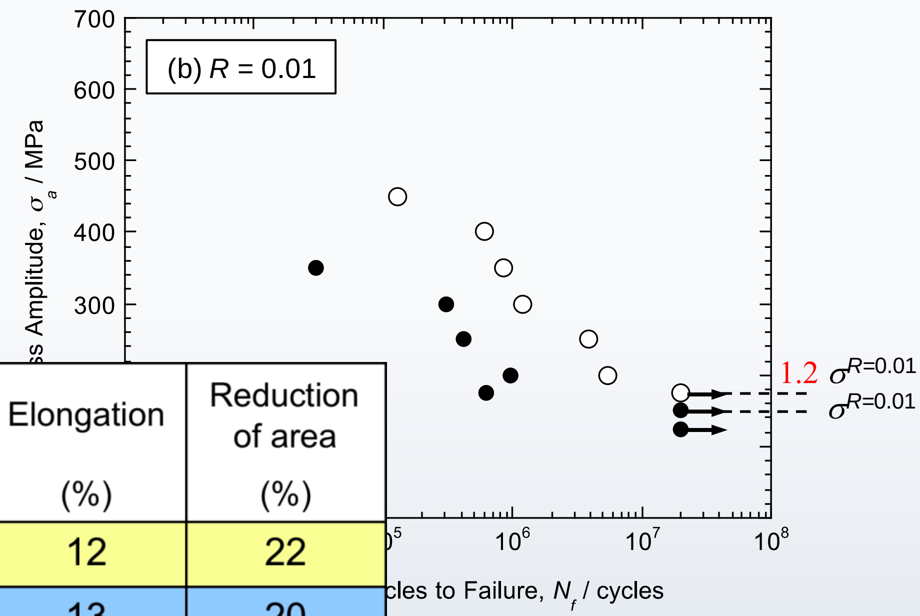
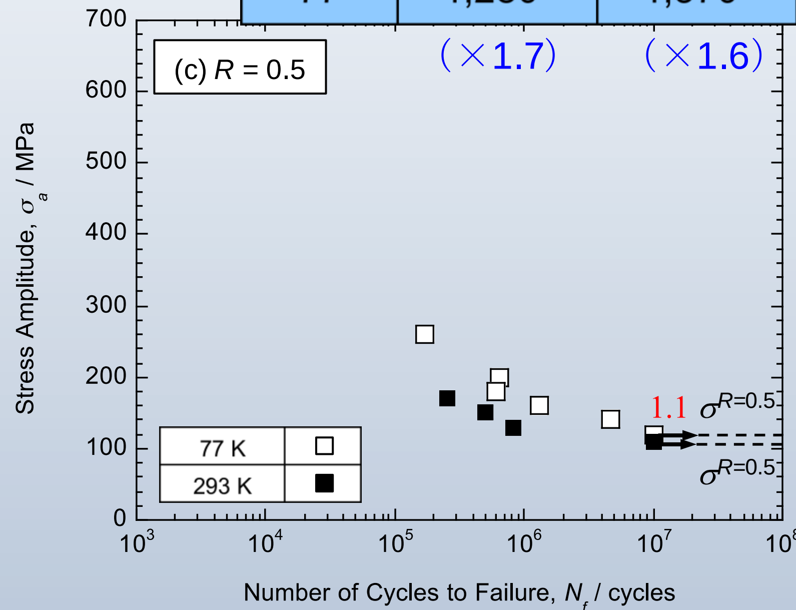
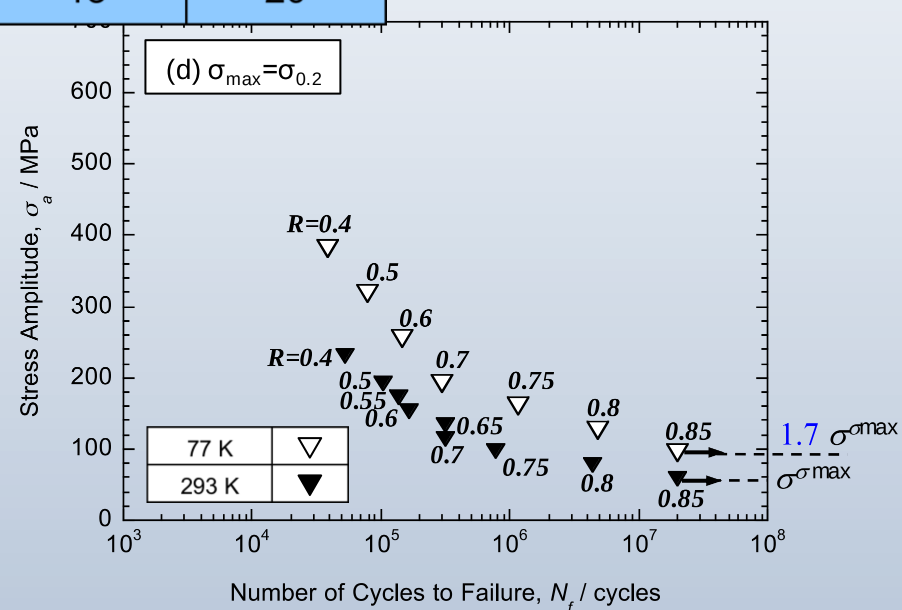
➤Results of Fatigue tests

Temp. / K	0.2% proof stress / MPa	Tensile strength / MPa	Elongation (%)	Reduction of area (%)
293	770	833	12	22
77	1,280	1,370	13	20
	(×1.7)	(×1.6)		









