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A Review of RHEPP Results in First-Wall Materials Treatment

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Sandia National Laboratories

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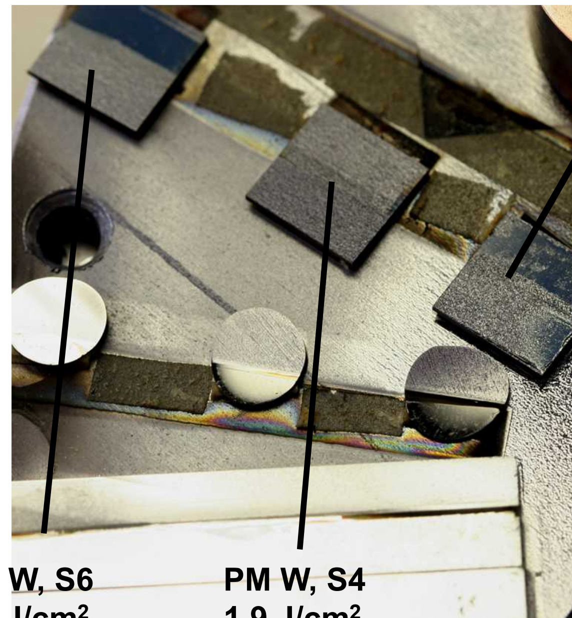
Executive Summary

- **Tungsten Exposures - presently at KS2_2400 shots and counting**
  - **Polycrystalline Tungsten roughens severely, loses mass**
  - **M182perp Plansee Tungsten (commercially available): little or no mass loss to 2400 pulses, controlled but unsaturated roughness growth. Single-crystal W, W-TiC (Kurishita) also robust.**
  - **Vapor-sprayed W over Steel appears to lose mass steadily**
  - **Lack of roughness saturation requires other facility for ultimate validation. JULICH-II coming up with multi-shot 30 keV e-beam capability**
- **Graphite exposures - C400, C2_400**
  - ~ 1 J/cm2 may be viable, large mass loss at higher fluences
  - Knowles CCW, CCW/W hold up well
  - CFCs should be oriented so that fibers go into material surface. PAN may be more attractive than PITCH due to mechanical robustness
- **‘Melt’ Campaign_400: Melting does not look viable**
- **SiC: no successful material yet. Diamond-coated SiC evolves with shot number into graphite-rich surface, protection is lost.**

Tungsten Materials

RHEPP-1 Roughening Threshold, PM W, Multi-pulse

Images and data from KS2000 series: S10 and S8 are sub-threshold for roughening, S6 above (Snead PM W). Note temperature excursions from modeling, based on fluence scatter from FCup data.



PM W, S2
3.5 J/cm^2
4300C_AP
Melt Duration 159 ns
Melt Depth 0.8 µm
R_a ~ 6-10 µm

Beam Center

S6 = 6 cm from Beam center

PM W, S10
0.2 J/cm2
270C_AP
Hi 415C
Lo 145C

PM W, S8
0.6-0.9 J/cm^2
1290C_AP
Hi 1960C
Lo 535C

PM W, S6
1.2 J/cm^2
1690C_AP
Hi 2278C (5%)
Lo 1175C (5%)
R_a ~ 2.5 µm

PM W, S4
1.9 J/cm^2
3070C_AP
Hi 3650C
Lo 2100C
R_a ~ 4 µm

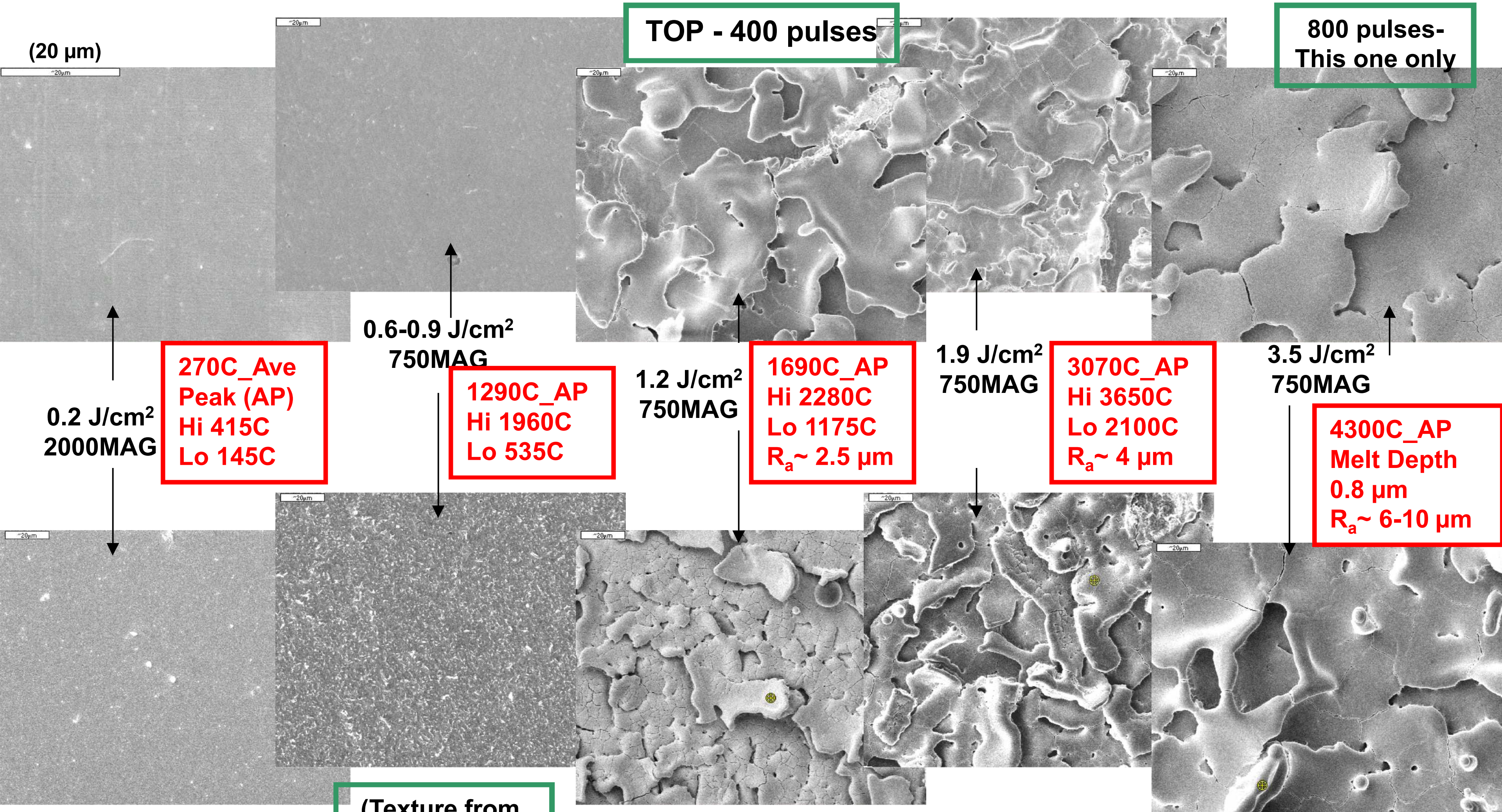
Recent series: Center gone, S10 < Fluence < S5

These PM W appear unaffected

These PM W are very rough

AP = Average High Surface Temp
Hi and Lo occur on 5% of pulses

SEMs of Polycrystalline (PM) Tungsten Roughening: Threshold at ~ 1 J/cm², roughening saturates after ~ 400 pulses

