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Title: THE EFFECT OF TWINNING ON THE WORK HARDENING BEHAVIOR IN HAFNIUM

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The Effect of Twinning on the Work Hardening Behavior of Hafnium

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In many HCP metals, both twinning and slip are known to be important modes of deformation. However, the interaction of the two mechanisms and their effect on work hardening is not well understood. In hafnium, twinning and work hardening rates increase with increasing strain, increasing strain rate, and decreasing temperature. At low strains and strain rates and at higher temperatures, slip dominates deformation and rates of work hardening are relatively lower. To characterize the interaction of slip and twinning, Hf specimens were prestrained quasi-statically in compression at 77K, creating specimens that were heavily twinned. These specimens were subsequently reloaded at room temperature. Twinning within the microstructures was characterized optically and using transmission electron microscopy. The interaction of slip with the twins was investigated as a function of prestrain and correlated with the observed rates of work hardening.

The Effect of Twinning on the Work Hardening Behavior of Hafnium

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Hafnium

- Group IVa of the Periodic Table

- HCP Structure
  - Hafnium → c/a = 1.581

- Applications:
  - Control material in nuclear reactors
  - Solid solution strengthener

- Properties:
  - High strength
  - High ductility
  - Resistant to corrosion and irradiation

21 Sc 45.0	22 Ti 47.9	23 V 50.9
39 Y 88.9	40 Zr 91.2	41 Nb 92.9
57 La 139	72 Hf 178	73 Ta 181
89 Ac 227	104 Rf 227	105 Db 262

Motivation

- Predictive models have success with capturing the mechanical behavior of high symmetry, isotropic metals.

- It is more difficult to model the behavior of highly textured, anisotropic materials:
  - The effects of texture on mechanical behavior are incompletely understood.
  - For these metals there is a lack of mechanical test data over a broad range of strain rates and temperatures.

- In the past we have examined the influence of temperature, strain rate, and texture on Hafnium on:
  - Mechanical properties
  - Microstructural and substructural evolution

Here we are study the effects of twinning on work hardening behavior

Outline

- **Materials and Testing**
- **The Mechanical Behavior of Hafnium**
  - Effects of Texture, Strain Rate and Temperature
- **Mechanical Test Data from Reload Experiments**
  - Work Hardening and Yield Stress
- **Microstructure and Substructure**
  - Evolution as a Function of Temperature
- **Conclusions**

Experimental Material

High purity crystal bar Hafnium

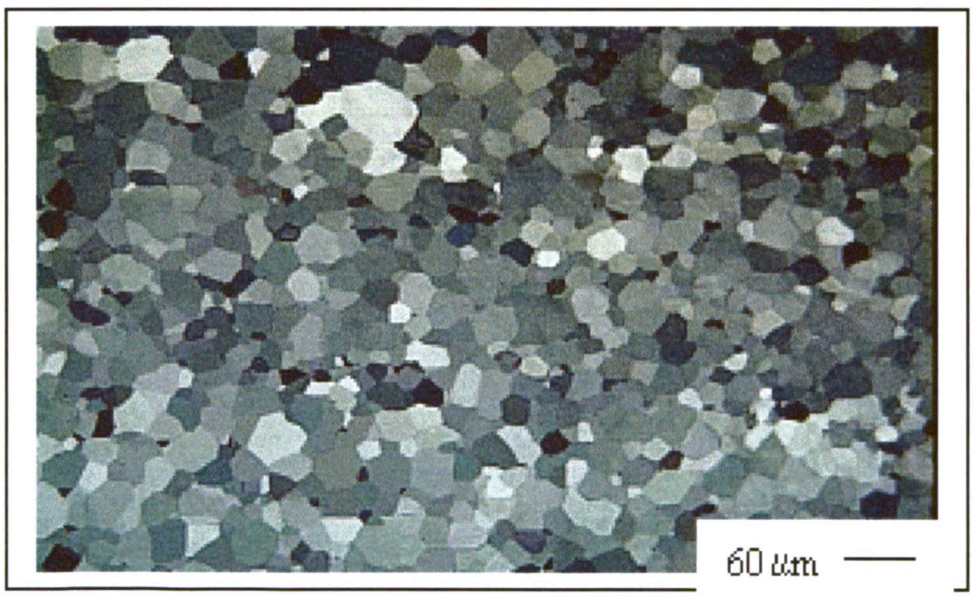
- Upset forged and rolled, annealed at 850°C for 1Hr.

Chemistry of the Crystal Bar Hafnium (wt% ppm)

Ag	Al	C	Cr	Cu	Fe	Mg	Mn	Mo	N	Ni	O	S	Si	Ti	V	Zr
5	25	20	20	25	50	10	10	10	4	25	7	10	25	25	10	.28

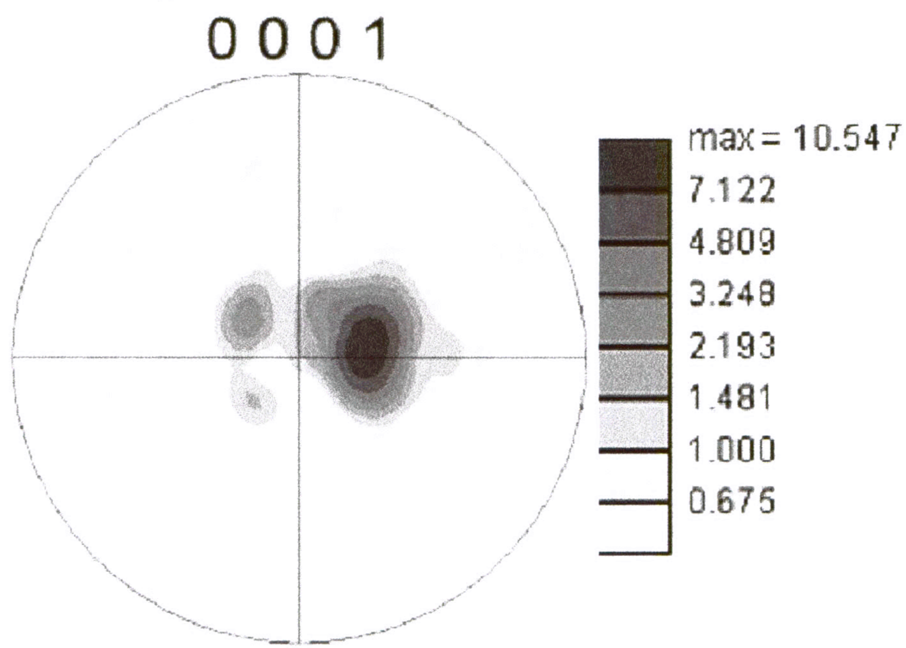
(Zr is in atom %)

