132nd Annual TMS Meeting

Fatigue Behavior and Associated Effect of Residual Stresses in Deep Rolled and Laser Shock Peened Ti-6Al-4V

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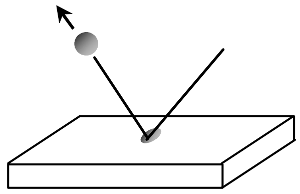
Problem Statement

Mechanical surface treatments, such as shot peening, are known to provide a marked benefit in enhancing the fatigue life of Ti-6Al-4V alloys

- Are deep rolling and laser shock peening similarly effective?
- Are the benefits of mechanical surface treatments on the fatigue behavior of Ti-6Al-4V retained at higher temperatures, as are commonly encountered under service conditions?

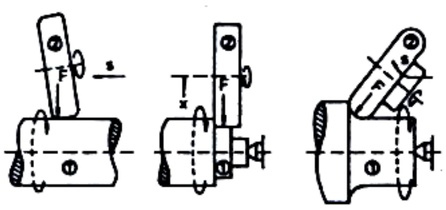
Aims and Motivation

- Ti-6Al-4V: Fatigue life enhancement by shot peening limited to service temperatures < 350°C ($T/T_m < 0.3$)



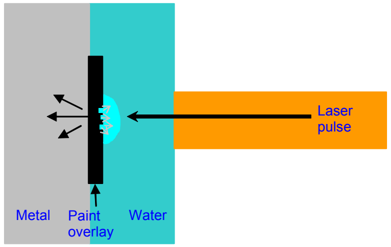
Shot Peening

- Practically no archival literature on the effect of mechanical surface treatments (e.g., deep rolling, laser shock peening) on *high temperature* fatigue



Deep Rolling

- Physical understanding of how surface treatments could affect fatigue at high temperature is essentially not documented



Laser Shock Peening

Approach

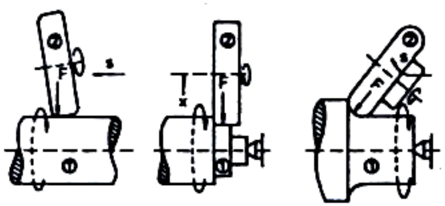
- Mechanical surface treatments
  - deep rolling
  - laser shock peening

- Fatigue characterization from 25°C upto 450°C (T/T_m ~ 0.4)
  - *S*/*N* behavior
  - cyclic deformation behavior