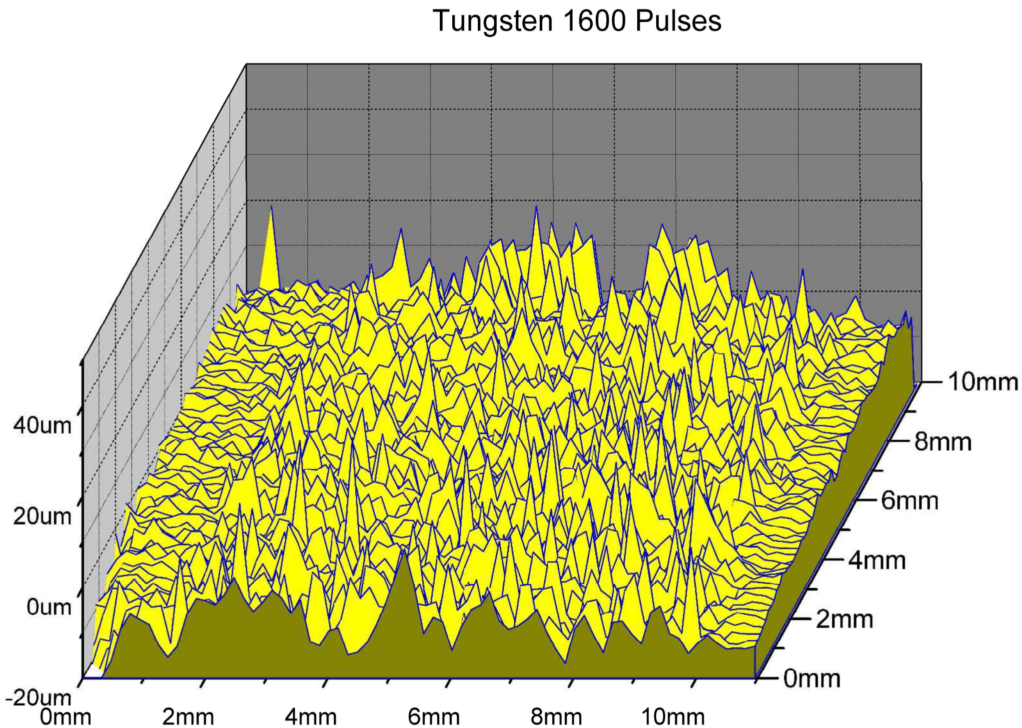


(Texture from Deposited film)

BOTTOM - 2000 pulses

All samples initially Room Temperature (RT)

Polycrystalline Tungsten after 1600 pulses (non-melting): Mostly mountains up to ~ 30 µm height



- Heated/treated Powder-Met (PM) Tungsten examined with NEXIV laser interferometry
- Comprehensive line-out scan: max height 30 µm, min height < 10 µm compared to untreated
- Very deep microcracking not visible here
- Hypothesis: mountains are due to CTE expansion that does not recover

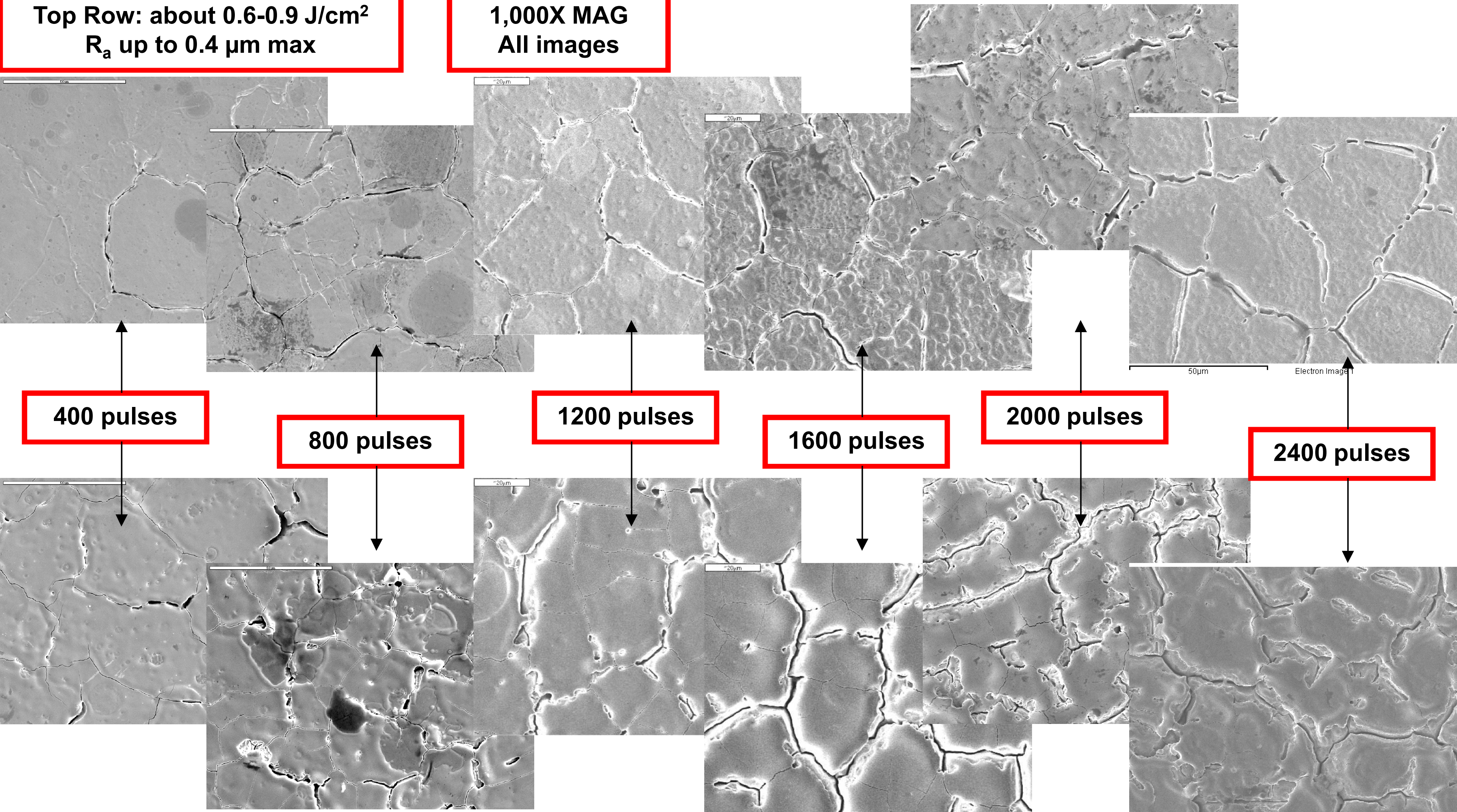
Cannot confirm mass loss by height study. Must weigh before/after exposure

From J. Linke, FZ Julich

SEMS of Tungsten M182 perp after 2400 pulses: Little topology change below 1 J/cm^2, some roughening w/ pulse number at ~ 1.5 J/cm^2

Top Row: about 0.6-0.9 J/cm^2
R_a up to 0.4 µm max

1,000X MAG
All images

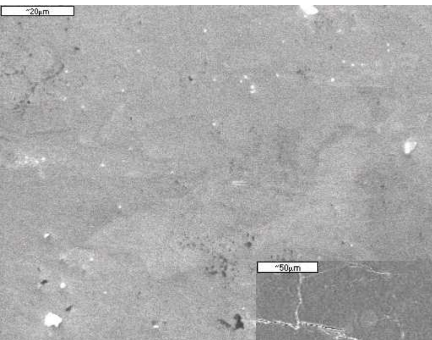


Bottom Row: ~ 1 - 1.5 J/cm^2
R_a 0.35 to ~ 1 µm

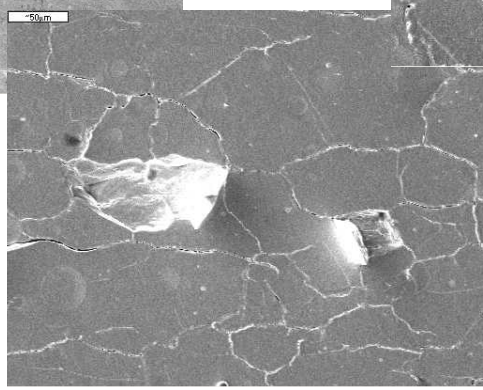
Little or no mass loss to 2400 pulses

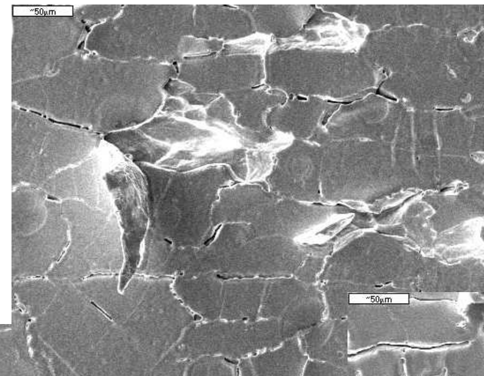
M182 Plansee Tungsten, cut with grains parallel to surface (SEMs): surface-lying grains become unzipped with increasing fluence