Initial Microstructure



35µm grain size

Pole Figure: Basal Texture



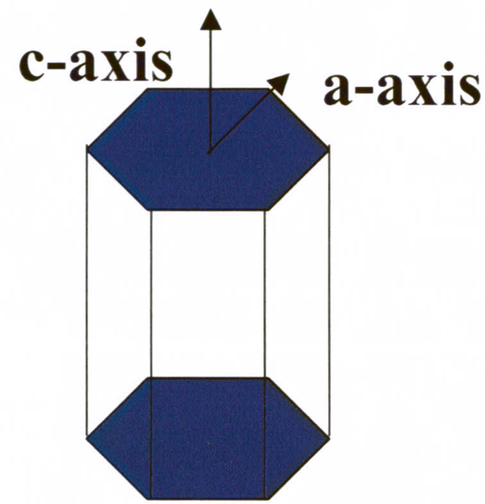
Compression Specimens

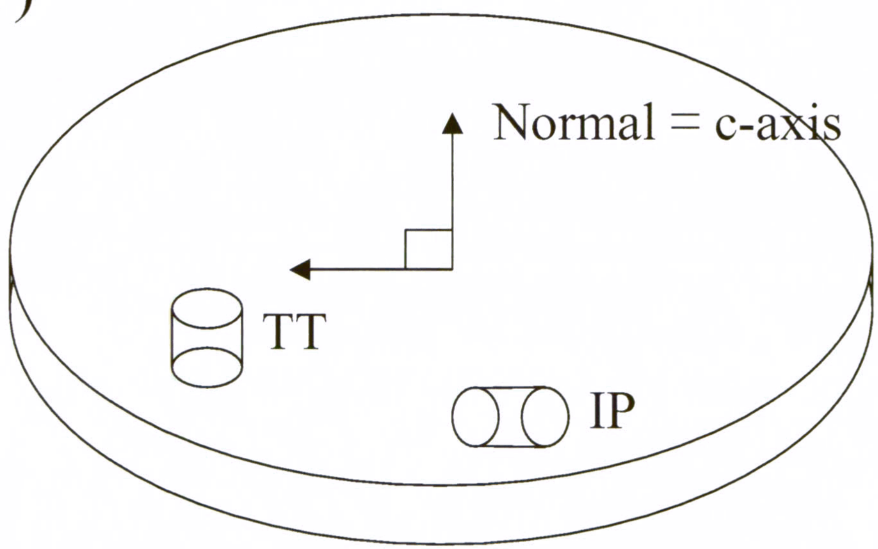
Dimensions:

- Diameter = 5mm
- Height = 5mm

Two Orientations:

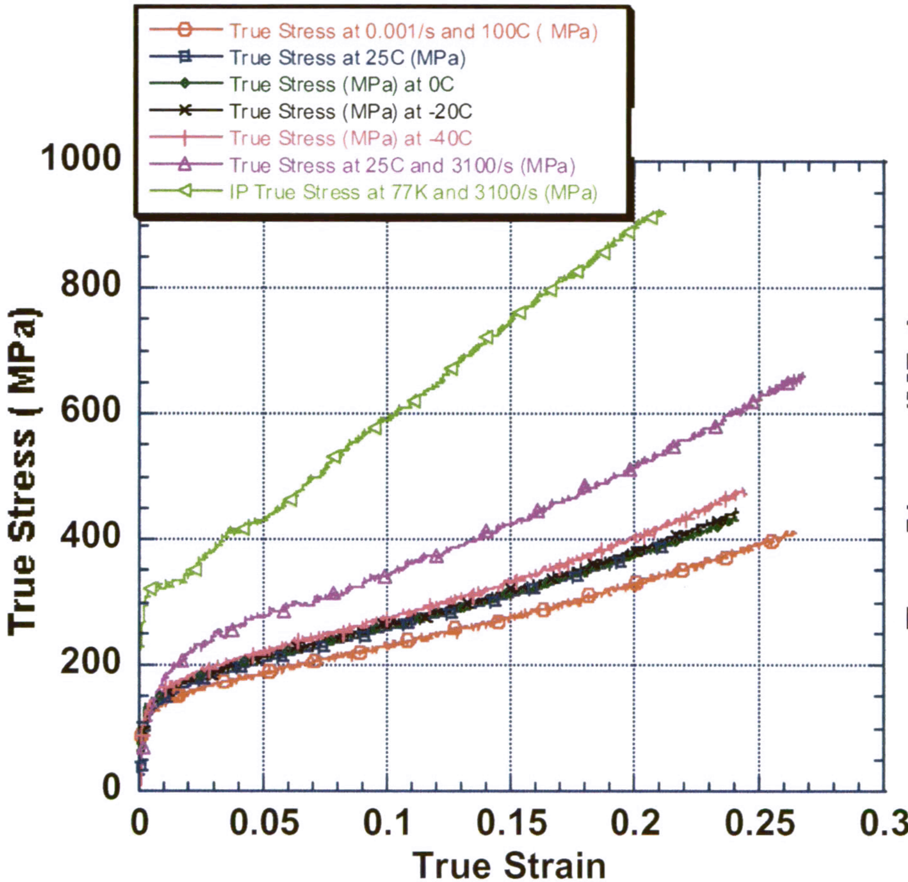
- Through Thickness (TT)
- In Plane (IP)