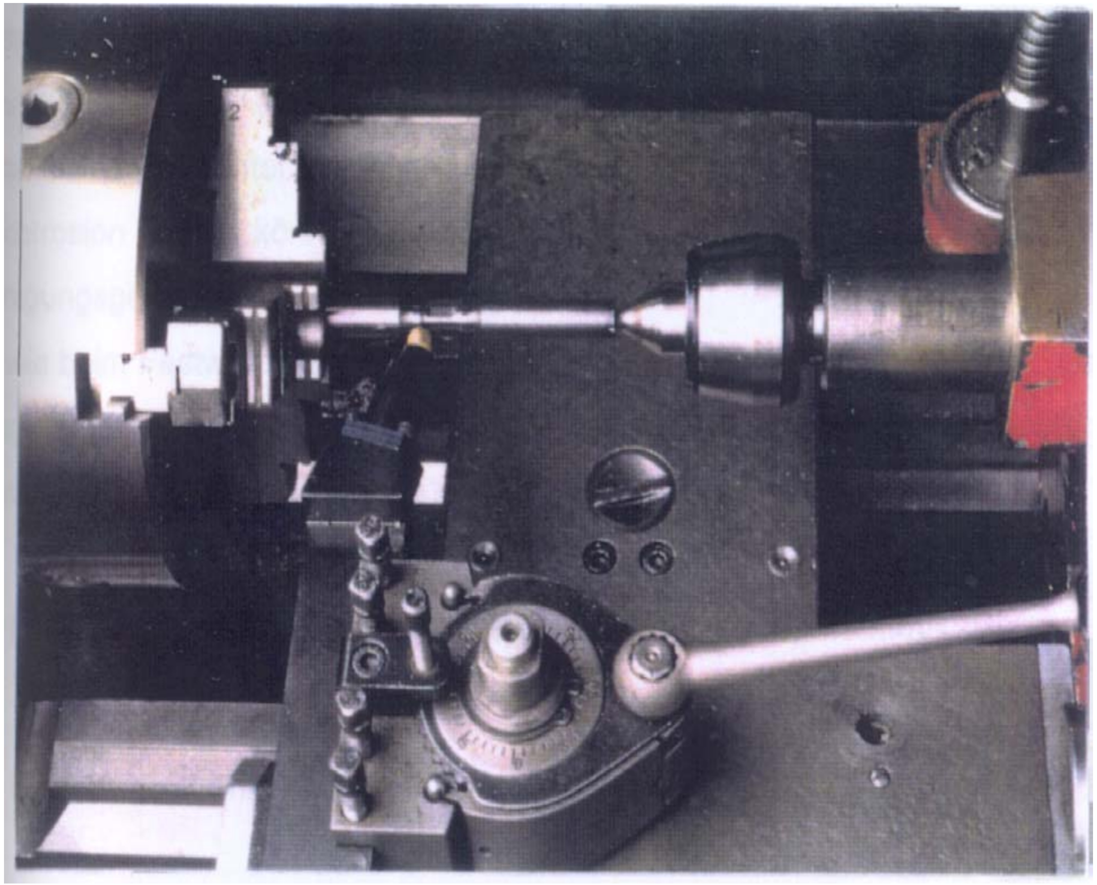
- Residual stress characterization

- TEM characterization of near-surface microstructure

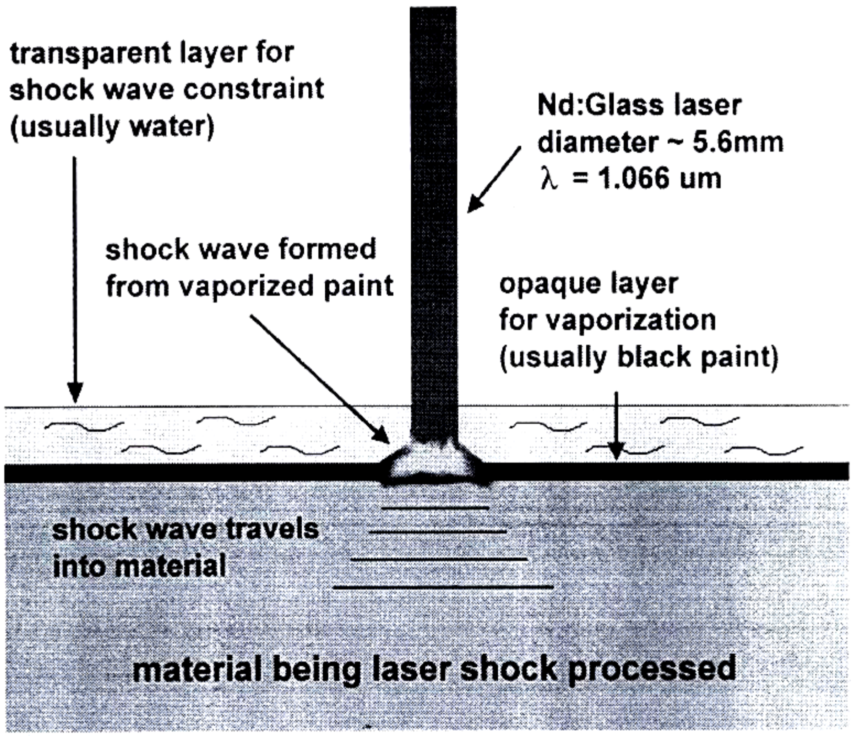
Deep Rolling Surface Treatment



- Like lathe machining with a hydrostatically-seated spherical rolling element
- 2-3 times deeper “case” than shot-peening
- Generates much smoother surfaces than shot-peening and laser shock peening
- Inexpensive compared to other techniques
- Limited to mainly symmetrically rotated geometries

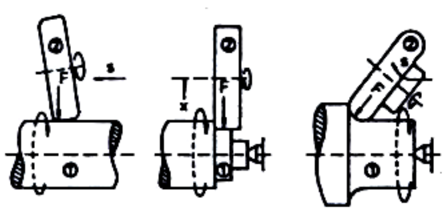


Laser Shock Peening Treatment



- Uses pulsed laser beam to generate shock waves
- Uses a sacrificial layer and transparent constraining layer on component
- Deeper "case" than shot-peening
- Produces much smoother surfaces than shot-peening
- Remains expensive compared to other techniques
- Not limited to symmetrically rotated geometries

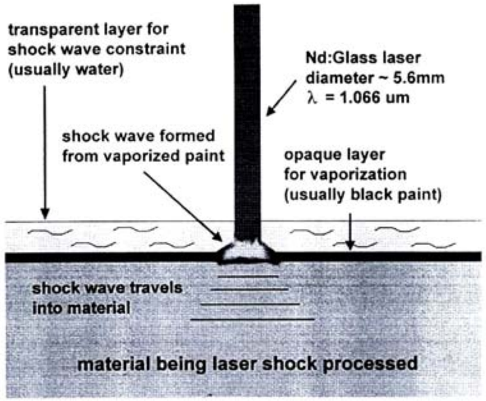
Mechanical Surface Treatment Methods



Shot Peening

Deep Rolling (DR)

Laser Shock Peening (LSP)



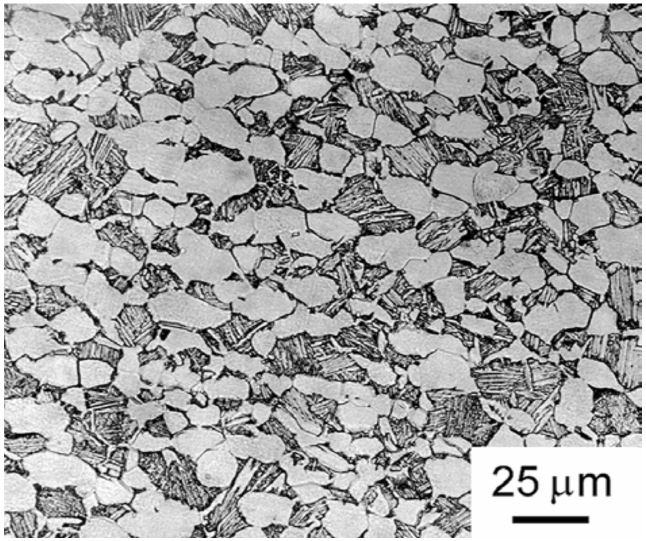
Main advantages of DR and LSP compared to shot peening :

- deeper "cases"
- smoother surfaces (particularly DR)

Main disadvantages:

- lower surface work hardening
- certain geometrical restrictions (DR)

Material Investigated: Ti-6Al-4V



Bimodal (STOA) structure

64% primary α

α grain size ~ 20 μm

α lath spacing ~ 1-2 μm

Alloy Composition (wt%)

Ti	Al	V	Fe	O	N	H
Bal.	6.29	4.17	0.19	0.19	0.013	0.0041

Uniaxial Tensile Properties

Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Reduction in Area (%)	Fracture Toughness K_{Ic} (MPa√m)
930	978	45	64

Experimental Procedures and Parameters

Deep Rolling (Hydrostatic Device):

- Rolling pressure: 150 bar (rolling force approx. 0.5 kN)
- Rolling element: sphere ∅ 6.6 mm
- "Coverage": 500 %

Laser Shock Peening:

- 2.6x2.6 mm laser beams, 18 ns pulses
- Intensity: power density 7 GW/cm^2
- "Coverage": 200 %

Fatigue Experiments:

- Push-pull, *R*-ratio ($\sigma_{min}/\sigma_{max}$): –1, Test frequency: 5 Hz
- Air Furnace, heating time: 45 min., Test temperatures: 25°C, 250°C and 450°C