No Treat

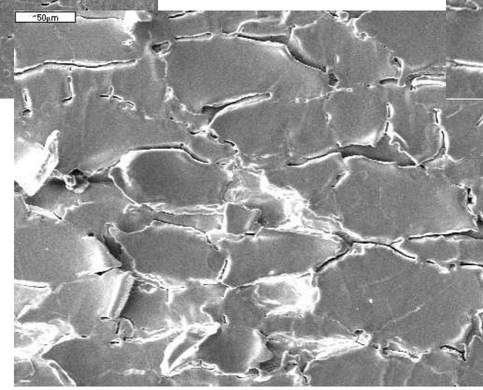


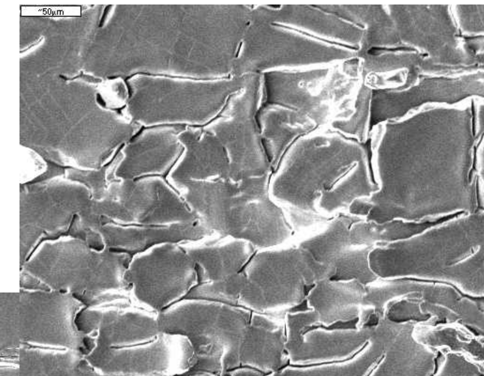
1,000X MAG





~ 0.7 J/cm^2



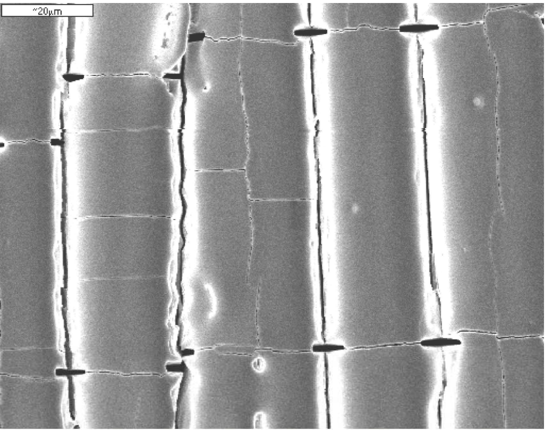


About 1.3 J/cm^2

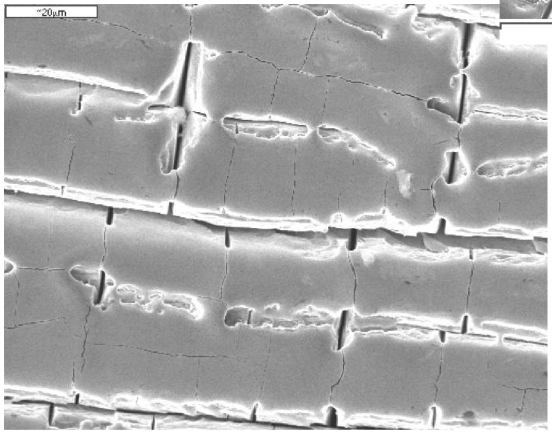
All treated images 300X MAG.

R_a : reaches 4 - 4.5 µm at 1.3 J/cm^2 (same as PM Tungsten)
Only apparent AFTER 400 pulses (these images)

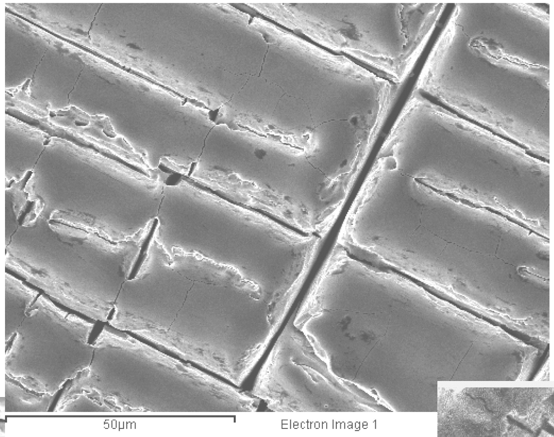
SEM, Single Crystal Tungsten at 300K, ~1.5 J/cm^2 : Evolution 0.4 to 1.3 µm R_a, erosion around crack edges indicated



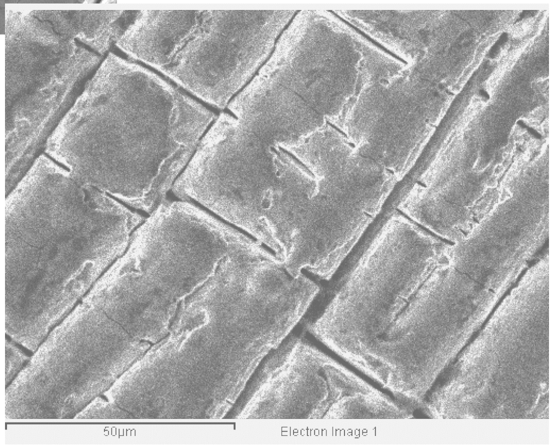
400 pulses



800 pulses



1200 pulses

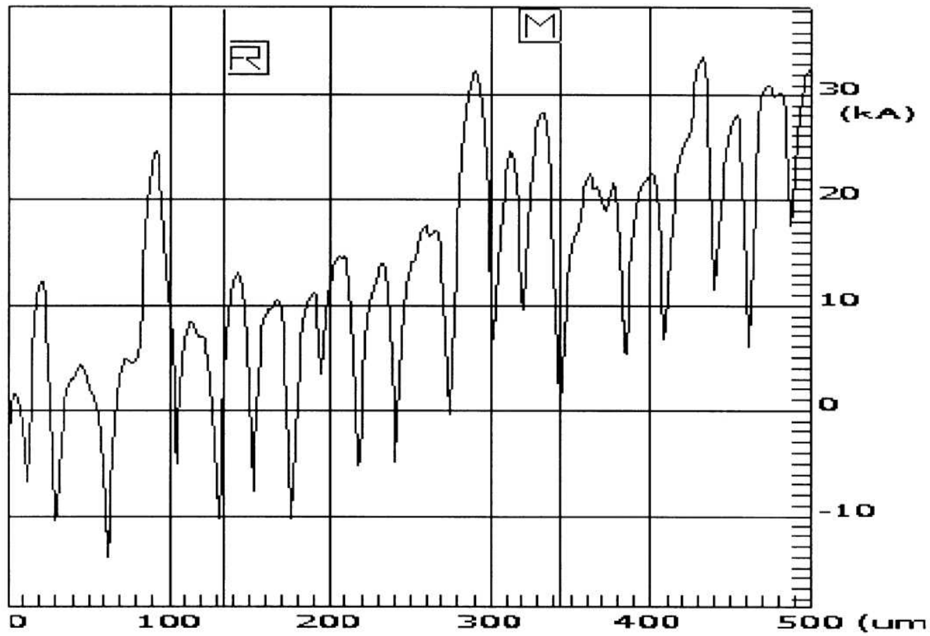


1600 pulses

This Retest of KS2000 at Request of MWG, with accompanying Mass Loss data. Morphology evolution looks the same as KS Series

KS2 Shot series 8/06 - 7/07

Single Crystal Tungsten at 300K, Weight 'Loss' Estimate: Implied mass loss from morphology profile not seen in measurements