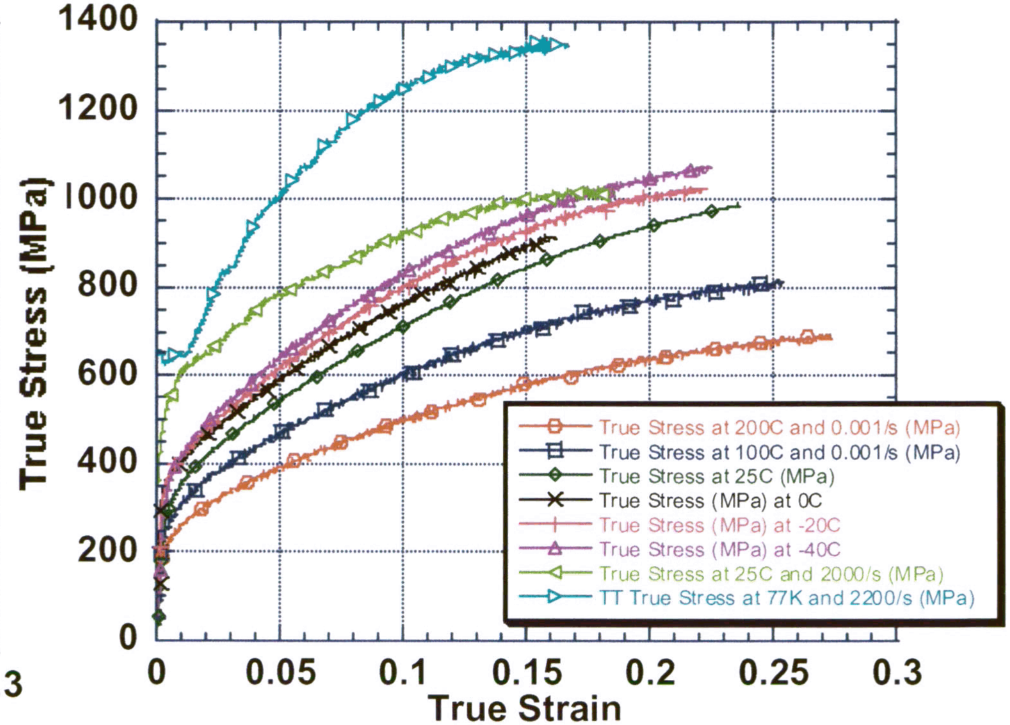


Mechanical Testing Results: Hafnium

In Plane



Through Thickness



Flow stresses and rates of work hardening are influence by texture, temperature, and strain rate