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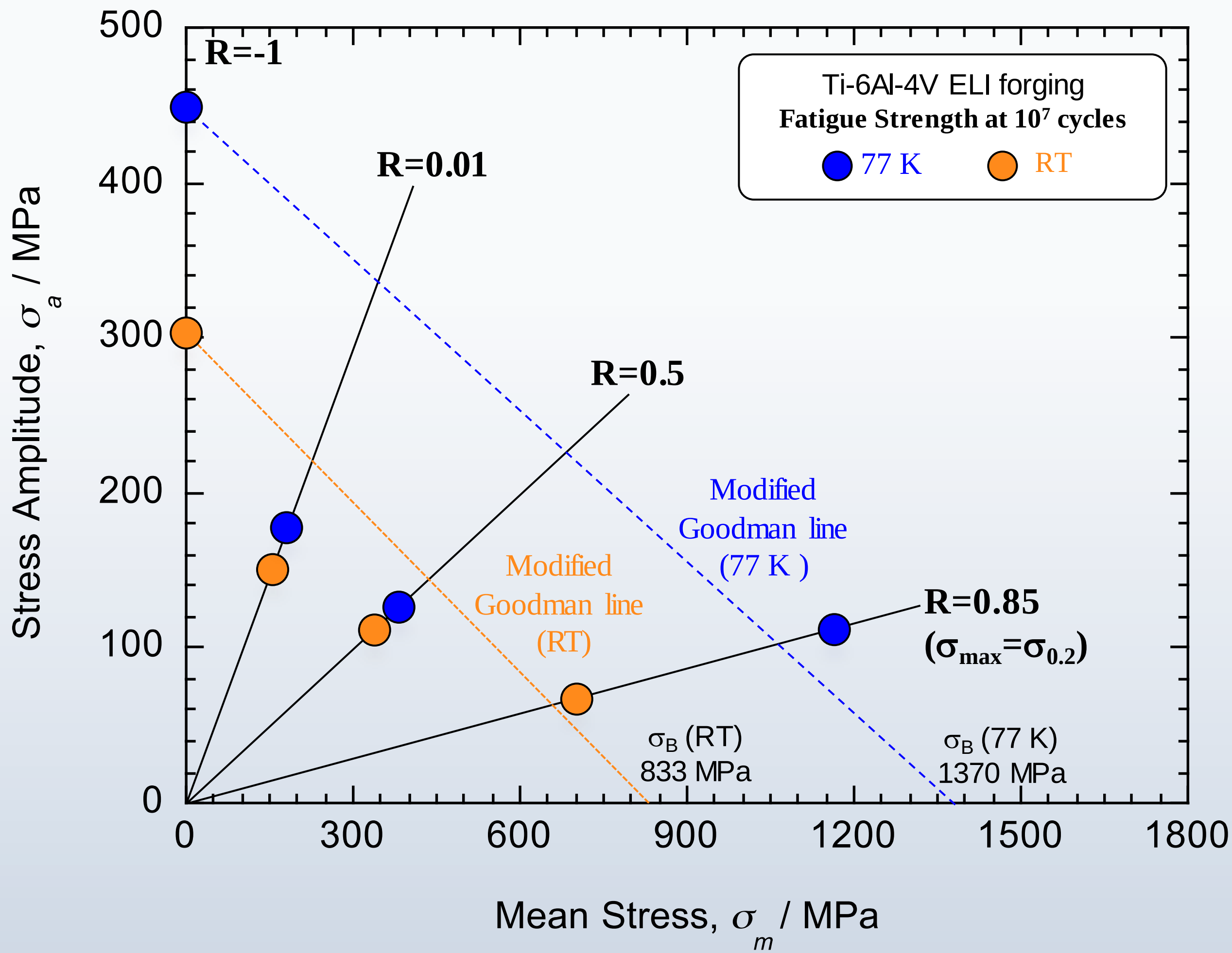
➢Modified Goodman diagram



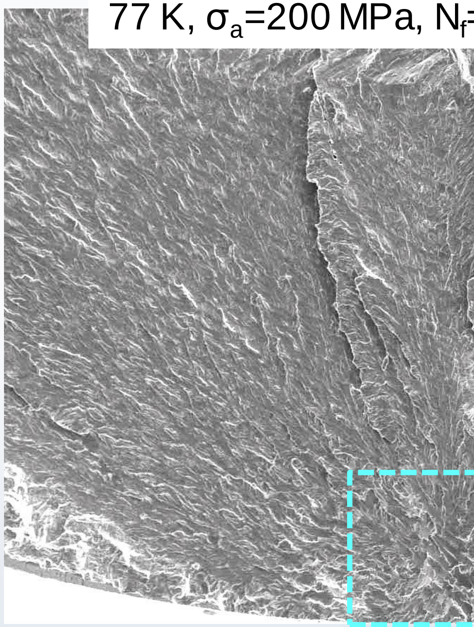
RT : Deviations of σa below the modified Goodman line in the R=0.01 and 0.5 tests.

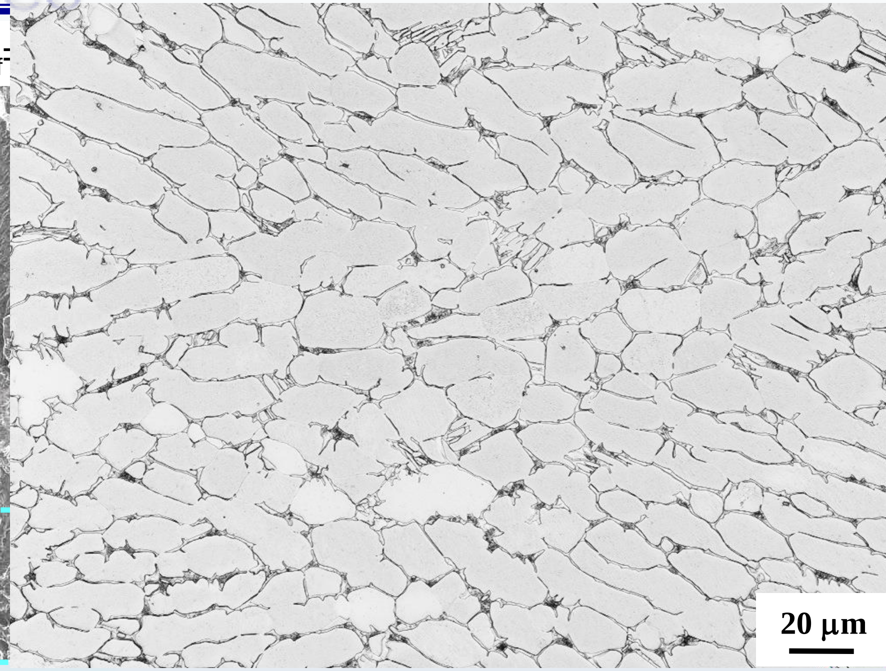
77K : Larger deviations of σa below the modified Goodman line were confirmed in the R=0.01 and 0.5 tests.