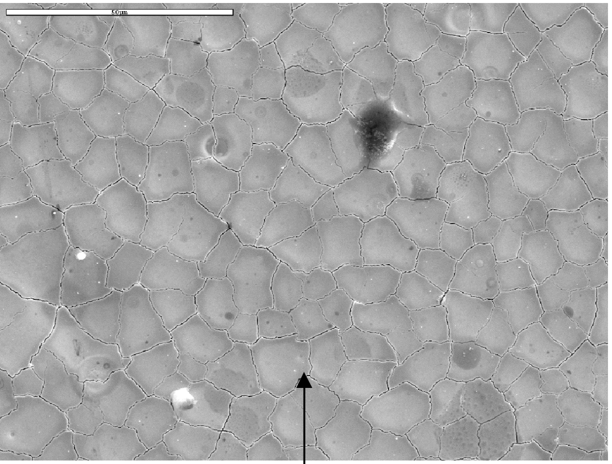
Dektak Scan - 800 pulses

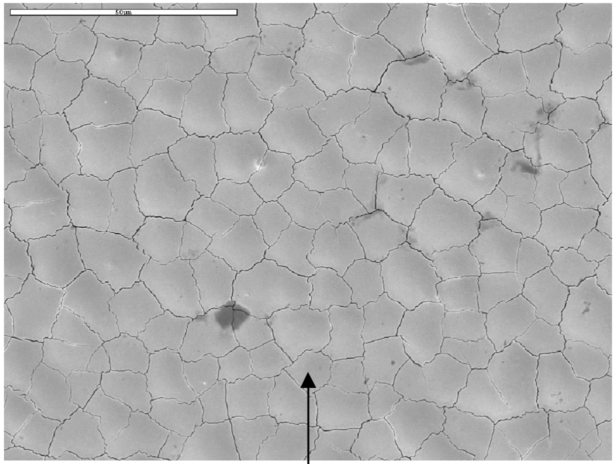
- [Left] 1-D Dektak of Single-crystal W surface shows periodic bumps at 800 pulses. Similar scans at 400 and 1200 pulses show same qualitative features - 0.5 - 1 µm R_a, and Peak-Valley heights up to 70 µm.
- Assume profile of 'flattened' triangular cross-section - height 25 µm, spacing 20 µm in rows, 5 µm flat-top in-between. Calculate volume implied by 'missing' triangles.
- Sample width 0.85 cm. Get 425 grooves, each 600 µm long. Total 'missing' volume 4.78e-5 cm-3, and @ 19.3 g/cc this is ~ 920µgr.
- There are transverse grooves, so this is an underestimate.
- Totals for Single Crystal sample tested (1600 pulses total): +11.5, -69.4, +34.9, +38 µgr = 15 µgr net GAIN. Error bar in this number is ±30 µgr.

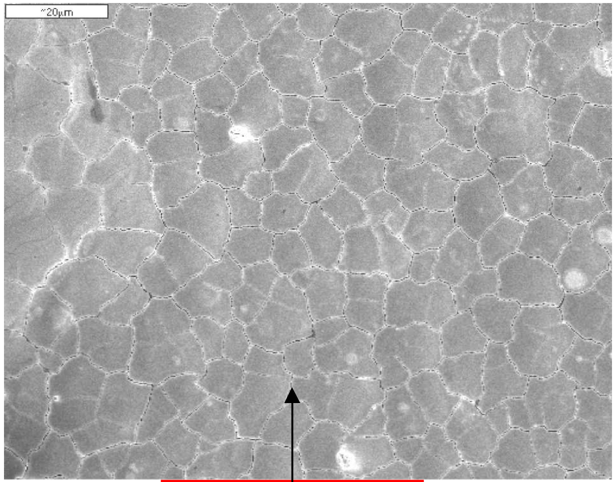
W-TiC-A 'pre-stressed*' 2.5 cm-wide sample (SEMs): (presumed) stress-relief seems to restrict grain corner exfoliation

Top Row~ 1.0 J/cm Ra ~ 0.16 µm

From H. Kurishita (Tohoku U.)



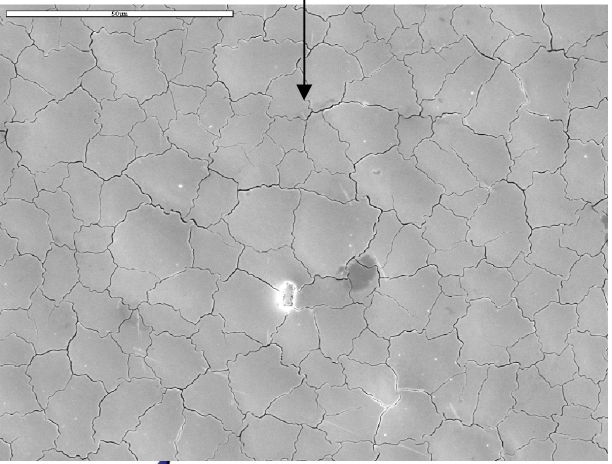


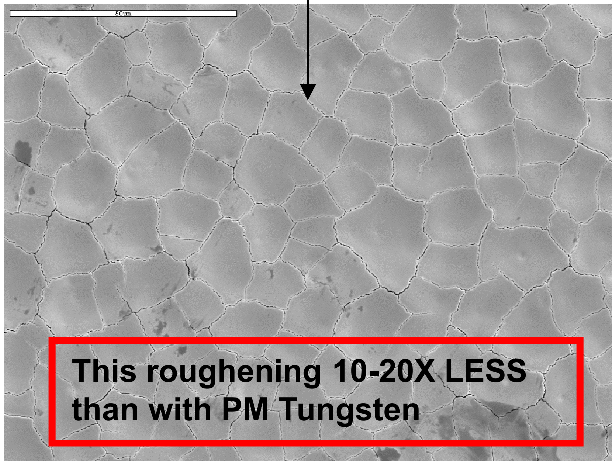


400pulses

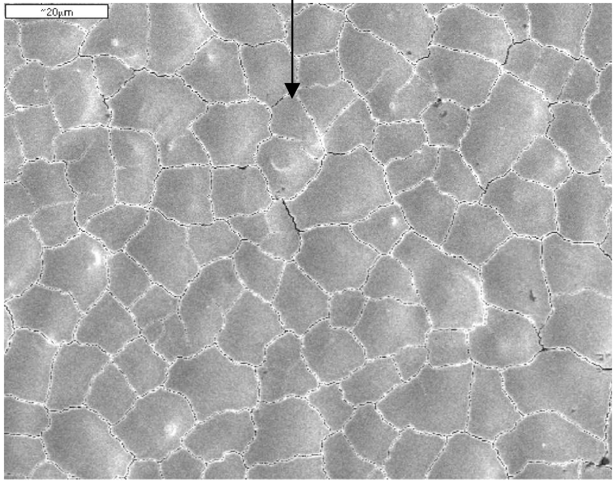
800 pulses

1200 pulses





This roughening 10-20X LESS than with PM Tungsten



~ 1.4 J/cm^2

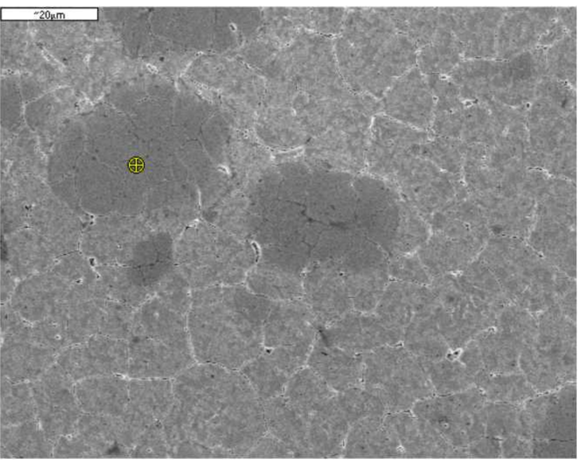
All images - 1,000X MAG

Right Two ~ 1.7 J/cm^2
Ra ~ 0.28 µm

RHEPP-1 Ion Exposure

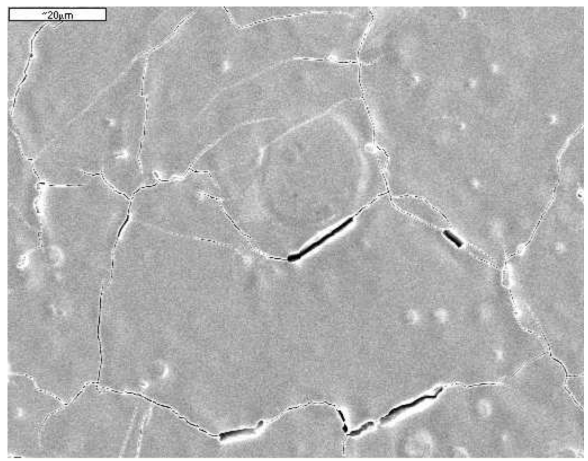
Three forms of Tungsten, treated at ~ same fluence (400 pulses): Grain-refinement/strengthening, or below-surface burial seem to restrict roughening/mass-loss.