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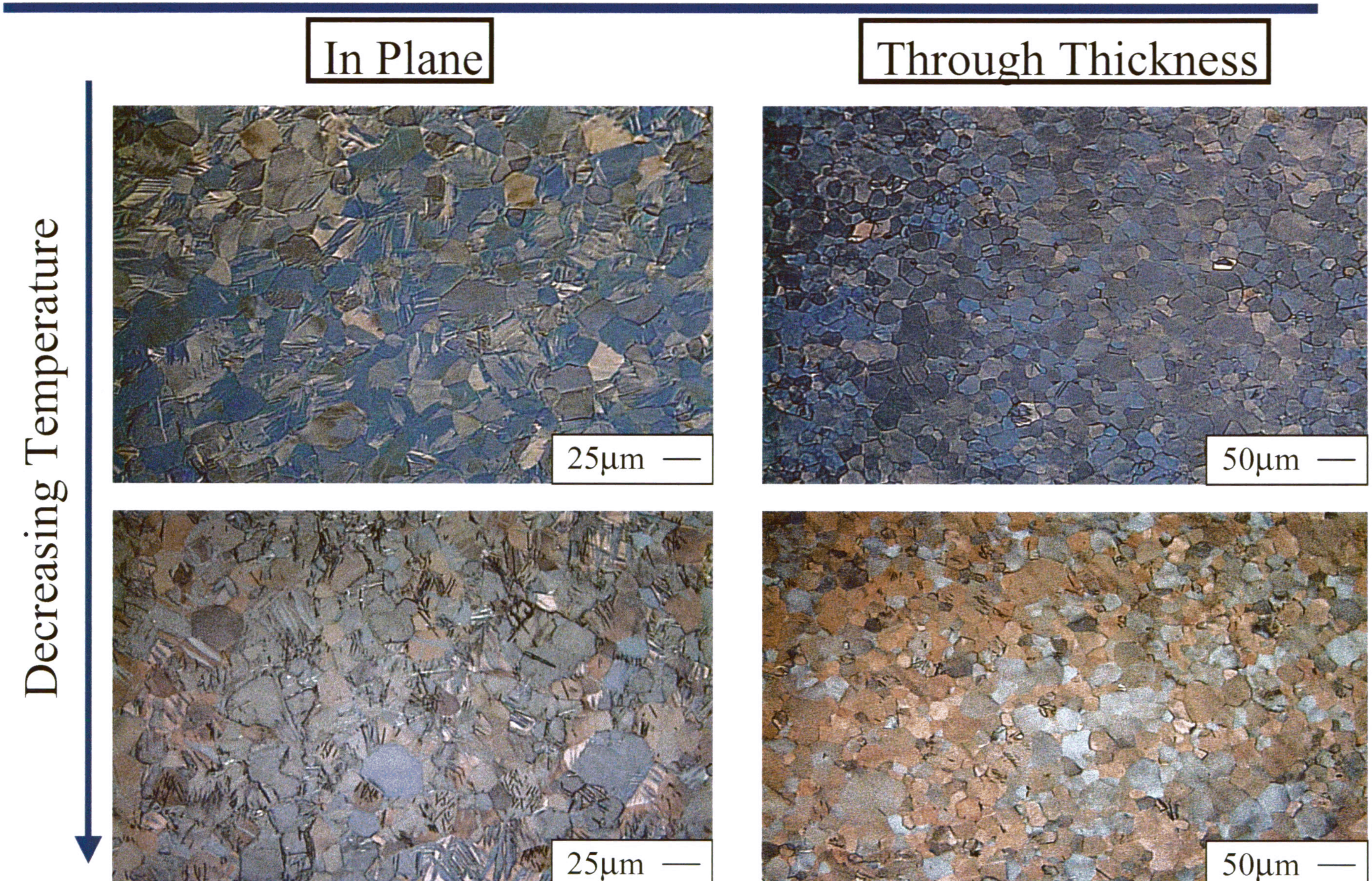
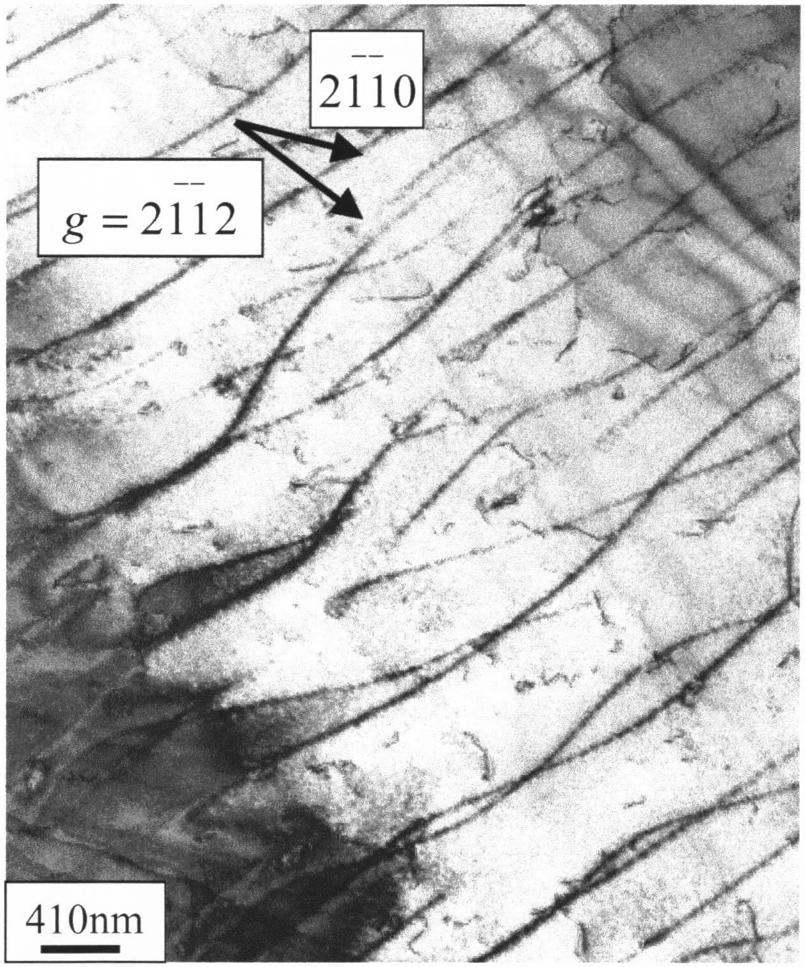
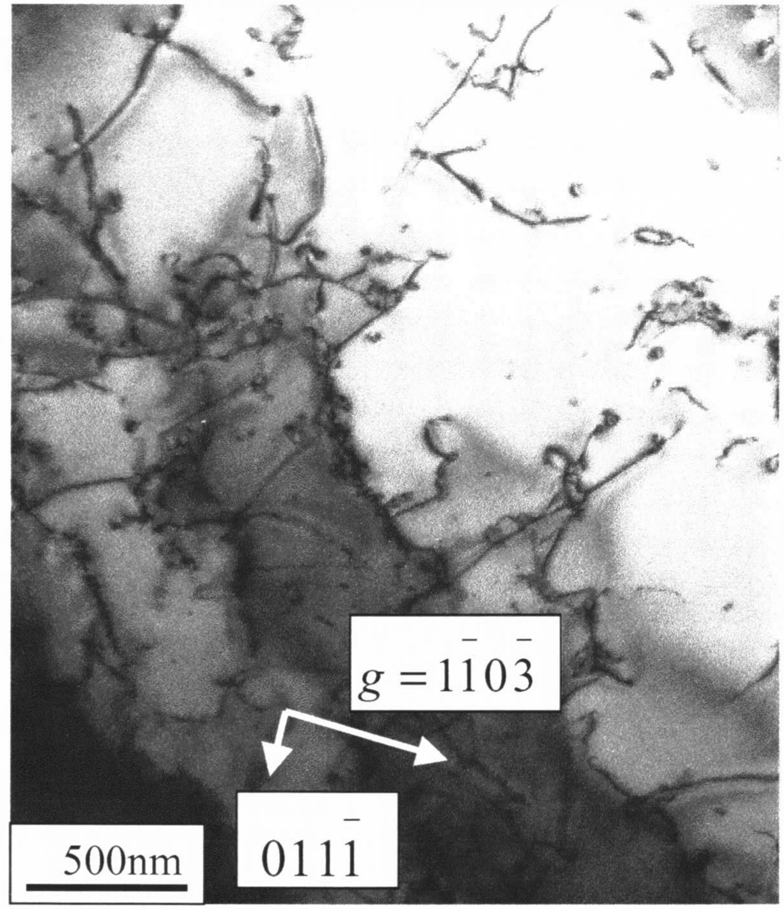
Microstructure as a Function of Temperature: Hafnium