HCF strength of the present alloy forging exhibit an anomalous mean stress dependency at both temperatures and this dependency becomes remarkable at low temperature.

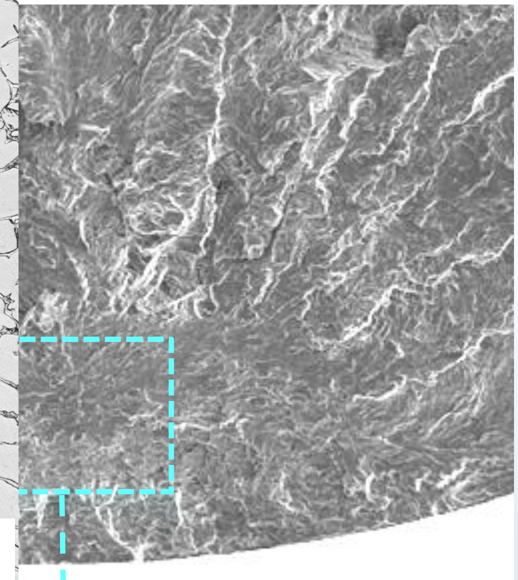
➢Fracture surface

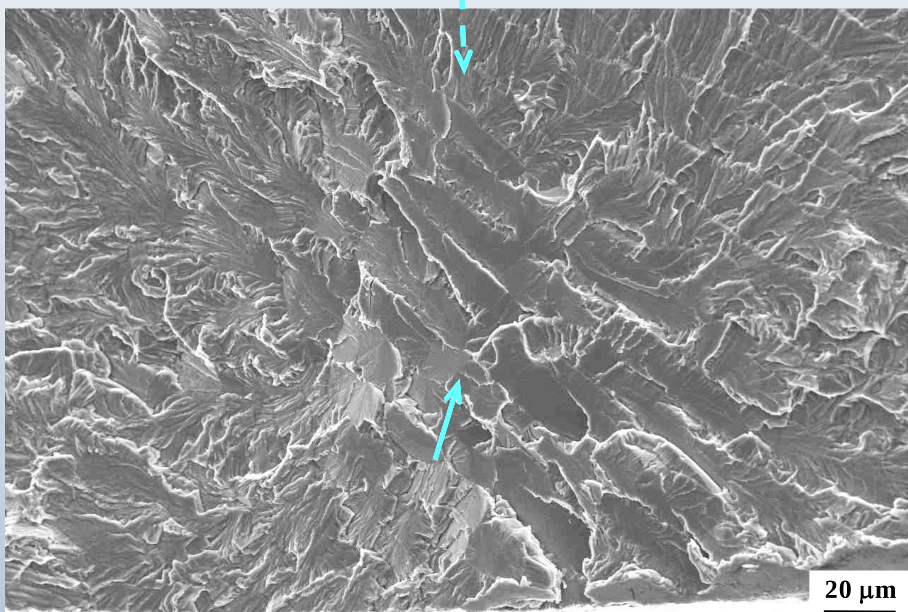
77 K, σ_a=200 MPa, N_f=