1,000X MAG



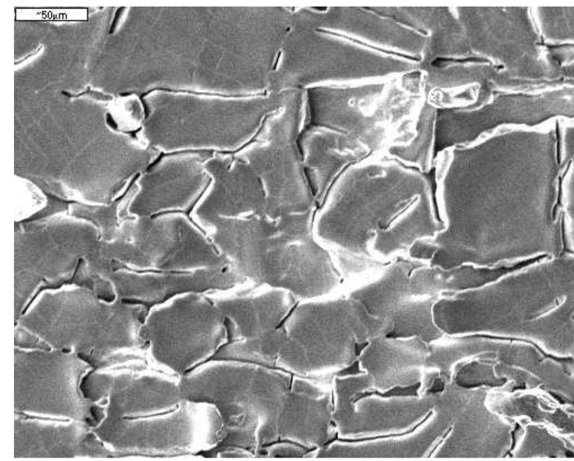
W-0.5%TiC 1.5 J/cm^2.
Ra = 0.04 µm

1,000X MAG



M182Perp ~ 1.25 - 1.5 J/cm^2
Ra ~ 0.15 µm

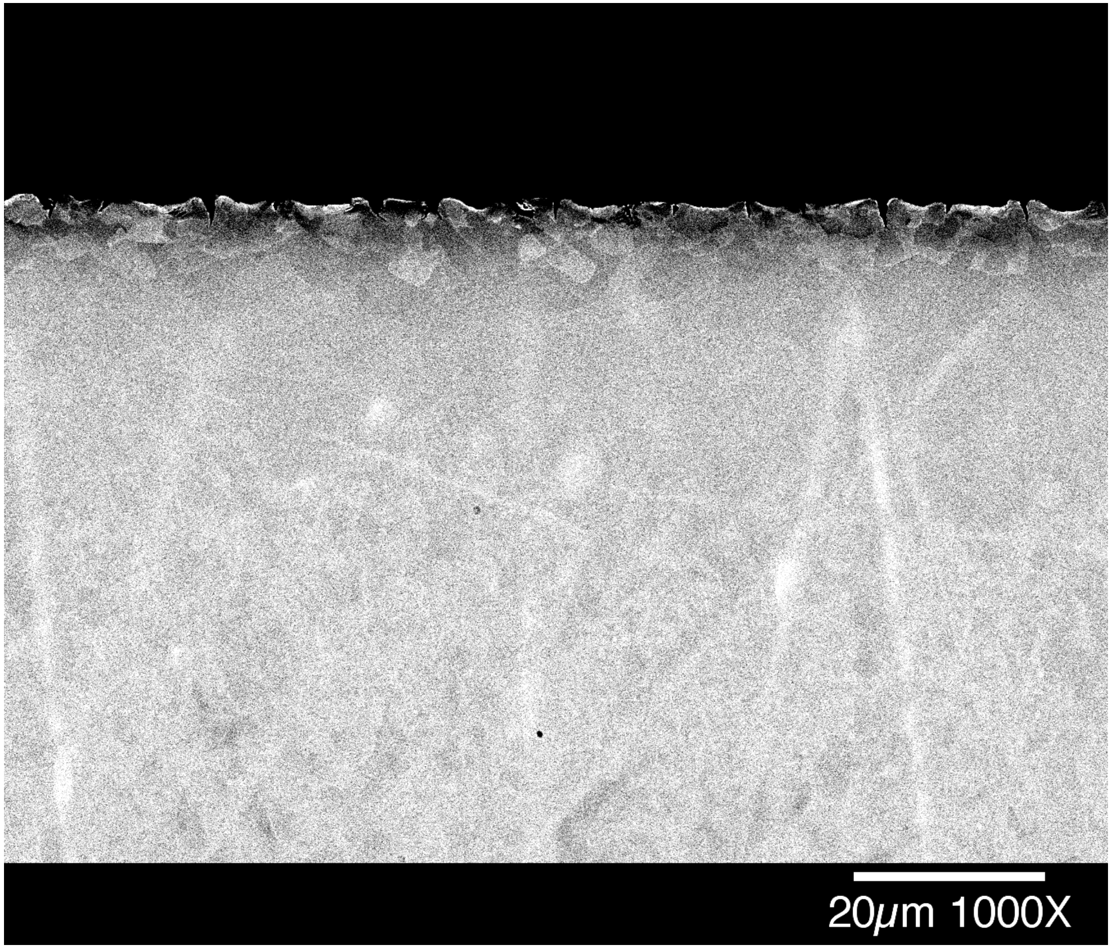
300X MAG



M182Parallel ~ 1.3 J/cm^2
Ra ~ 4.5 µm

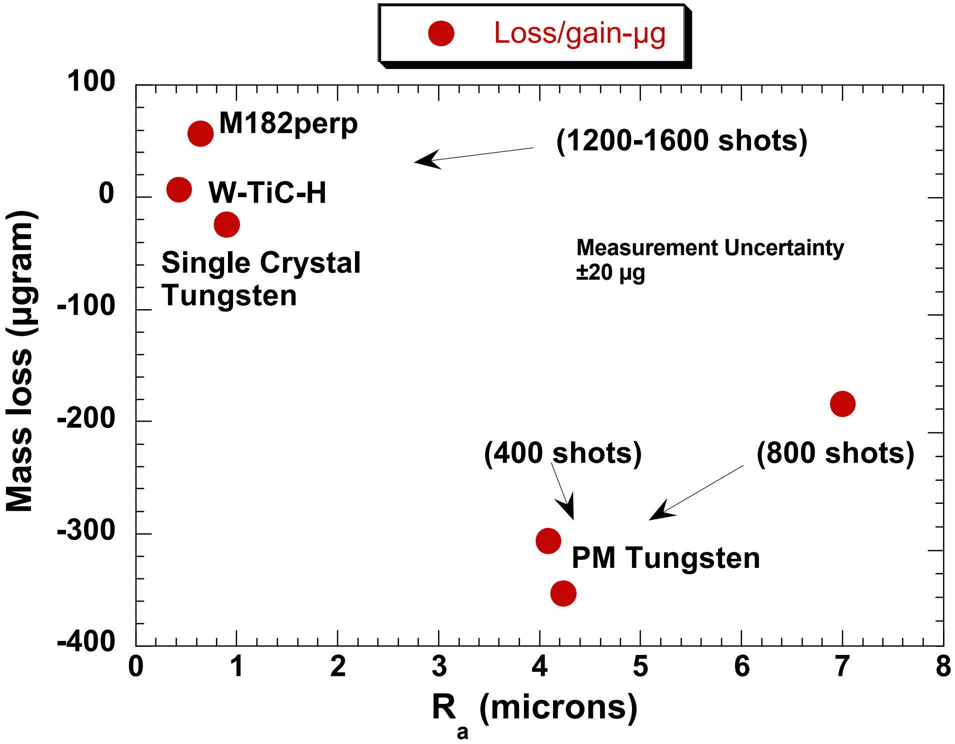
Two on right are SAME material

Treated N6 2000X (520C) SEM: Clear evidence of recrystallization



Mass Loss Measurements

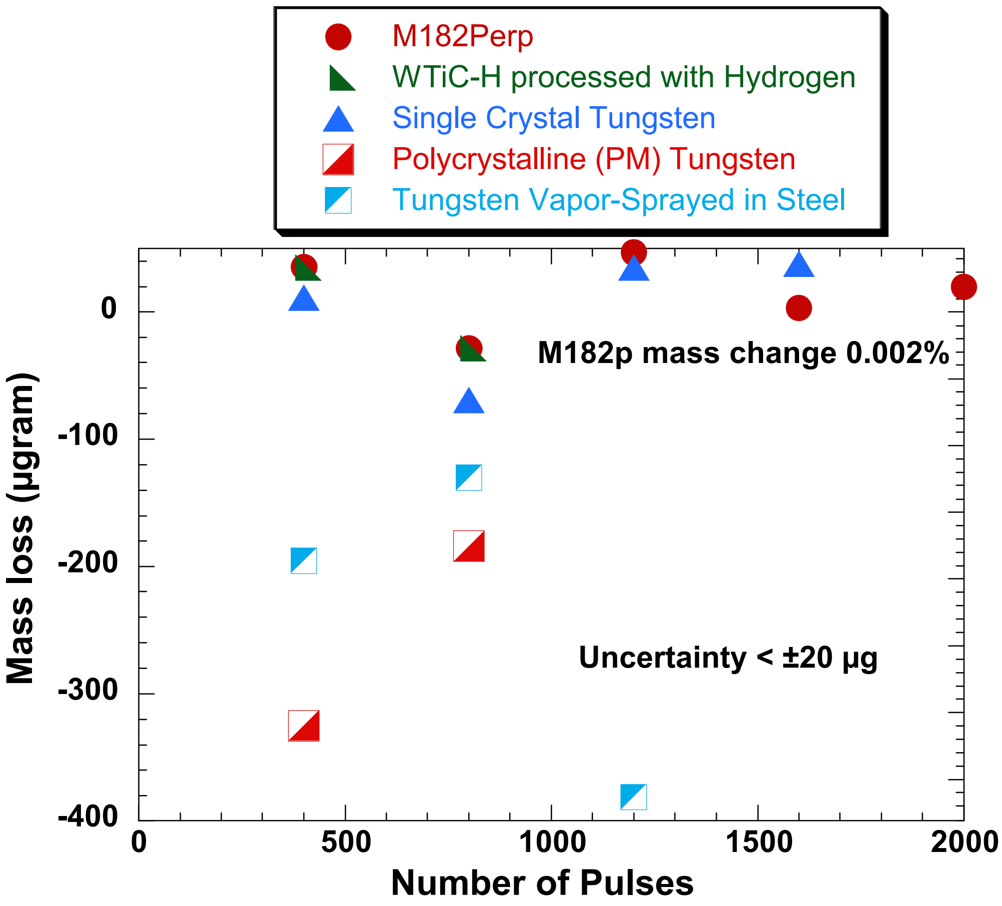
Sandia Metrology weight measurements support connection between Roughening and Mass Loss