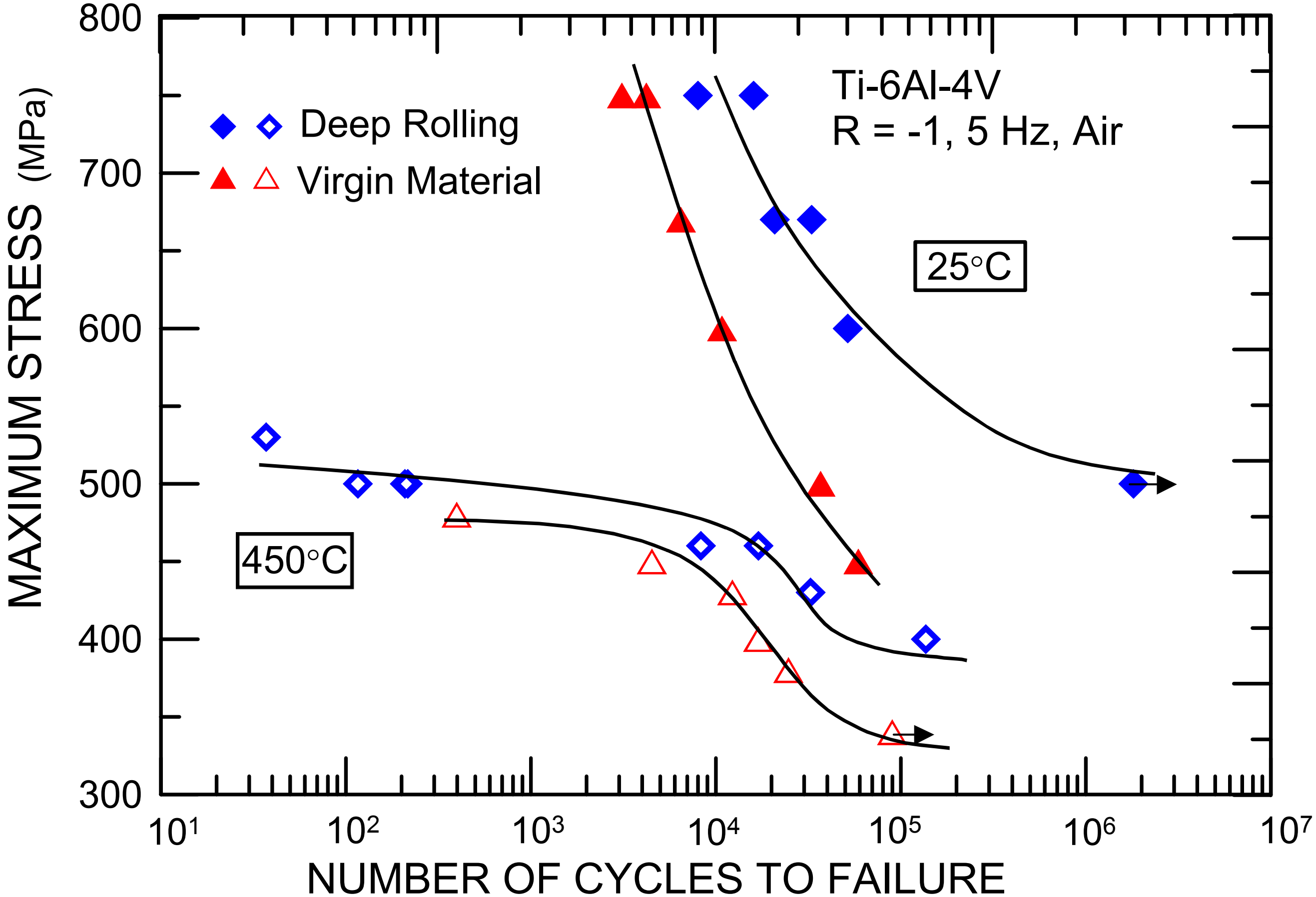
Residual Stress Measurements:

- Cr K_α-radiation at {201}-planes of the hexagonal α-phase
- $Sin^2\psi$-method used (elastic constant $\frac{1}{2} s_2 = (1 + \nu)/E = 12.09 \times 10^{-6}$ mm^2/N)
- No stress correction was carried out

Transmission Electron Microscopy:

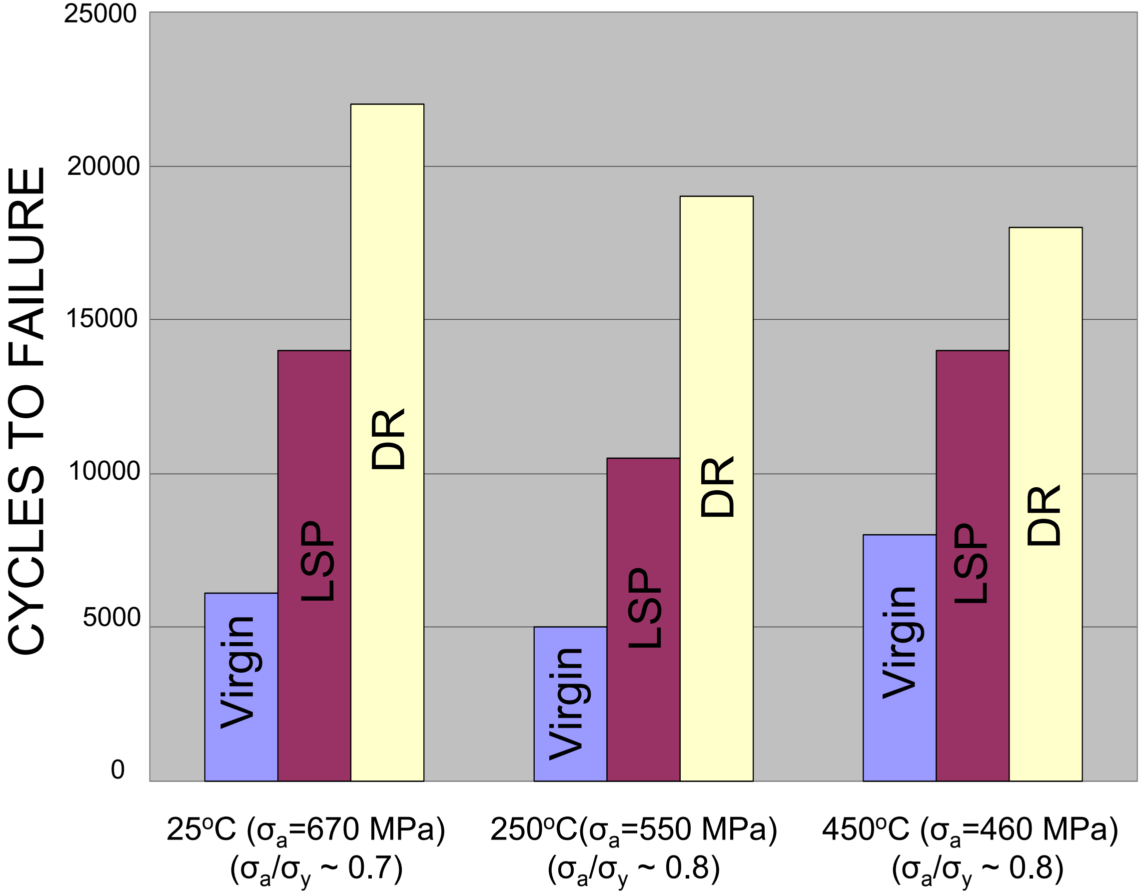
- JEOL 200 kV TEM, JEOL 3010 300 kV TEM for *in situ* studies
- Cross-sectional preparation of direct surface region

Stress-Life (*S*/*N*) Data



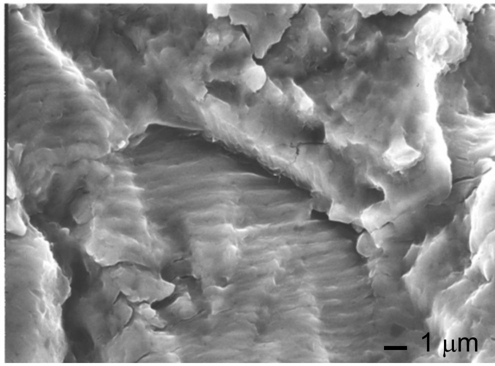
- Deep rolling markedly increases fatigue lifetimes at 25°C
- Main effect seen in the HCF regime
- Effect is reduced, but still significant, at 450°C (T/T_m~0.4)