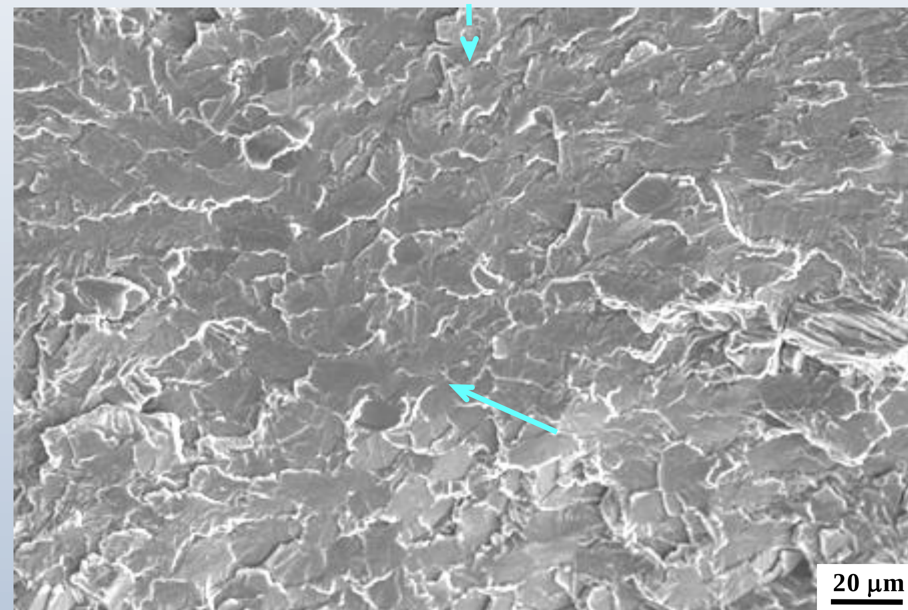




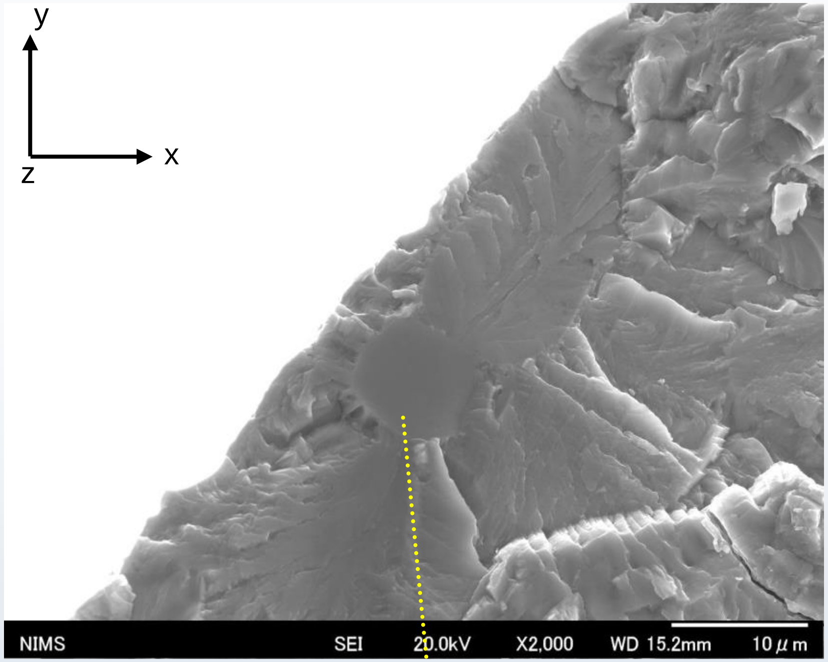
=4,768,804, σ_{max}=$\sigma_{0.2}$, R=0.8

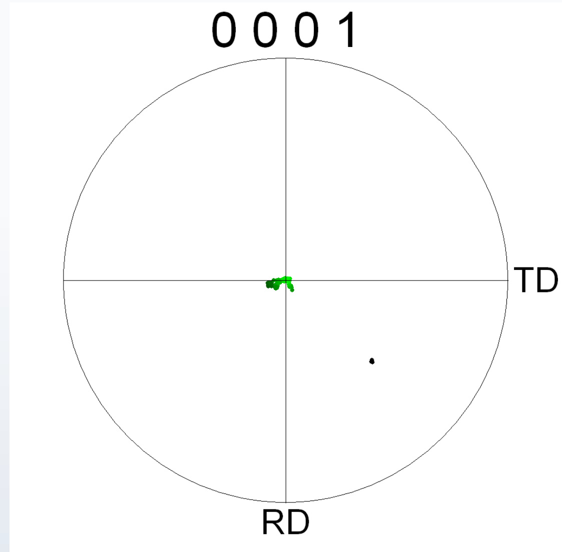




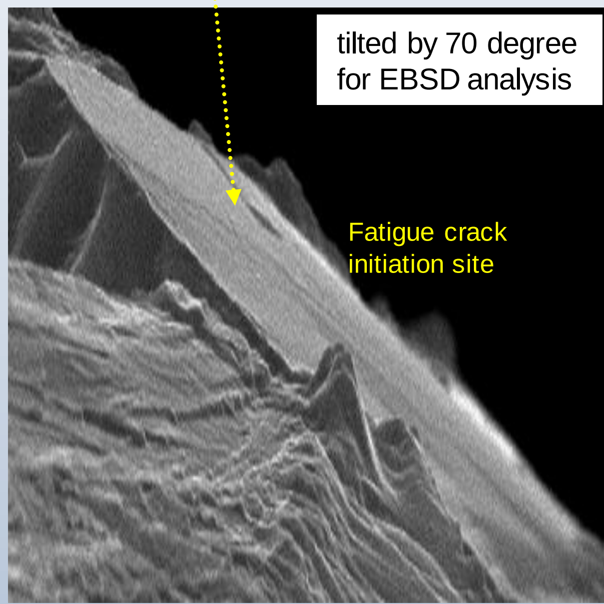


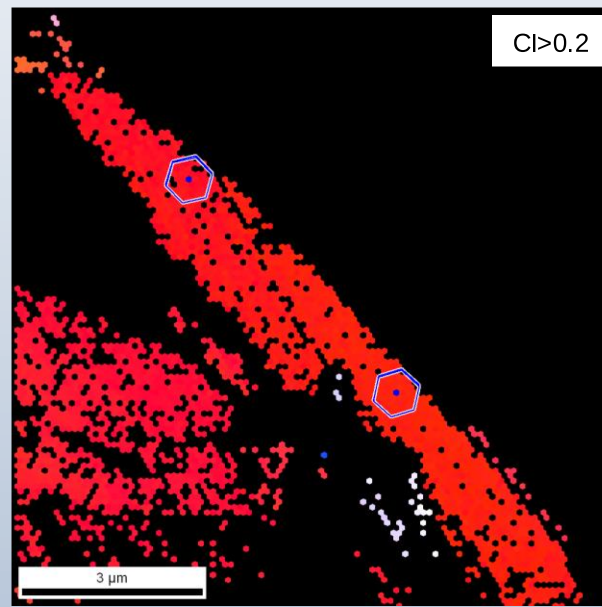
➢SEM-EBSD analysis -Specimen fatigue-tested at 20 K