- Samples of each listed material exposed for multiple 400-shot series, and weighed pre- and post-shot
- Exposure level/pulse: 1.2 - 1.7 J/cm^2 Measurement Uncertainty < ± 20 µg
- Two samples of polycrystalline (PM) Tungsten lost ~350 µg in 400 pulses, with Ra ~ 4 µm; another 400 pulses produced even more roughening, -184 µm more mass loss
- M182Perp, W-TiC-H, and Single Crystal Tungsten remained < 1 µm Ra, and suffered little mass loss.

Pulsed Power Sciences, Sandia National Laboratories
TJR 04/16/2004

Mass Loss with Shot Number: M182Perp and Single Crystal W show almost no loss



- **Mass loss for PM Tungsten terminated after 800 pulses - 350 and 184 µg loss on two 400 shot sets**
- **Vapor-Sprayed Tungsten (on Ferritic Steel) losses up to 400 µg per 400 pulses**
- **Mass Gain due to entrained material (Cu) from diode region**

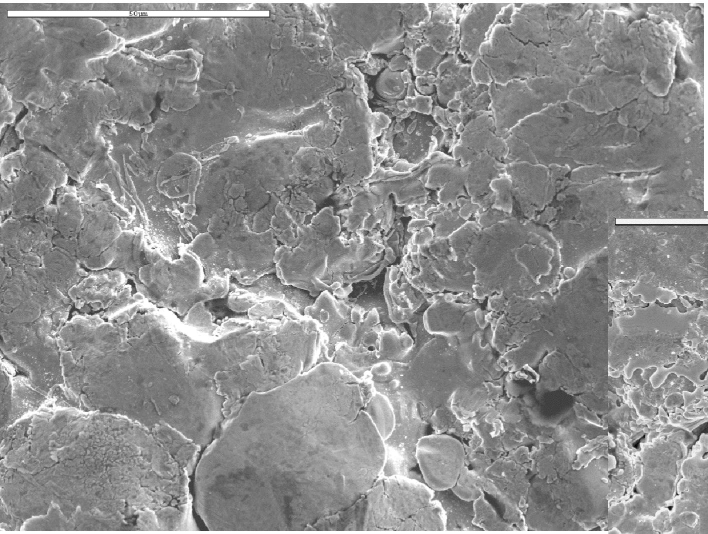
RHEPP-1 Ion Exposure

VPS Tungsten (SEMs): slight roughening, Evidence of scouring/erosion at S6

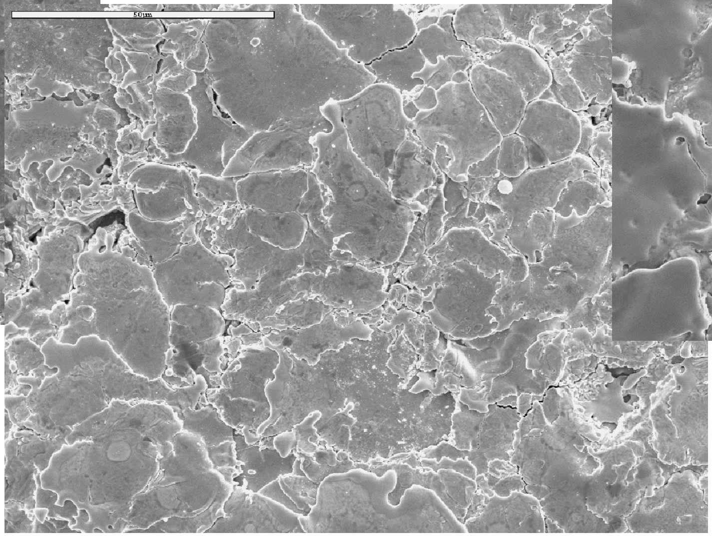
Near S6 No Treat

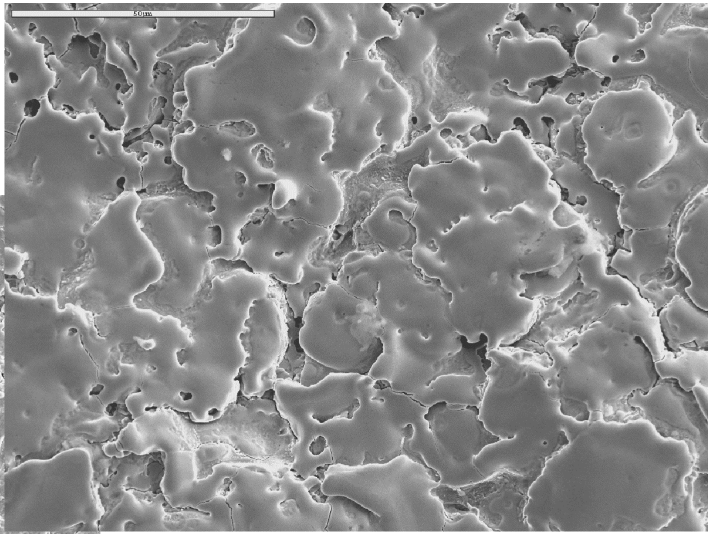
400 pulses

S6 - 1.1 J/cm^2



S8 - 0.6 J/cm^2





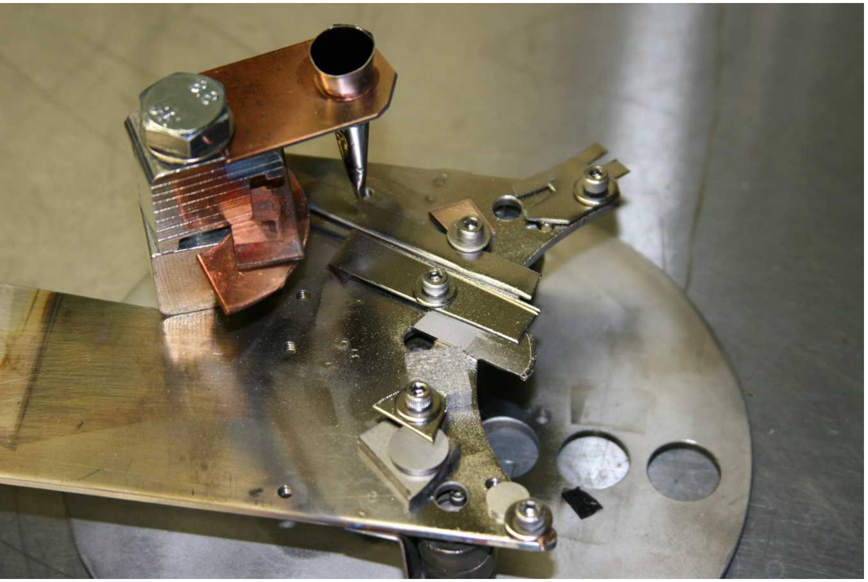
1,000X MAG

R_a increases from ~3.1 µm to 3.3 µm at S6

Mass Loss = 195.5µg

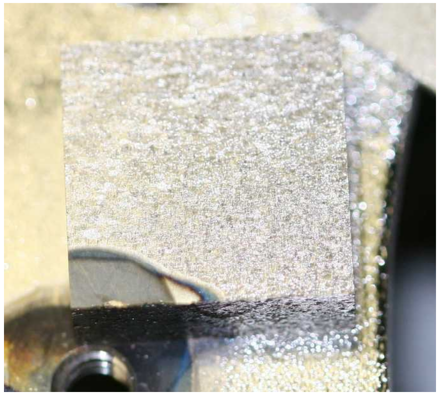
Sample Images after KS2_2400 Series (Nitrogen)