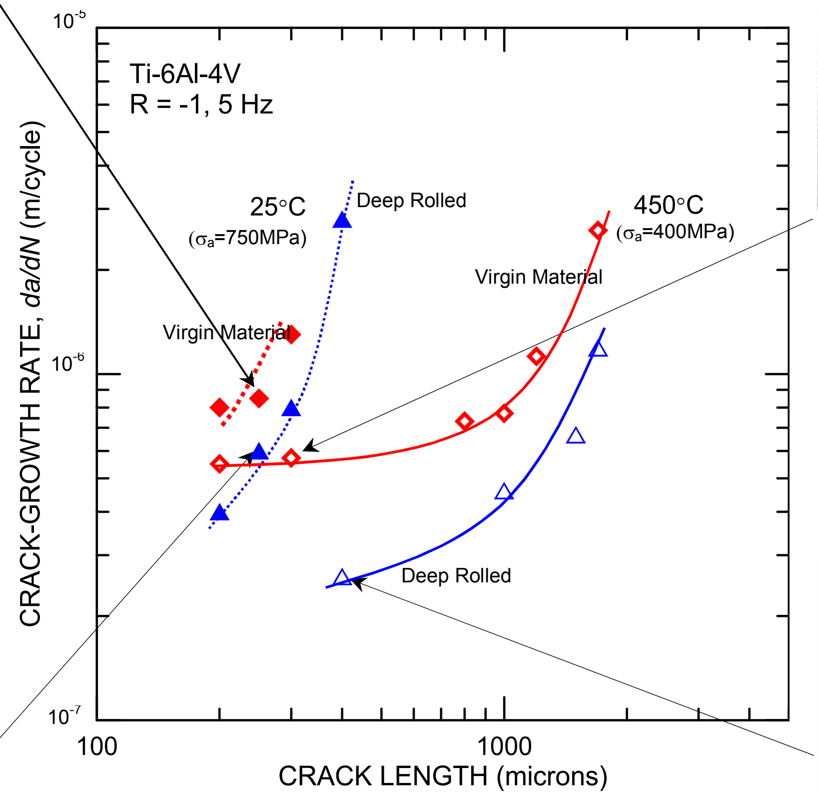
Mean Fatigue Lifetime Comparisons

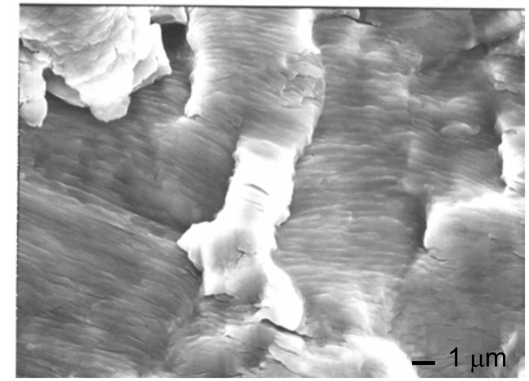


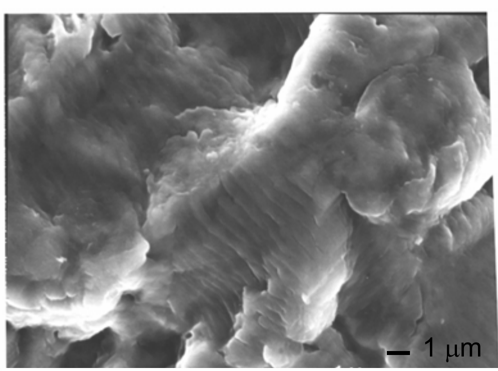
- Beneficial effect of mechanical surface treatments also seen in the LCF regime (σ_a/σ_y ~ 0.7-0.8)
- Marked lifetime improvement seen with laser shock peening and deep rolling at both ambient and elevated temperature
- Effect is more significant after deep rolling than after laser shock peening

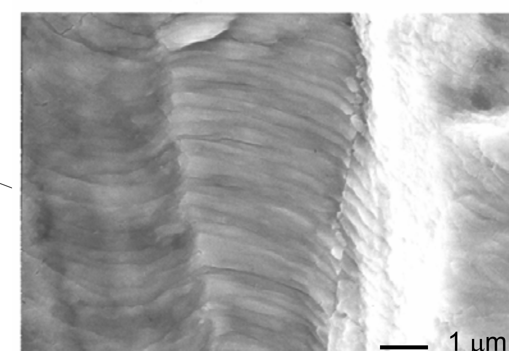
Crack-Growth Rates from Striation Spacings











- Deep rolling reduces local crack-growth rates at 25° and 450°C

Summary of Fatigue Data

- Deep rolling and Laser shock peening appear to be a very effective mechanical surface treatments for enhancing fatigue properties, in the form of:

    - longer lifetimes

    - lower crack-propagation rates

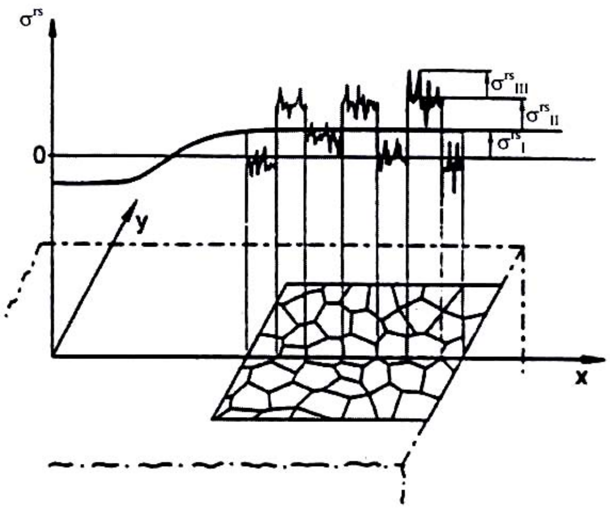
- Beneficial effect is seen at both ambient and elevated (up to $T/T_m \sim 0.4$) temperatures

- Why?

Summary of Fatigue Data

- Beneficial effect of mechanical surface treatment on fatigue properties can be attributed to:
    - residual compressive stresses
    - strain-hardened surface layers
    - near-surface microstructure
- However, are these effects stable at high temperatures?