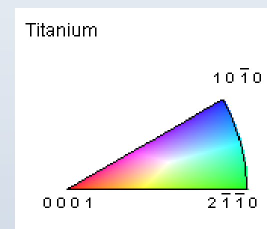




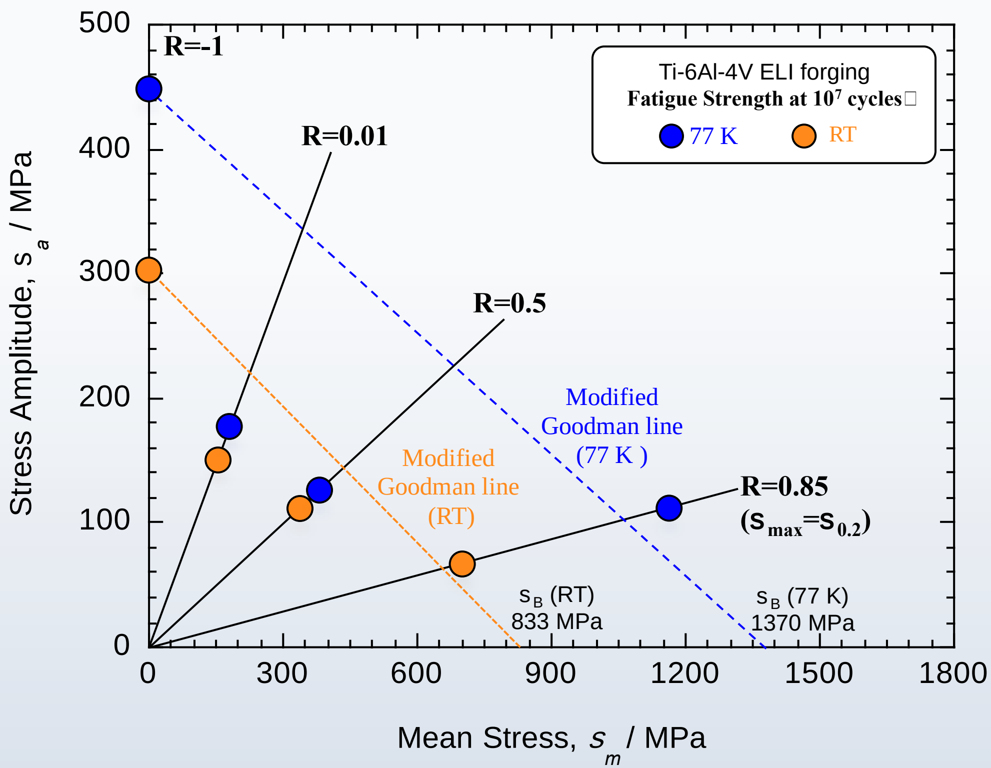
Facet is (0001) basal plane.







➢Summary



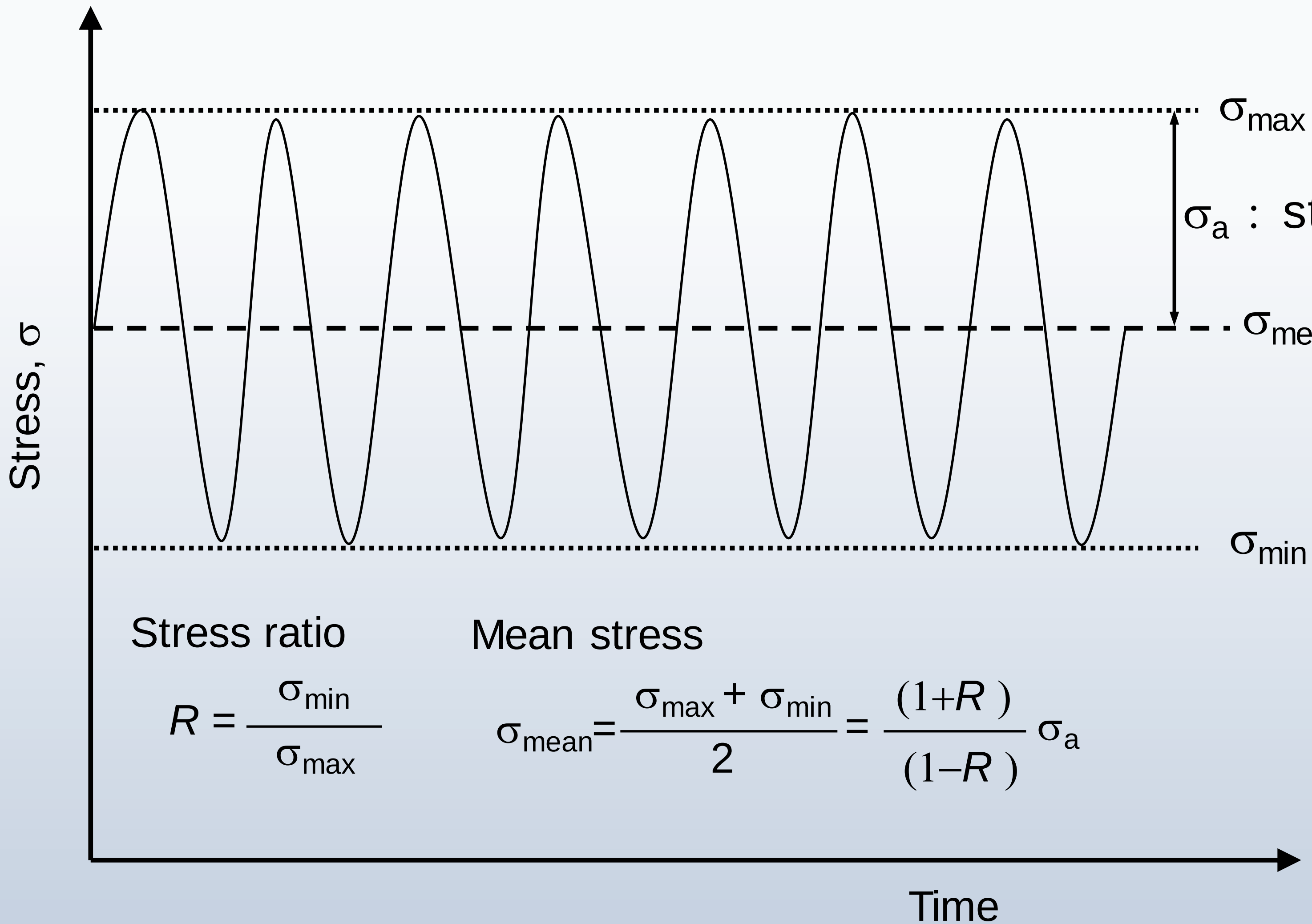
- HCF strength of Ti-6Al-4V ELI forging exhibit an anomalous mean stress dependency at 293 and 77 K.

- This dependency becomes remarkable at low temperature.

➢Future works

1. The mechanism of the anomalous mean stress dependency.
2. Endurance limit diagram instead of modified Goodman diagram.