Evolution of Substructure: IP Case – Hafnium

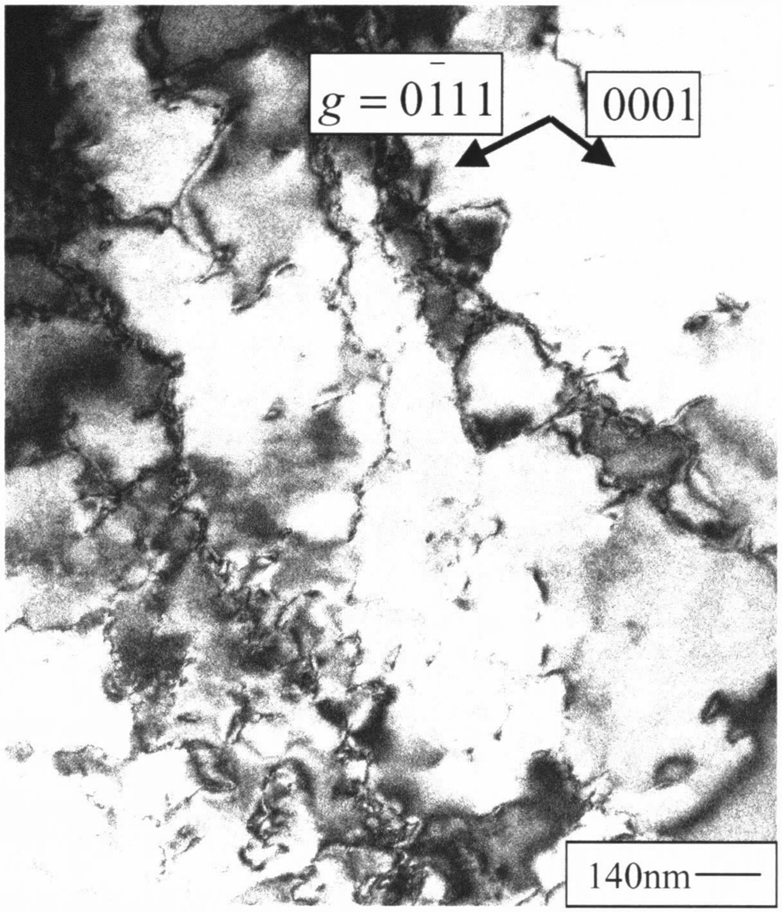


IP, Hf, ε = 2.87%, 1/3[-2110] dislocations gliding on the (01-10) plane

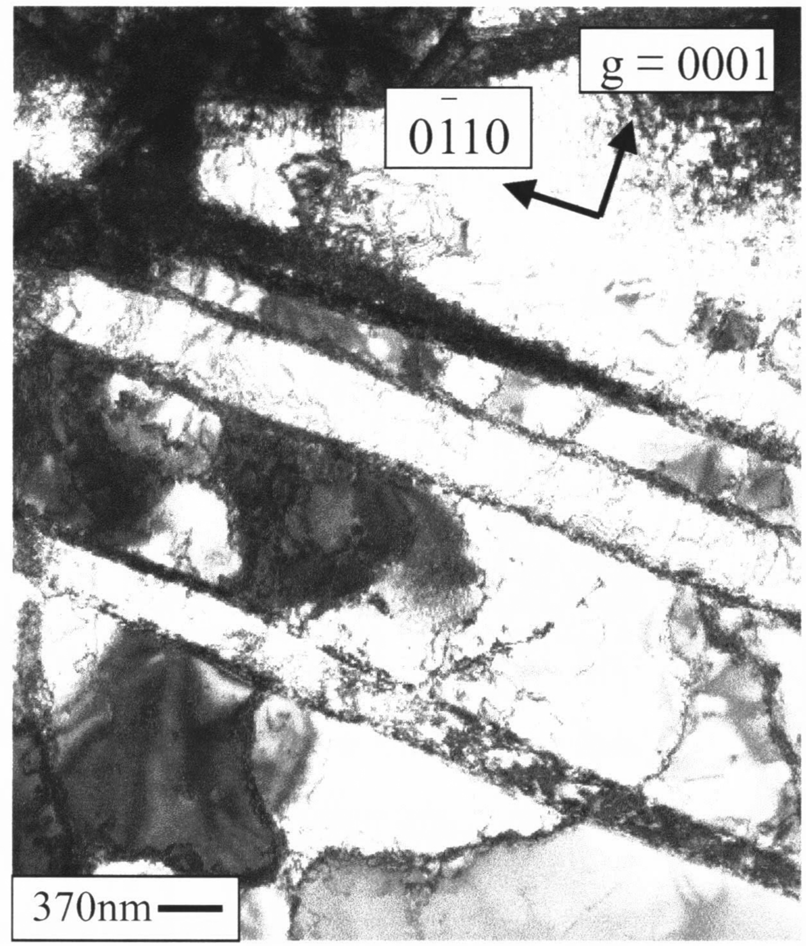


IP Hf, ε = 5.02%, dislocations are 1/3[1-210] on the (-1010) plane, other areas contained loose subgrains

Evolution of Substructure: IP Case – Hafnium, Cont.



HF IP, ε = 10%, dislocations are a-type, most of the substructure contained well formed subgrains



Hf IP, ε = 21%, Matrix dislocations are a-type, twin is on the (-211-1) plane, dislocations within the twin are [0001]

Experimental

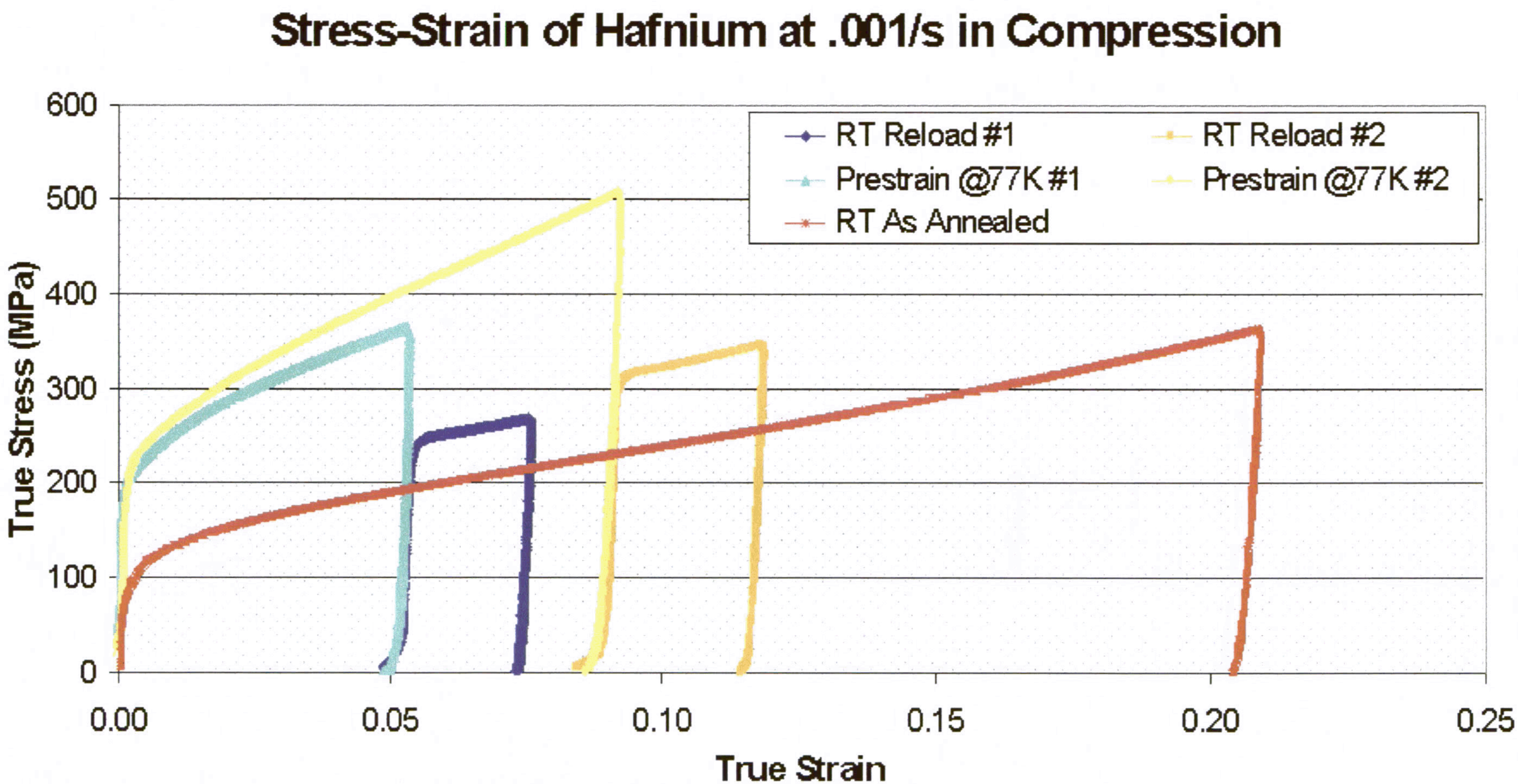
Quasi-Static Compression Testing

- Instron Screw Driven Load Frame
- Strain Rate: 10^{-3}/s
- Temperatures:
  - Loaded at 77 K to 5 and 10%
  - Reloaded at 298 K an additional 2% strain