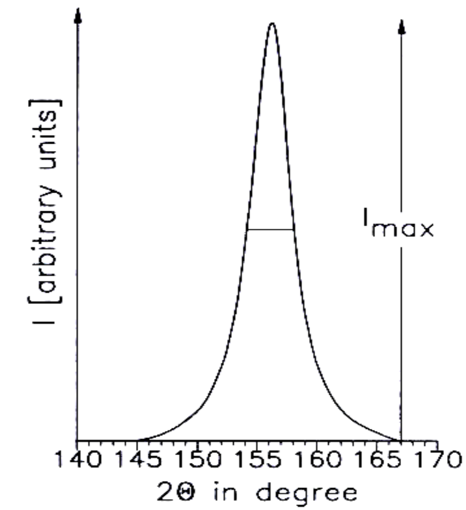
Macro- and Micro- Residual Stresses



σ_I : X-ray line shifts

σ_{II} : X-ray line shifts/broadening

σ_{III} : X-ray line broadening

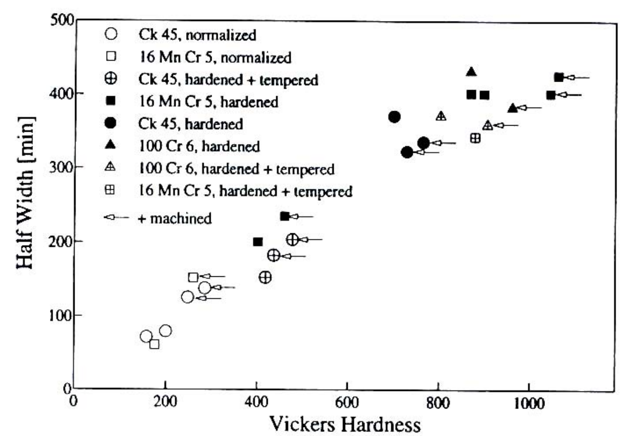


Definition of "Half-Width" (FWHM)

Macro-residual stresses: σ_I (first order)
Averaging over several grains (*e.g.*, by thermomechanical processing)

Micro-residual stresses: σ_{II} (second order)
Averaging within one grain (*e.g.*, by crystal anisotropy)

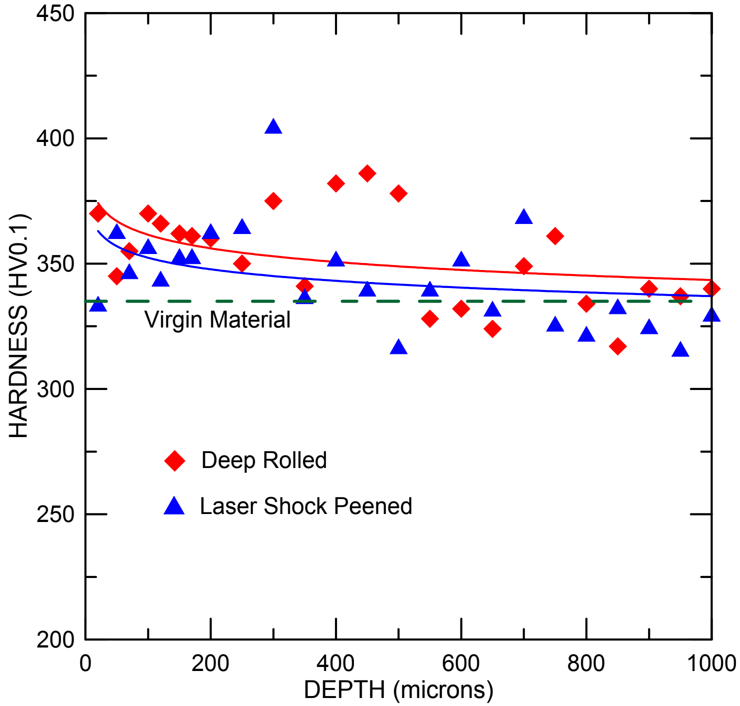
Micro-residual stresses: σ_{III} (third order)
Inhomogeneous within one grain
(*e.g.*, by dislocations, *i.e.*, work hardening)