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$



Stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

Mean stress

$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2} = \frac{(1+R)}{(1-R)}\sigma_a$$

➢Anomalous mean stress dependency in Ti-6Al-4V

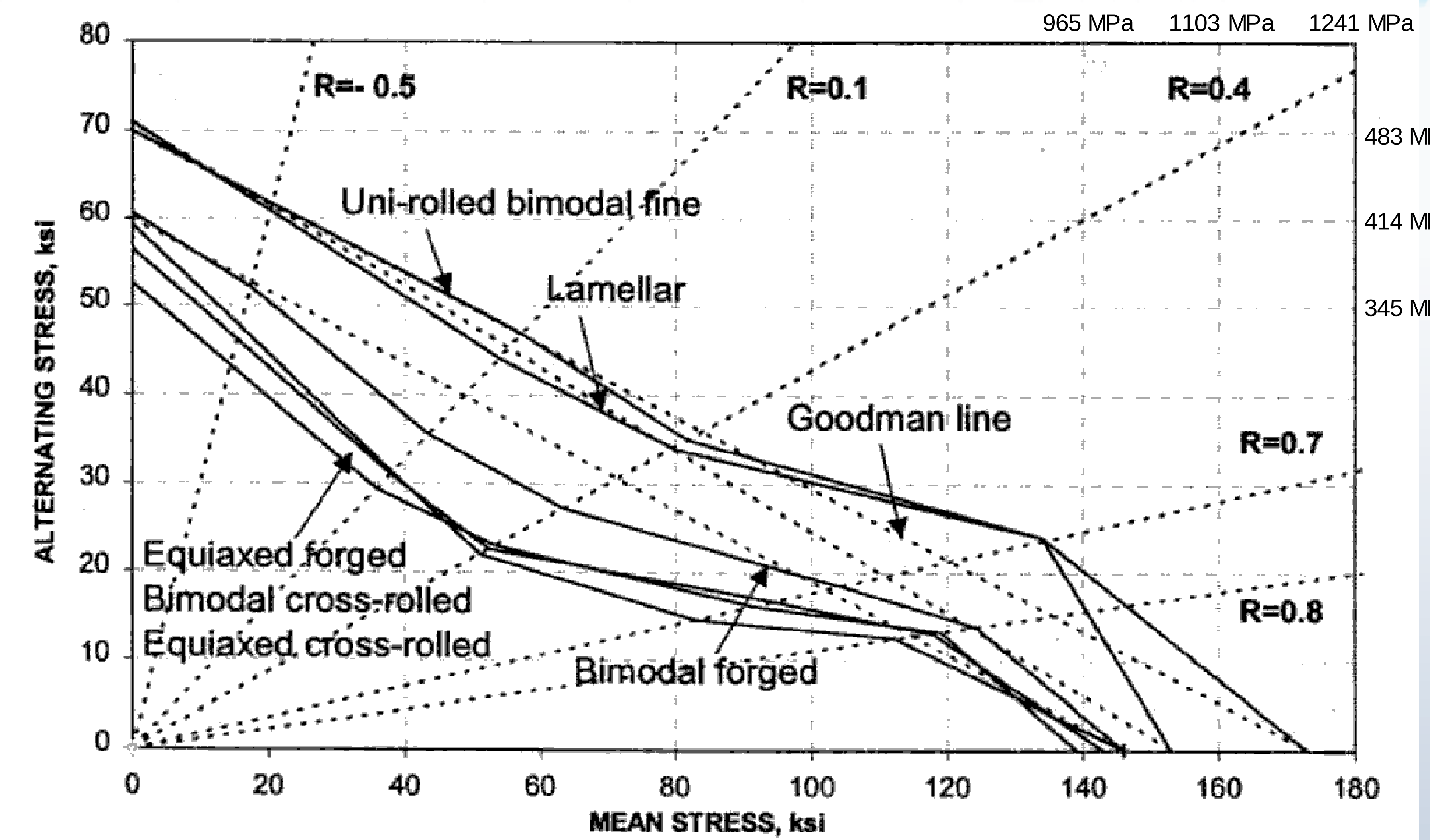
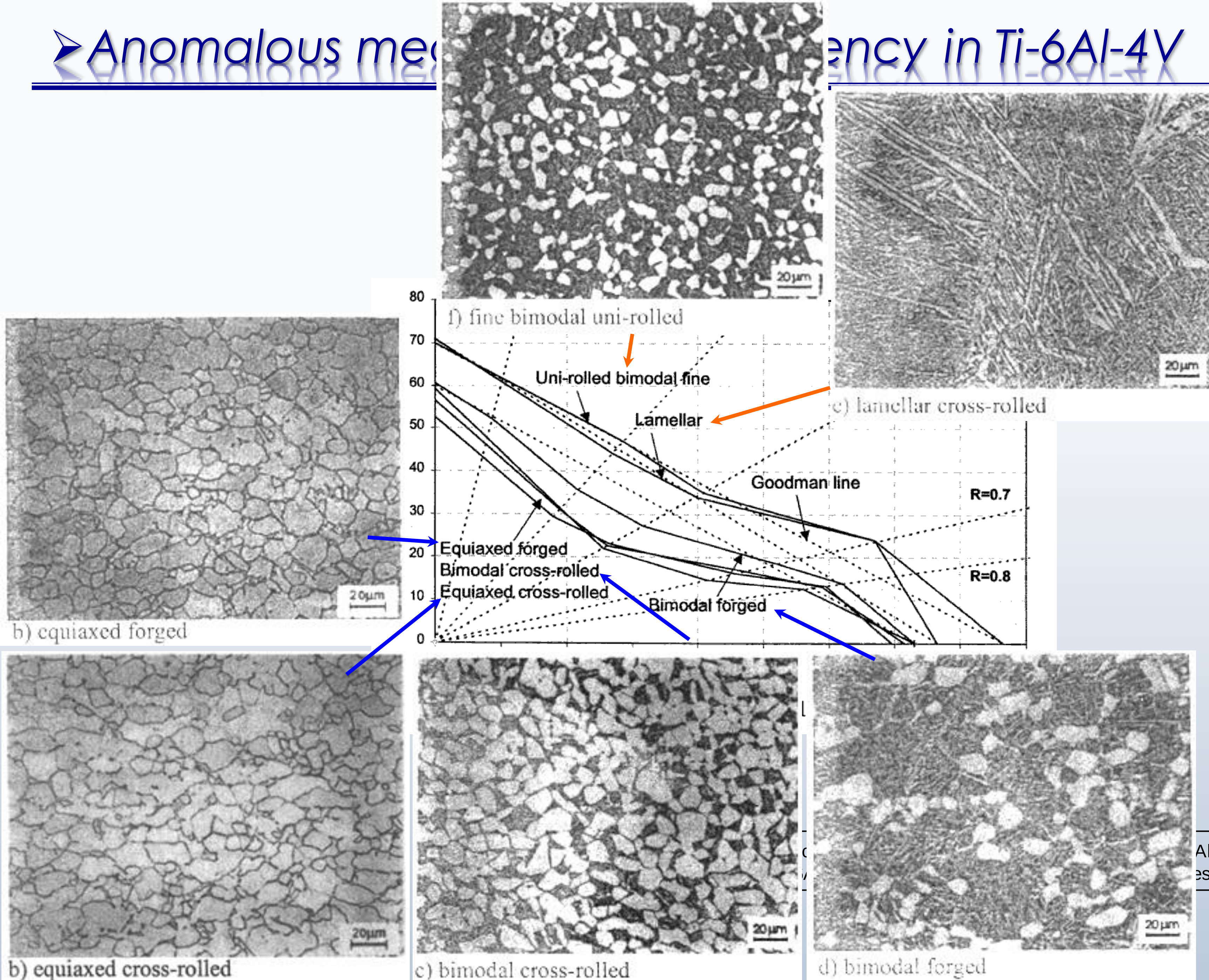