Shown after 400 shots
Beam Center off to Right

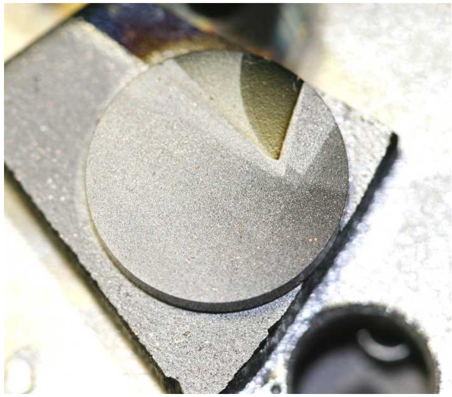


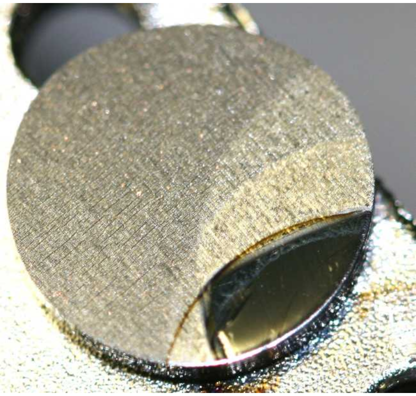
- Samples:
  - M182Perp: ~ 0.75 - 1.15 J/cm2
  - W-0.5%TiC-A, R ~ 6cm to 3.5 cm
    - Sample fell off after ~ 100 shots
  - W-0.5%TiC-H, R ~ 6cm to 3.5 cm
  - W25Re: R=4.5 cm to beyond 9cm radius
  - M168 Polycrystalline Tungsten: ~ 1.15 - 1.5 J/cm2
  - Ta Cone at large radius
- Only 2 Fcups worked: Center (1.7 J/cm^2 ave $\pm$ 30%) and Bottom (1.15 J/cm^2 ave $\pm$25%). Sample exposure normalized to closest FCup
- Vacuum ~ 1e-5 Torr. Ta Cone LOST 1 mg. We need to repeat more systematically to understand mass loss numbers better

Ta Cone: deposition on cone sides



M168 Poly W



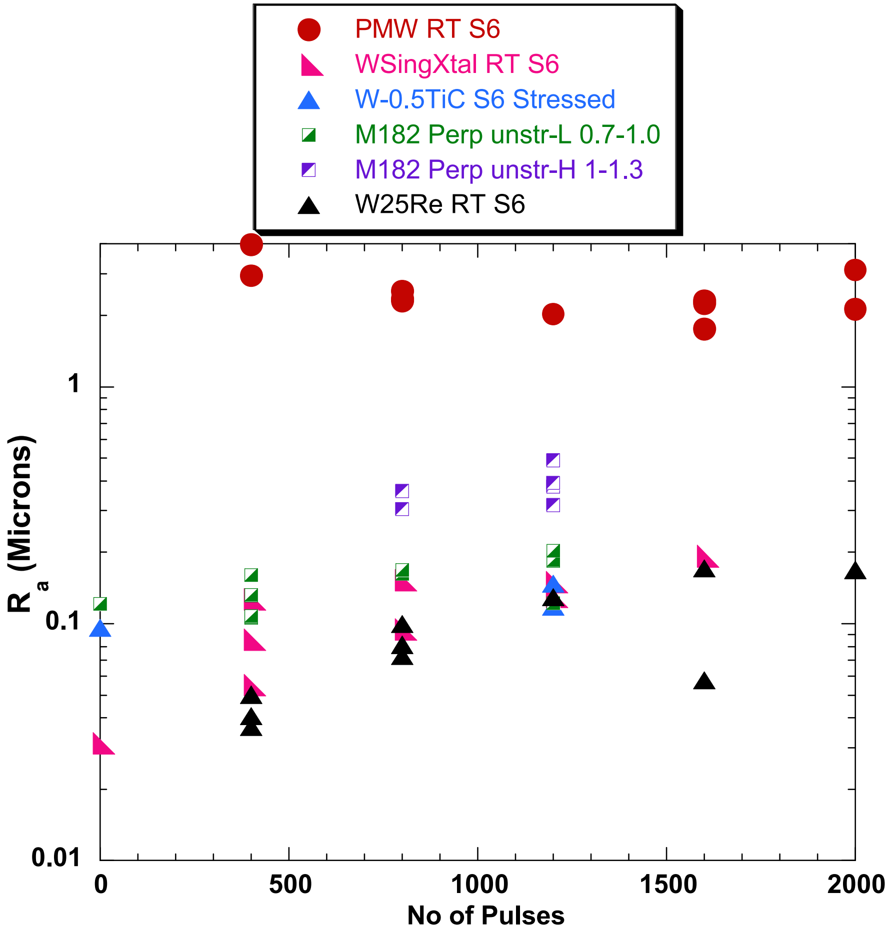


M182Perp (L) Single Crystal (R)

Roughness Measurements

RHEPP-1 Surface Roughening, KS2000 Series + KS2-1200

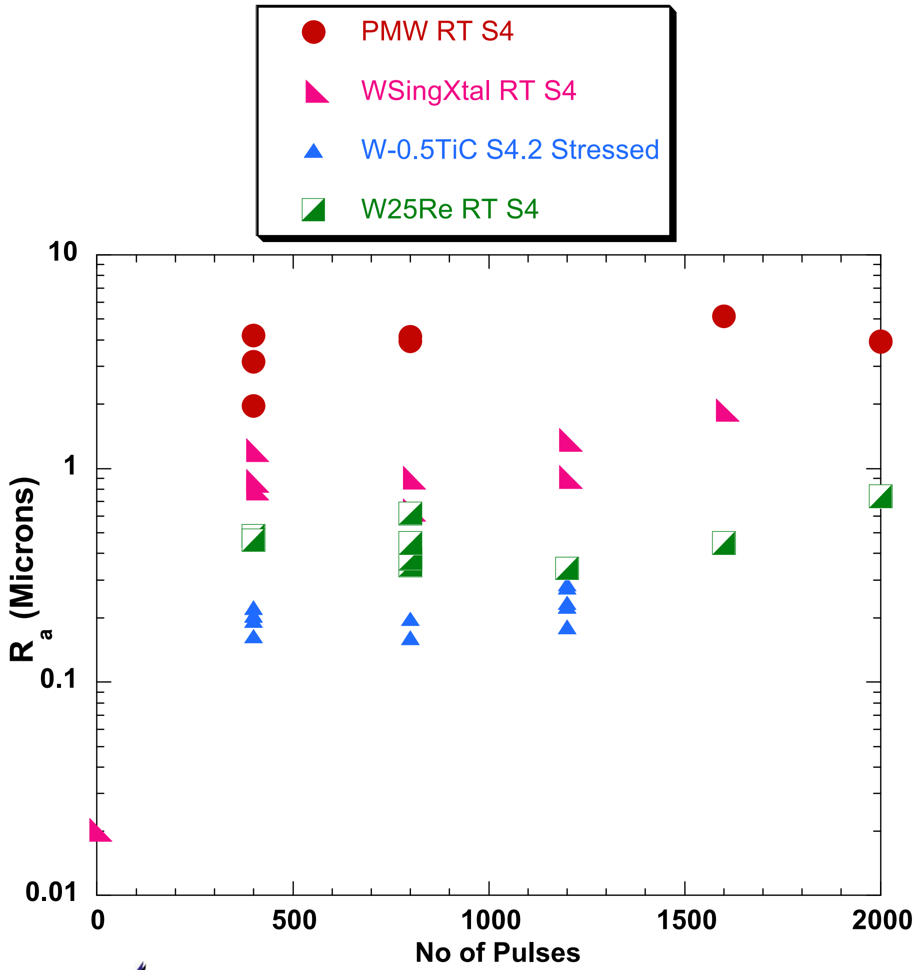
Evolution of R_a Roughness, PMW + SIngXtal, other Ws: PM W is roughening Champ, but only one that tends to saturate



- Red Dots - PMW RT S6, for comparison (1.1 J/cm^2). Data saturates above 400X
- Pink - SingXtal RT S6: R_a starts low, but increases w/o saturating
- W-TiC stressed, M182 perp comparable to W25Re.