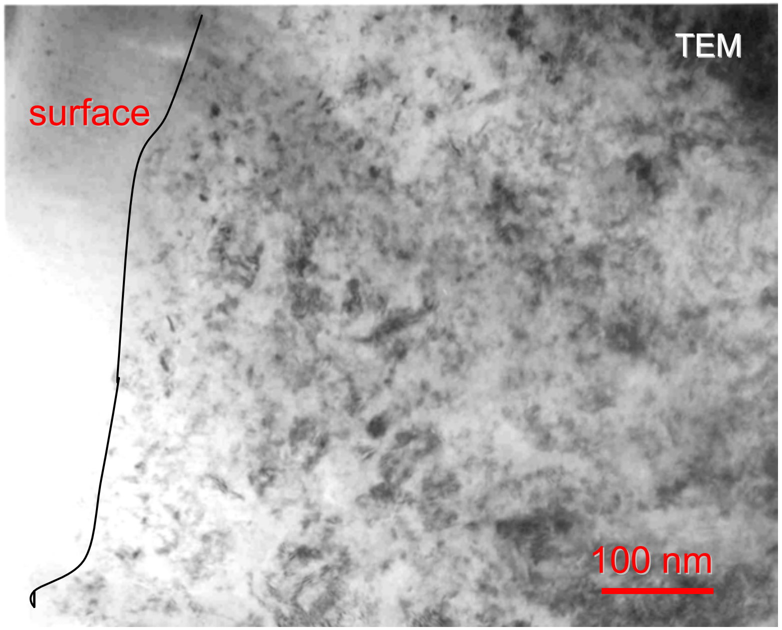


FWHM characterizes work hardening

Characterization of Near-Surface Properties

prior to fatigue cycling



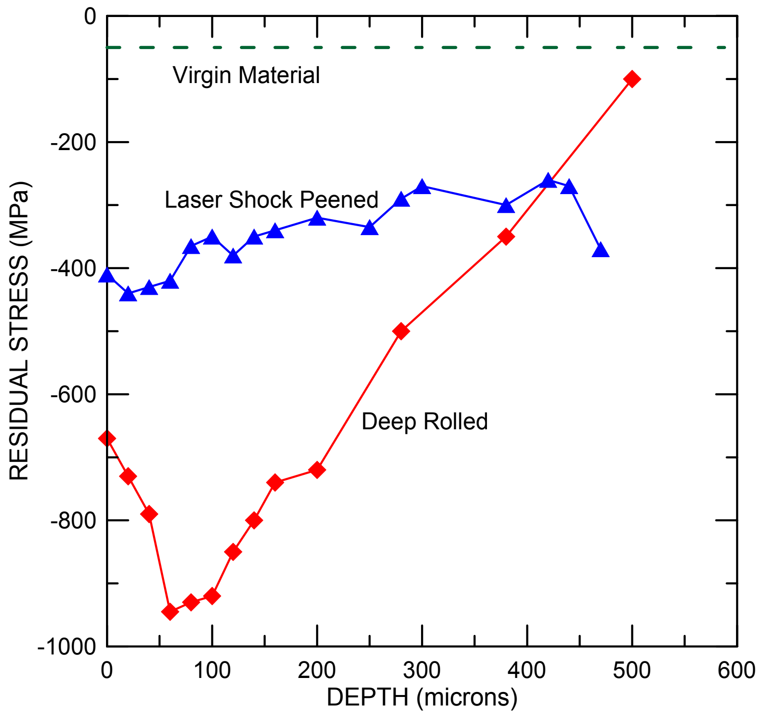


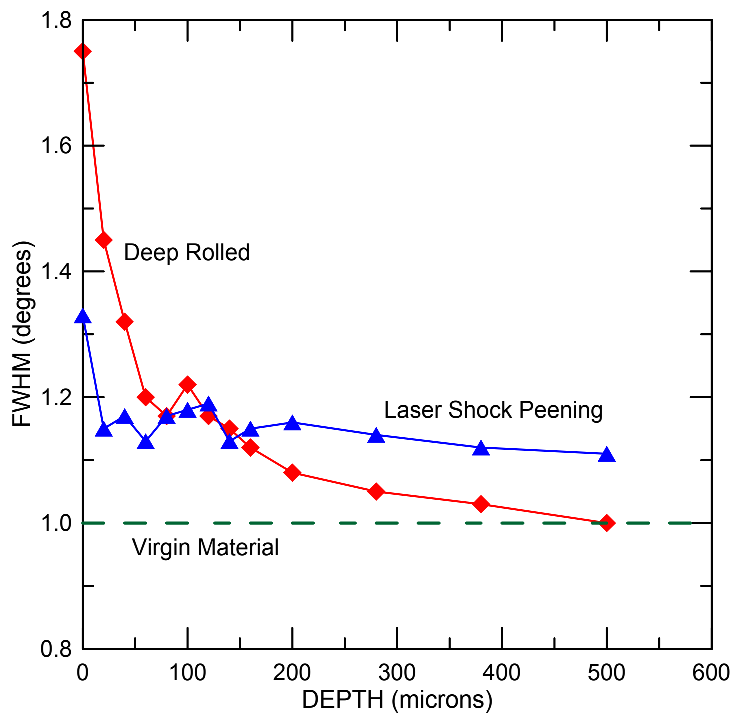
Dislocation tangles and nano-scale sub grains after DR

- Near-surface layers following mechanical surface treatment show:
  - work-hardened material to a depth of ~500 to 1000 μm
  - significantly higher dislocation density (~10^{11} /cm^2)

Characterization of Near-Surface Properties

prior to fatigue cycling

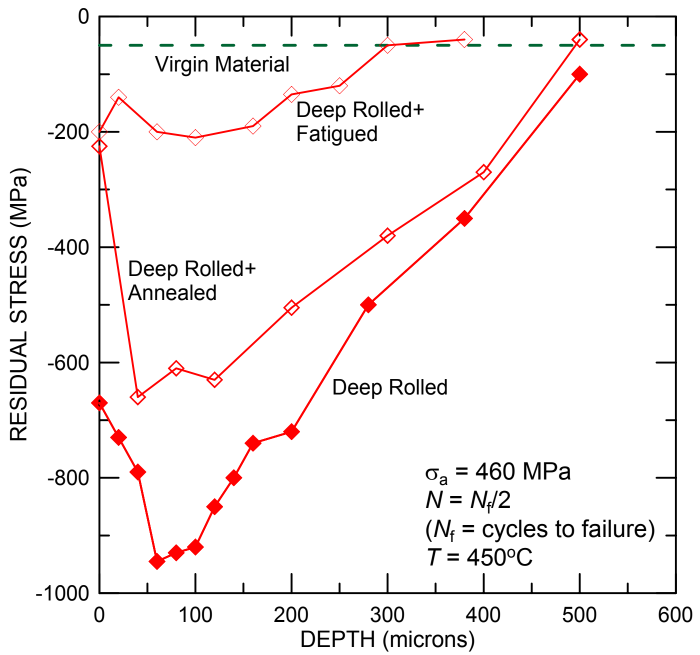


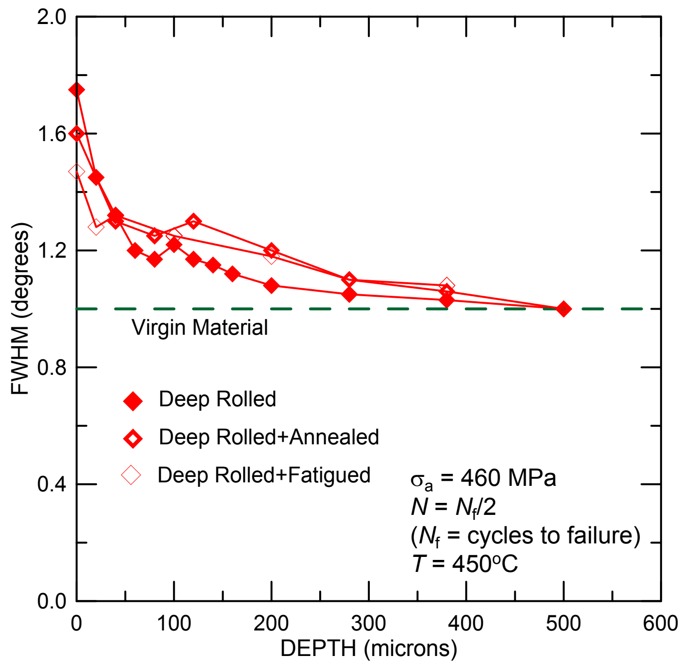


- Deep rolling leads to:
  - higher (macro) residual stresses than LSP
  - higher surface work hardening
  - but a slightly shallower case (~500 μm)