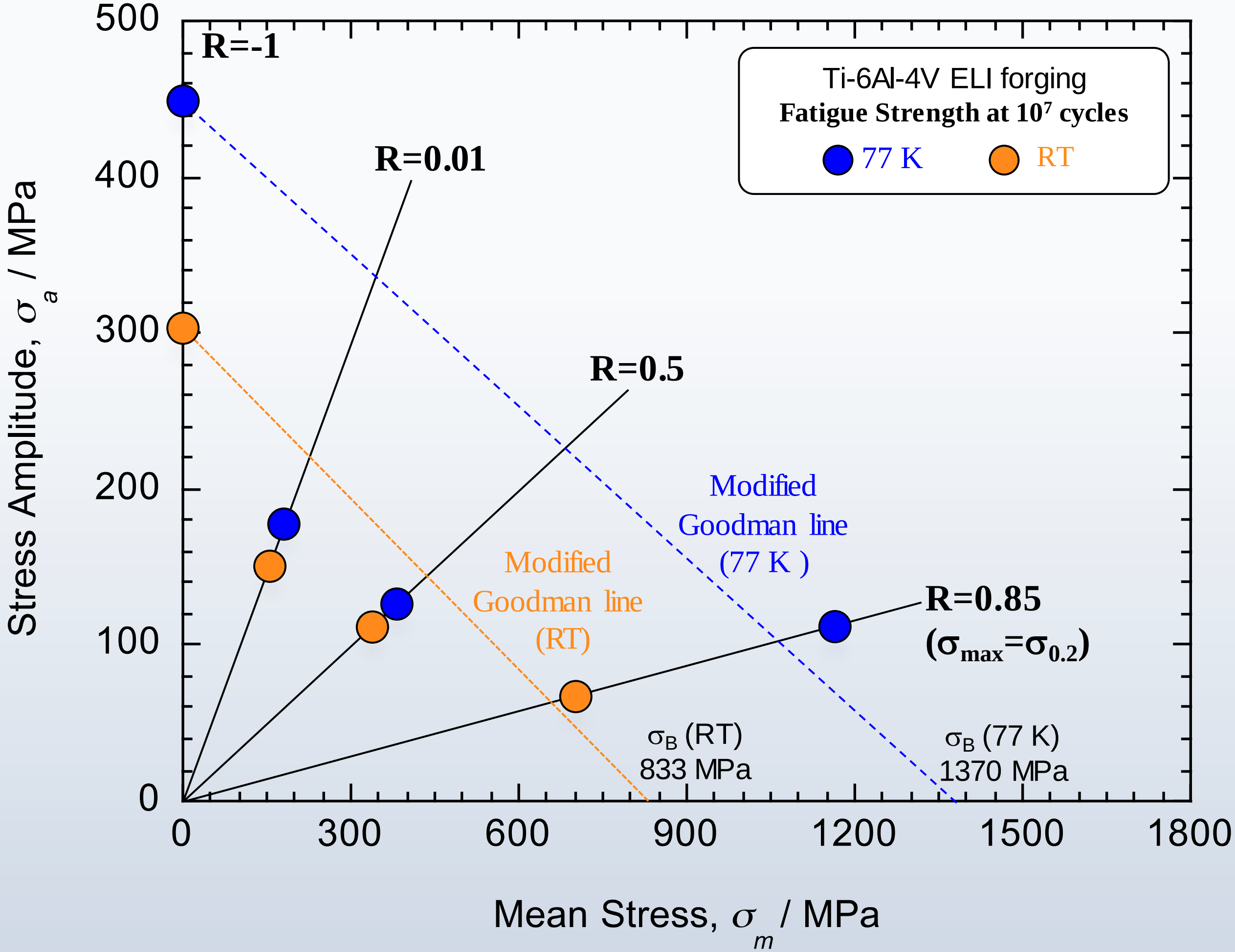
Fig.3. Constant life diagrams (10^7 cycles).