Characterization

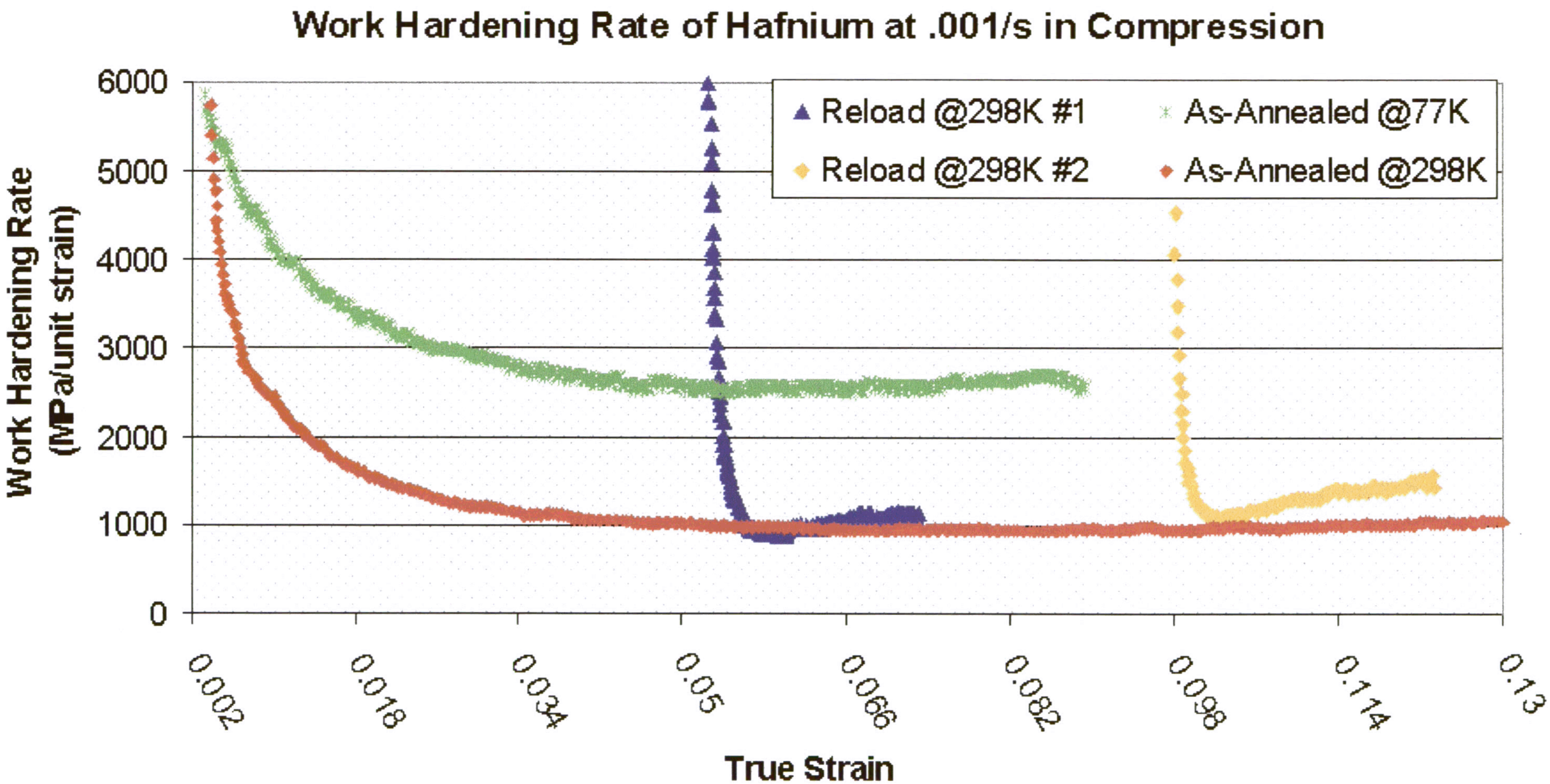
- X-ray Analysis
- Optical Metallography
- Transmission Electron Microscopy

Mechanical Testing: Reload Results



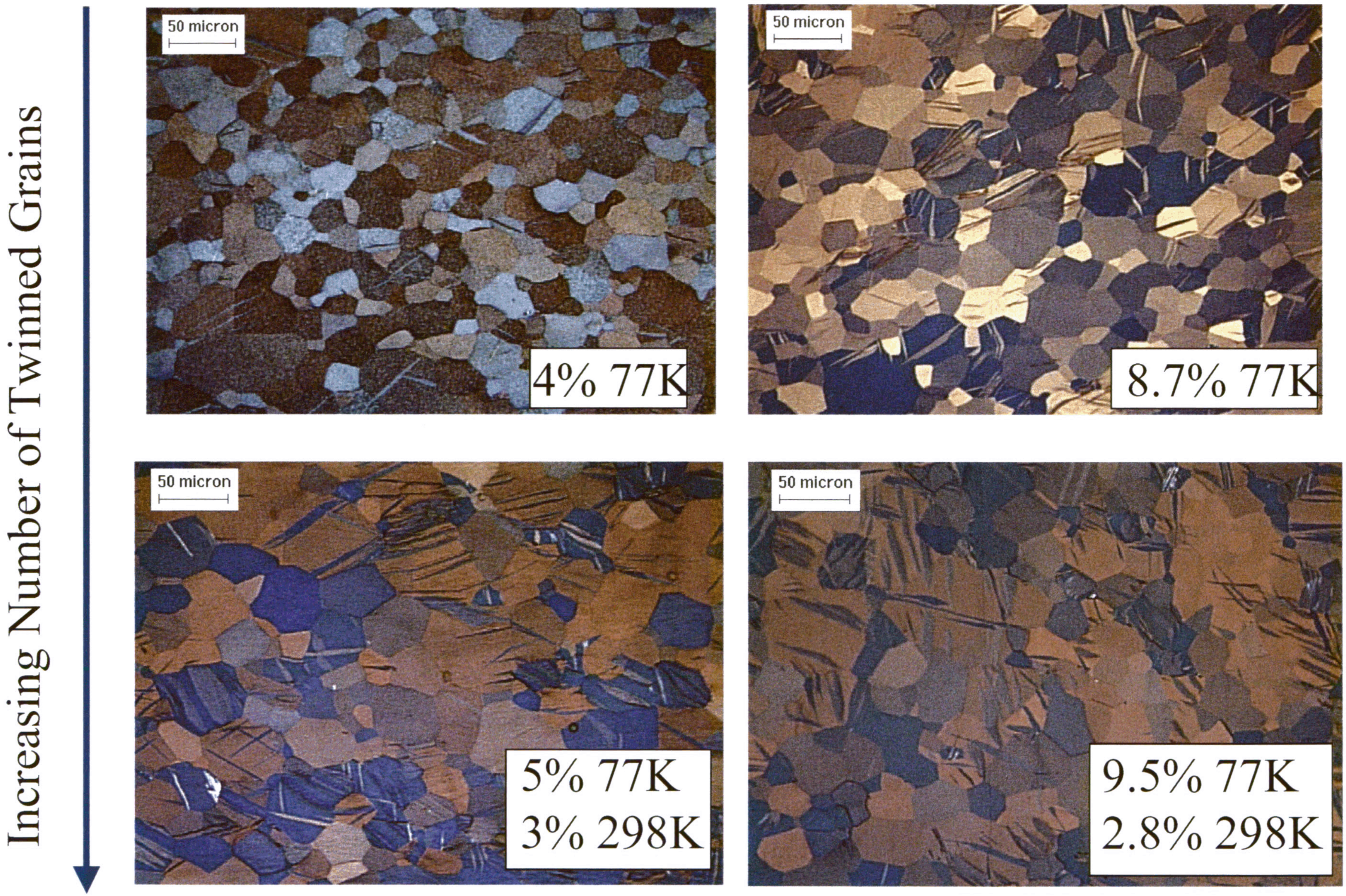
- Yield stresses and work hardening rates increase with decreasing temperature
- Room temperature reloaded specimens, prestrained at 77K, display higher flow stresses than room temperature specimens, with no prestrain.