Stability of Deep Rolled Surface Properties

after high-temperature (450˚C) fatigue cycling

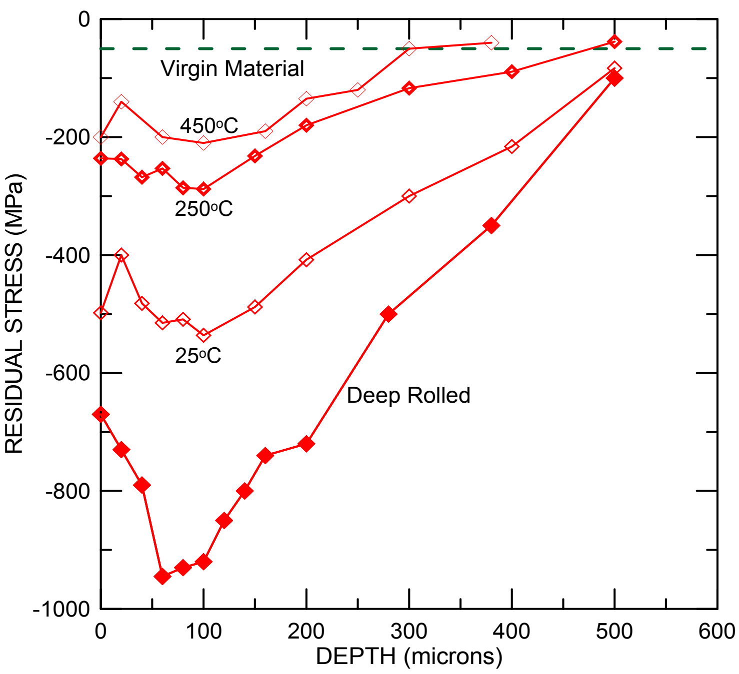


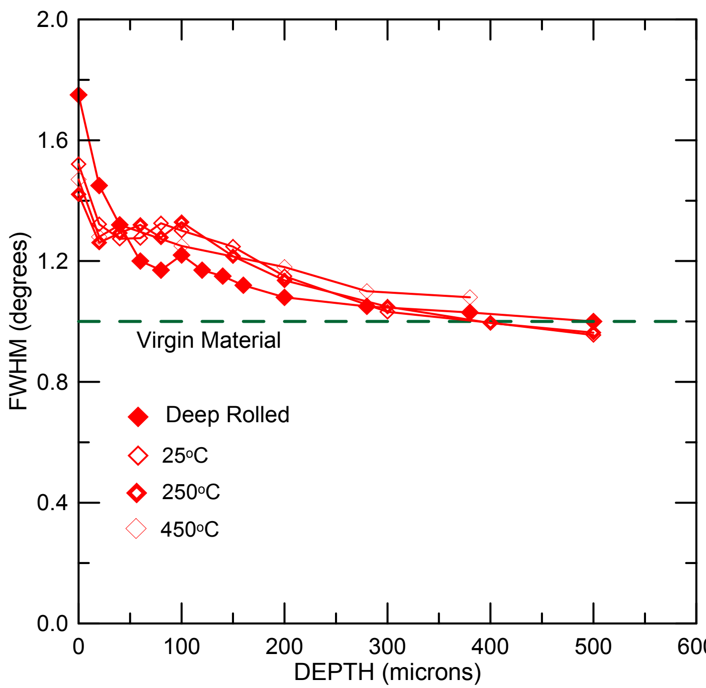


- Thermal exposure alone leads to residual stress relaxation at the surface
- High-temperature fatigue cycling leads to almost complete residual stress relaxation throughout the “case”
- Work hardened surface layer is much more stable at high temperatures and under fatigue cycling than residual stresses

Stability of Deep Rolled Surface Properties

after high-temperature (250˚C) fatigue cycling

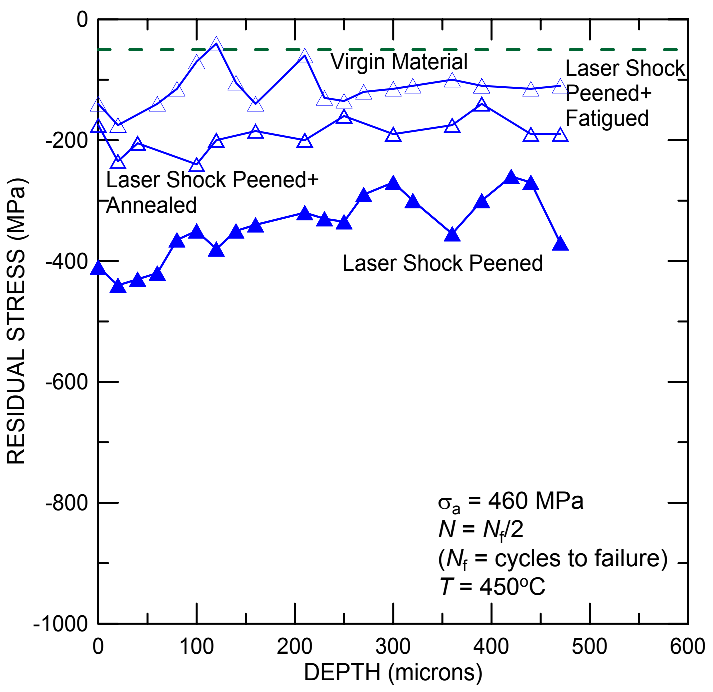


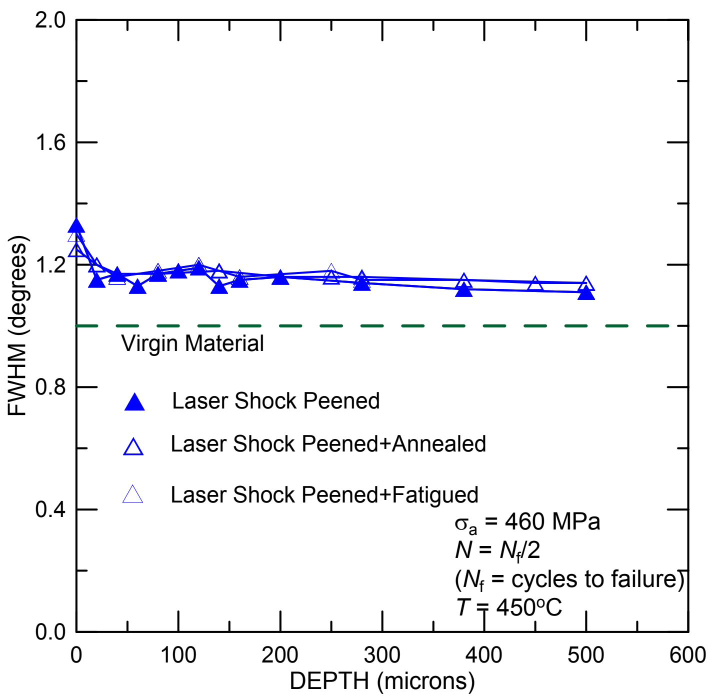


- Residual stress relaxation observed at 250˚C, similar to observations at 450˚C, but of lower magnitude
- Work hardened surface layer remains stable after high temperature fatigue cycling