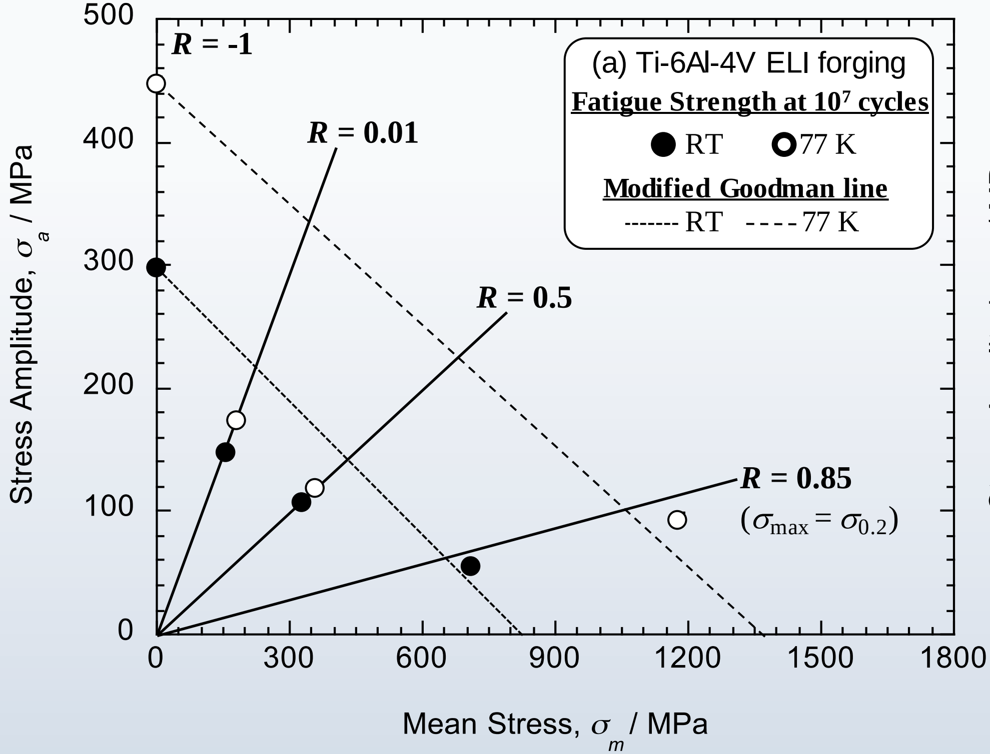
参考データ: Frederic S. Cohen et al., Fatigue Behavior of Titanium Alloys, (2007), p.39-46, Ti-6Al-4V Normal, bar or rod, RT, Fatigue Strength at 10^7 cycles

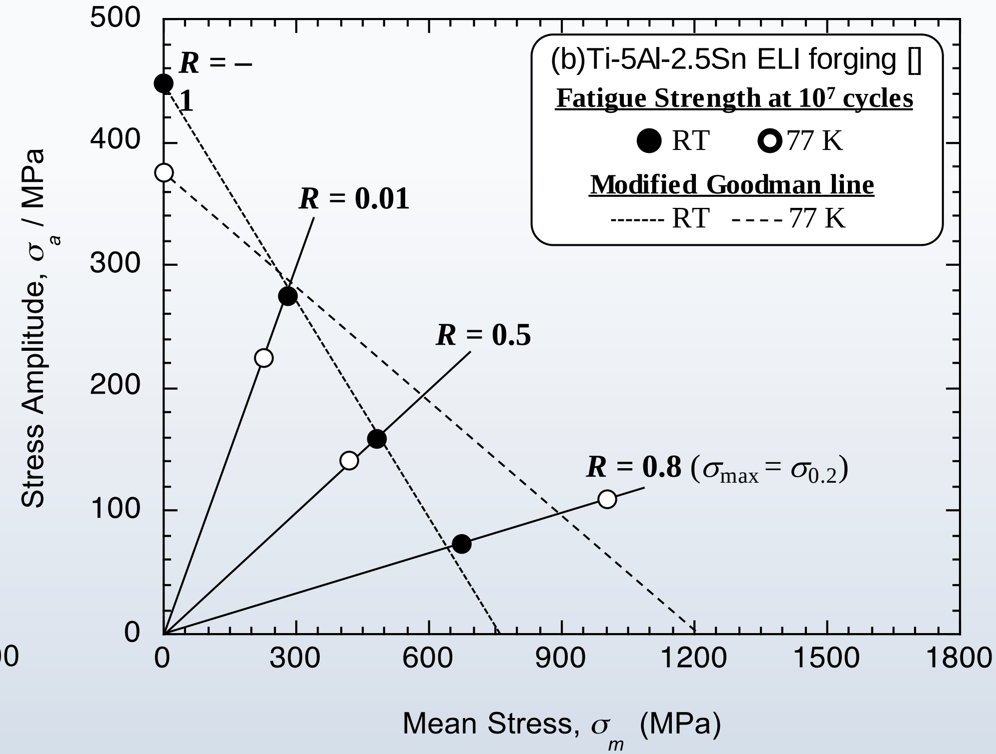
➢Anomalous me… …ency in Ti-6Al-4V



Alloys,
es


Ti-6Al-4V ELI forging
Fatigue Strength at 10^7 cycles
77 K
RT
R=-1
R=0.01
R=0.5
R=0.85
(σmax=σ0.2)
Modified Goodman line (77 K)
Modified Goodman line (RT)
σB (RT) 833 MPa
σB (77 K) 1370 MPa
Stress Amplitude, σa / MPa
Mean Stress, σm / MPa
0
100
200
300
400
500
0
300
600
900
1200
1500
1800


(a) Ti-6Al-4V ELI forging
Fatigue Strength at 10^7 cycles
RT
77 K
Modified Goodman line
------- RT ---- 77 K
R = -1
R = 0.01
R = 0.5
R = 0.85
(σmax = σ0.2)
Stress Amplitude, σa / MPa
Mean Stress, σm / MPa
0
100
200
300
400
500
0
300
600
900
1200
1500
1800


(b)Ti-5Al-2.5Sn ELI forging
Fatigue Strength at 10^7 cycles
RT
77 K
Modified Goodman line
------- RT ---- 77 K
R = –1
R = 0.01
R = 0.5
R = 0.8 (σmax = σ0.2)
Stress Amplitude, σa / MPa
Mean Stress, σm (MPa)
0
100
200
300
400
500
0
300
600
900
1200
1500
1800