Work Hardening: Reload Results

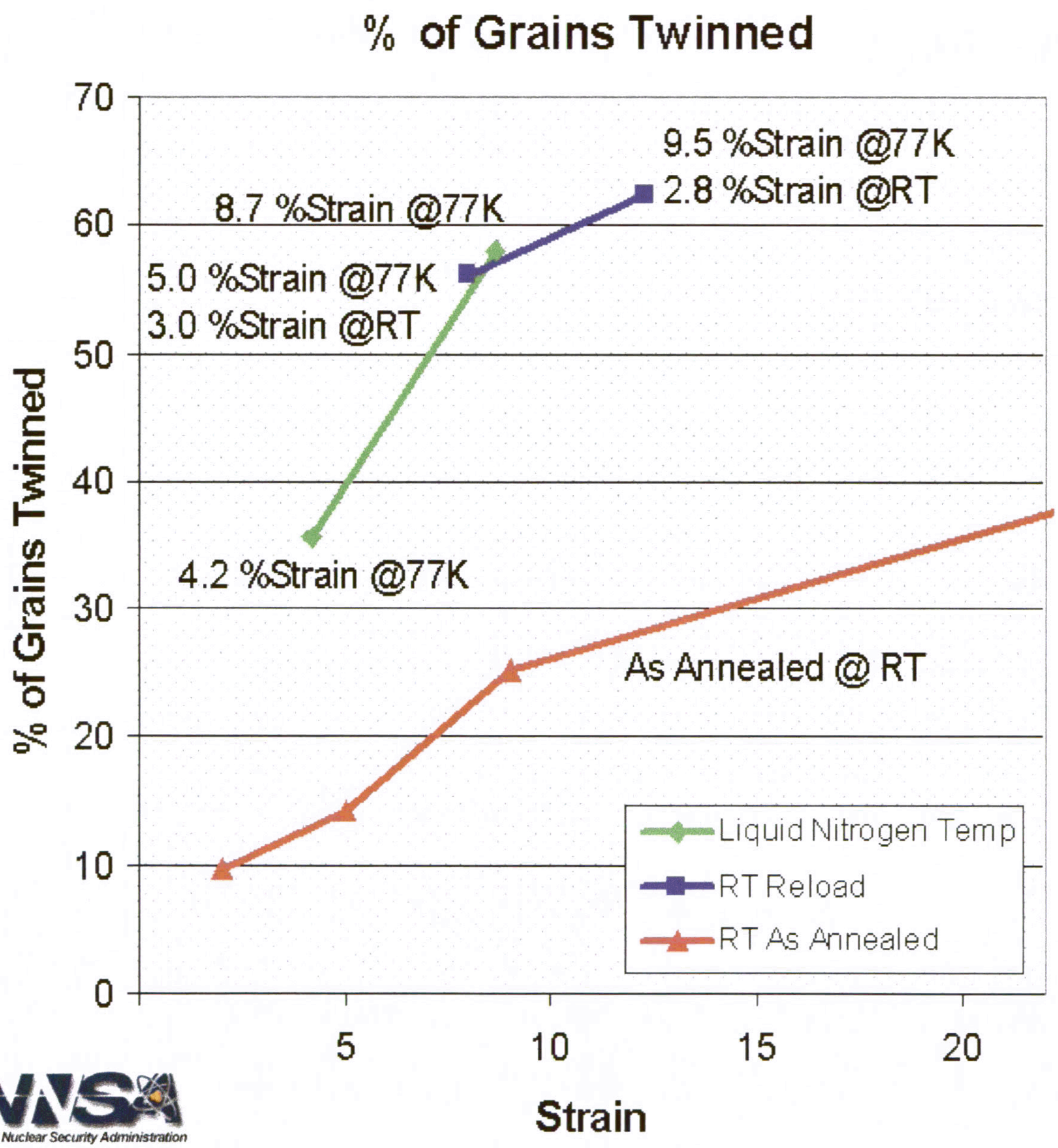


Room temperature reloaded specimens, prestrained at 77K, display higher rates of work hardening than room temperature specimens, with no prestrain.

Microstructure



Influence of Temperature on Twinning



- More grains contain twins at lower test temperatures.
- Twinning increases with strain.
- At both 77K and at 298K there is a sharp increase in the amount of twinned grains between 5 and 10% strain.