Stability of LSP Surface Properties

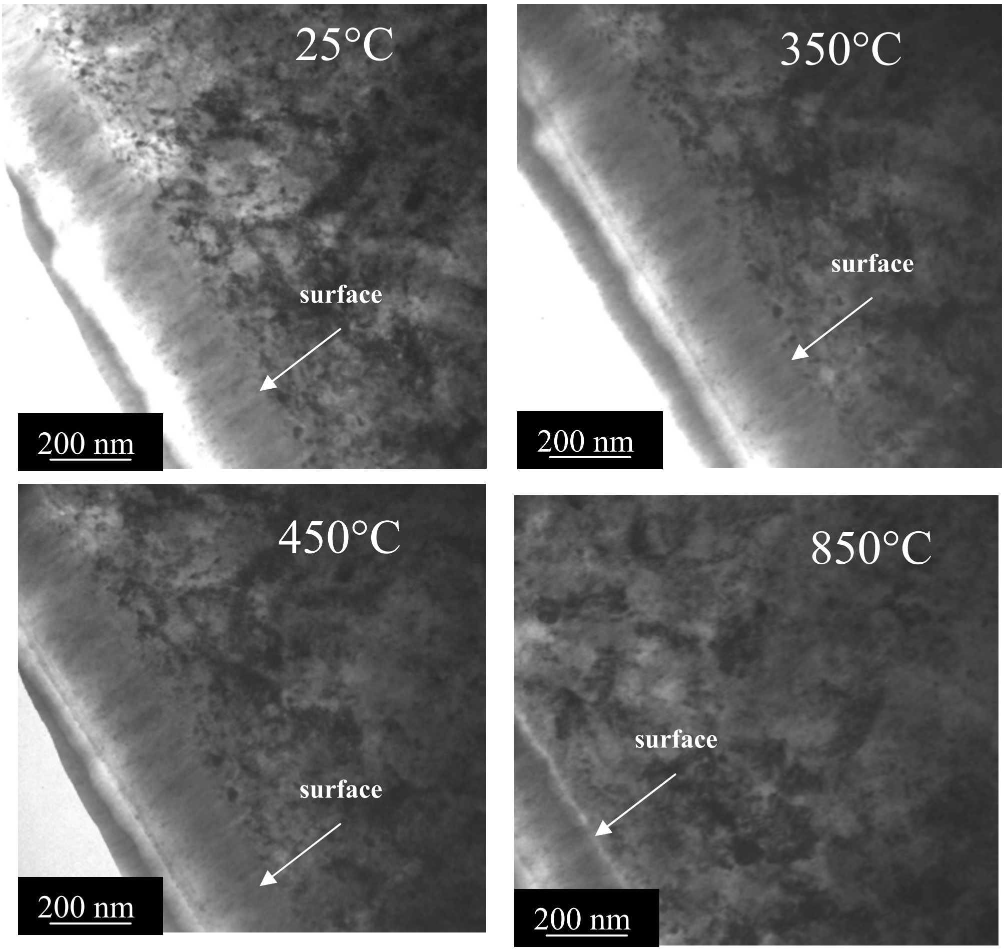
after high-temperature (450˚C) fatigue cycling





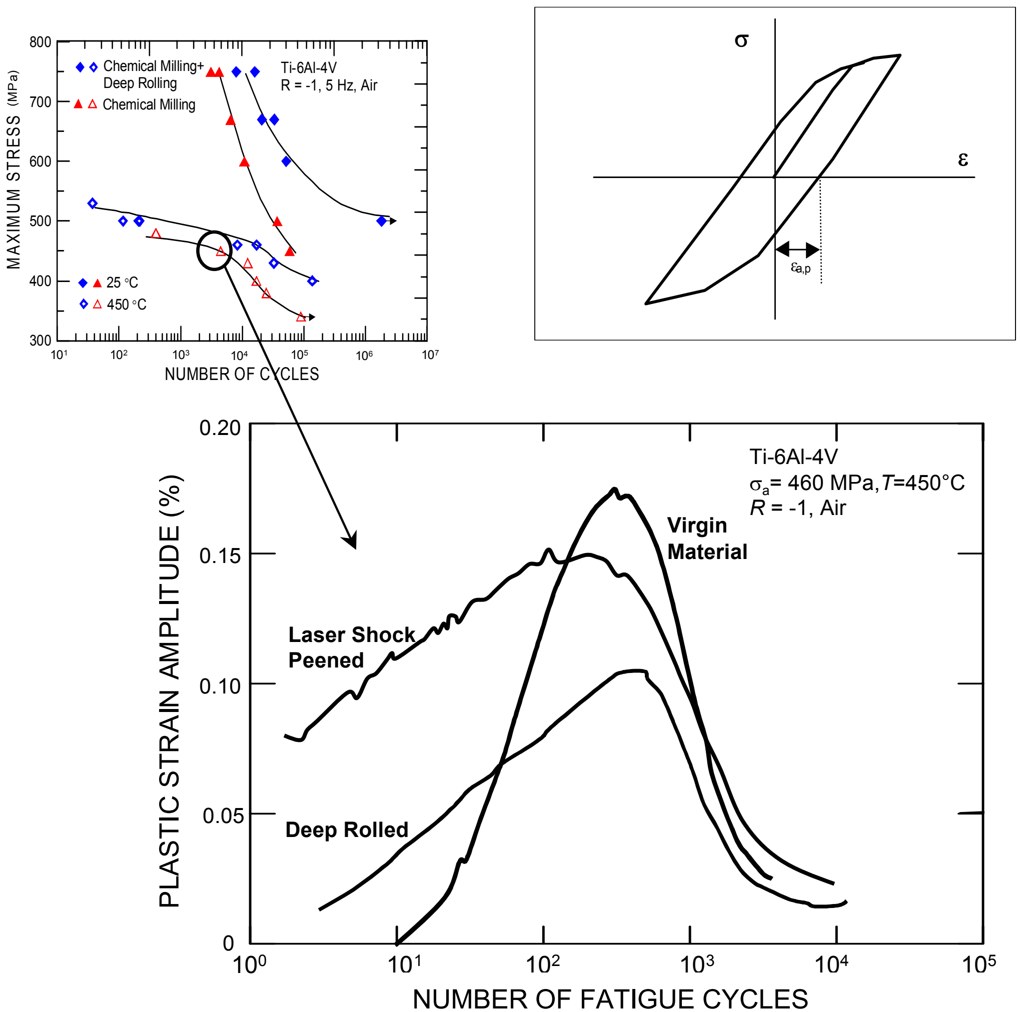
- Thermal exposure alone leads to residual stress relaxation throughout the “case”
- High-temperature fatigue cycling also leads to stress relaxation throughout the “case”
- Thermomechanically-induced stress relaxation similar to that for deep rolled material
- Work hardened surface layer is very stable to high temperatures and cycling

In Situ Thermal Exposure in TEM



- Near-surface “nano-scale” microstructure after deep rolling
- Microstructure perfectly stable at 450˚C and even up to 850˚C
- Holding times of 5-20 minutes at elevated temperatures do not affect the microstructure
- The nanoscopic small grain size as well as the high dislocation densities act as obstacles to stable dislocation slip (and thus crack initiation)

Cyclic Deformation Behavior (450^{o}C)



- Deep rolling reduces the cyclic plasticity (plastic strain amplitude, $\varepsilon_{a,p}$) at 450^{o}C
- Similar behavior also seen at 250^{o}C, 350^{o}C and 550^{o}C
- Reduced cyclic plasticity reflected in improved fatigue lifetimes

Conclusions

- Laser shock peening and particularly deep rolling can enhance the HCF- and LCF-fatigue strength of Ti-6Al-4V from ambient to high temperatures, *i.e.,* up to 450°C (T/T_m ~ 0.4)
- Although almost complete relaxation of residual stresses occurs at 450°C, there is still a significant benefit for fatigue resistance from mechanical surface treatment
- This benefit is primarily due to the formation of a stable, near-surface work-hardened layer with a nano-scale microstructure
- The increased near-surface dislocation density acts to decrease the plastic strain amplitude, and hence delays crack initiation. Moreover, it reduces crack-propagation rates at 450°C, as compared to the untreated material. As a result, the *S*/*N* fatigue life is improved.

Acknowledgements

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