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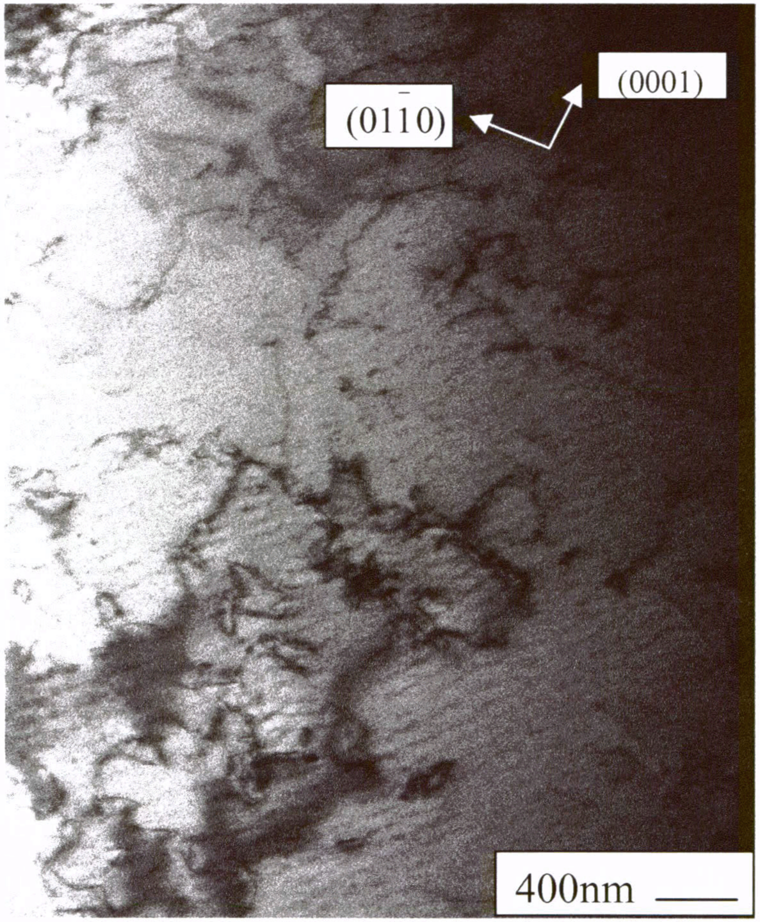
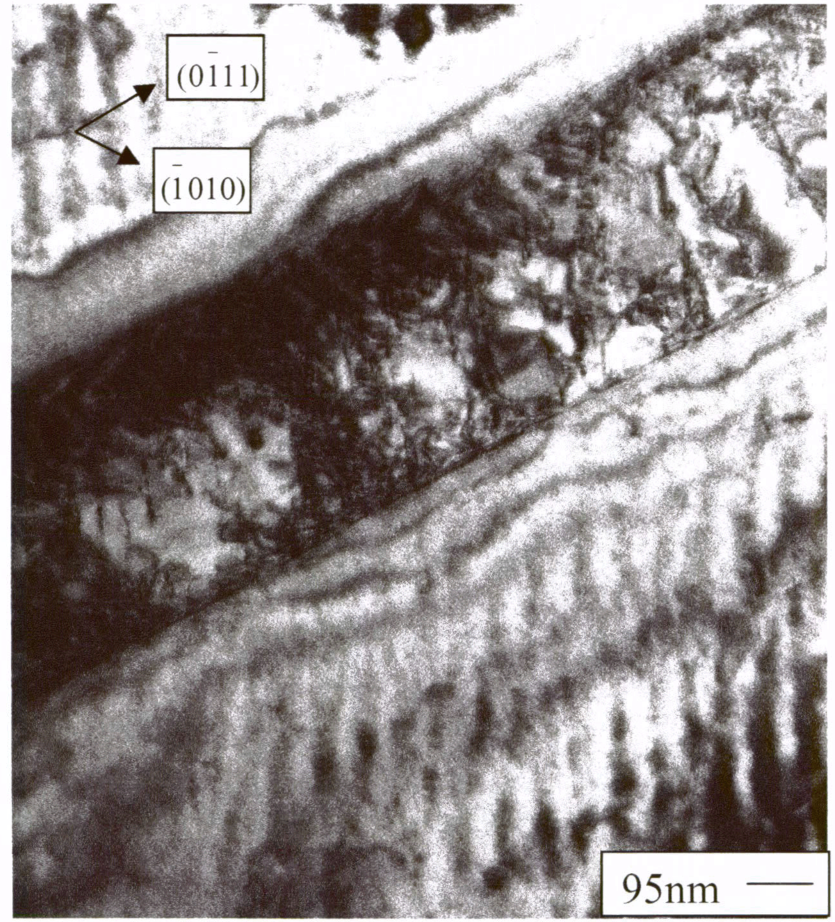
Substructure of Hf at 77 K



Matrix at 5% ε, tangled a-type dislocations

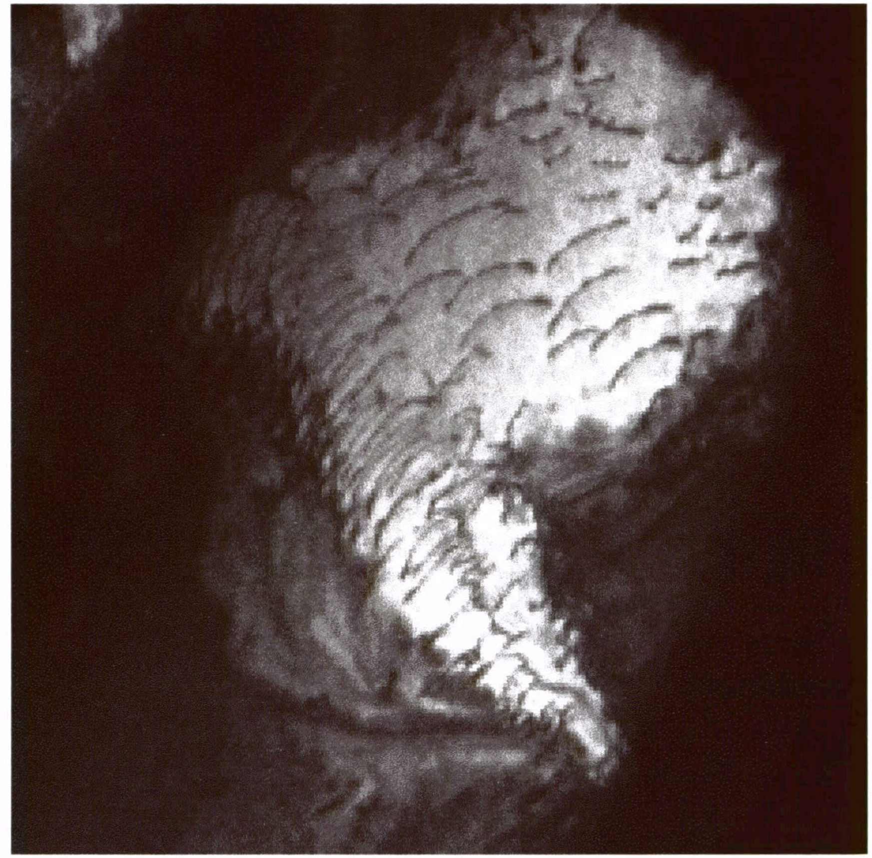


Twin at 5% strain, on the $\{11\bar{2}2\}$ plane, contains debris

Substructure similar to the 298K substructure at 5% ε, except volume fraction of twins is significantly higher at 77K

Substructure of Reloaded Hf

Low magnification image of the twins and matrix



Higher magnification image of a-type dislocations accumulating between two twins

Dislocation pile-ups between twin boundaries cause higher flow stresses and rates of work hardening in reloaded specimens

Conclusions

- Room temperature reloaded specimens, prestrained at 77K, display higher flow stresses and rates of work hardening than room temperature specimens, with no prestrain at a comparable strain.

- The volume fraction of twinned grains increases with increasing strain and decreasing temperature

- Twins effect work hardening rates in two ways:
  1.) Dislocations pile up between twinned areas, the refined glide distances inhibit motion.
  2.) Twins contain high density of dislocation debris, difficult to glide within twinned regions.