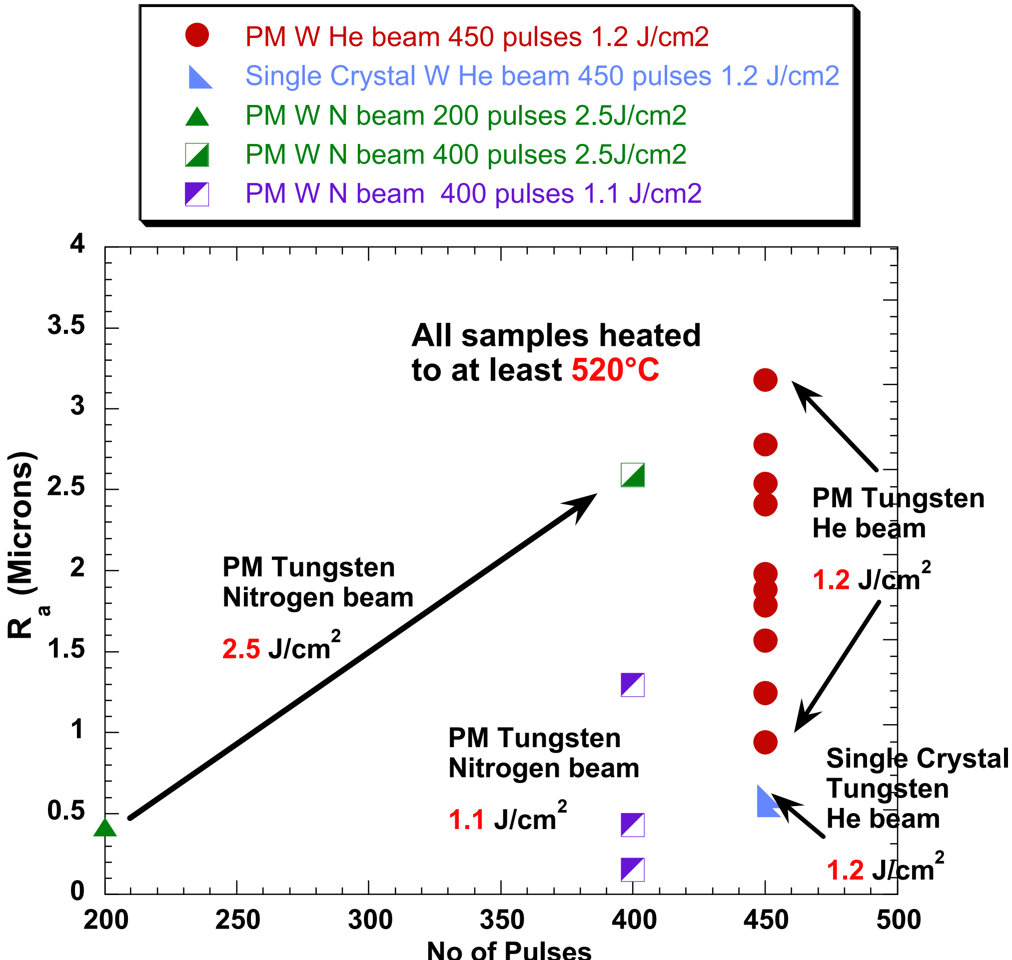
RHEPP-1 Surface Roughening, KS2000 Series + KS2-1200

Evolution of R_a Roughness, PMW + SIngXtal, other Ws, S4: PM W is roughening Champ, but only one that tends to saturate



- Red Dots - PMW RT S4, for comparison (1.9 J/cm²). Data saturates above 400X
- Pink - SingXtal RT S4: R_a much higher than for S6
- W-TiC stressed remains low, W25Re exceeds W-TiC

Comparison of R_a Roughness, PMW: He beam produces more roughening with the same fluence (~ 1.2 J/cm²)



- **Red Dots - PM W exposed to He beam, 1.2 J/cm², 450 pulses**
- **Purple Squares - PM W exposed to N beam, 400 pulses, 1.1 J/cm²**
- **He beam roughens PM W worse than N beam (note data scatter). Roughness similar to N beam at 2.5 J/cm² (above melt threshold)**
- **SingXtal W (pink triangles) shows much less roughening at 400 pulses**

Melting the Surface - Experiments

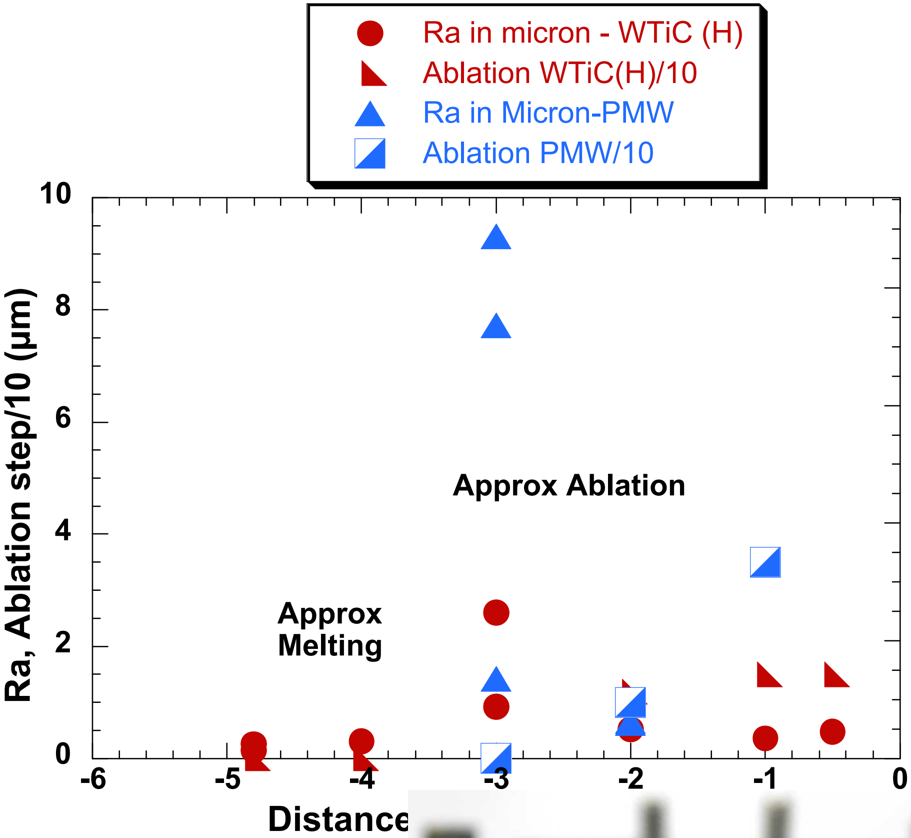
What if we allow the surface to melt? Will this smooth it out? Higher Fluence Test

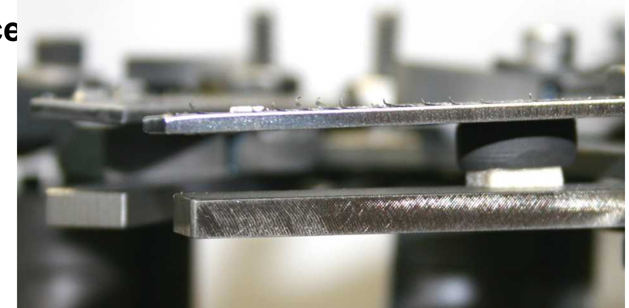
Samples mounted before Start
Beam Center off to Right

Nitrogen beam

- Samples mounted at Left:
  - M182Perp
  - W-0.5%TiC-Argon (Kurishita)
  - W-0.5%TiC-Hydrogen (Kurishita)
  - W25%Re
  - PM Tungsten
  - Single Crystal W
  - Mo
  - Nb
  - Cu 3 9s
  - Cu 5 9s
- ‘Normal’ exposure towards Left. Beam center at right (up to 10 J/cm^2)
- PM Tungsten strips used to mask samples
- Vacuum ~ 1e-5 Torr

Roughening behavior of W-0.5%TiC(H), PM W at high fluence: R_a highest at ablation onset. Melting leads to increased roughness

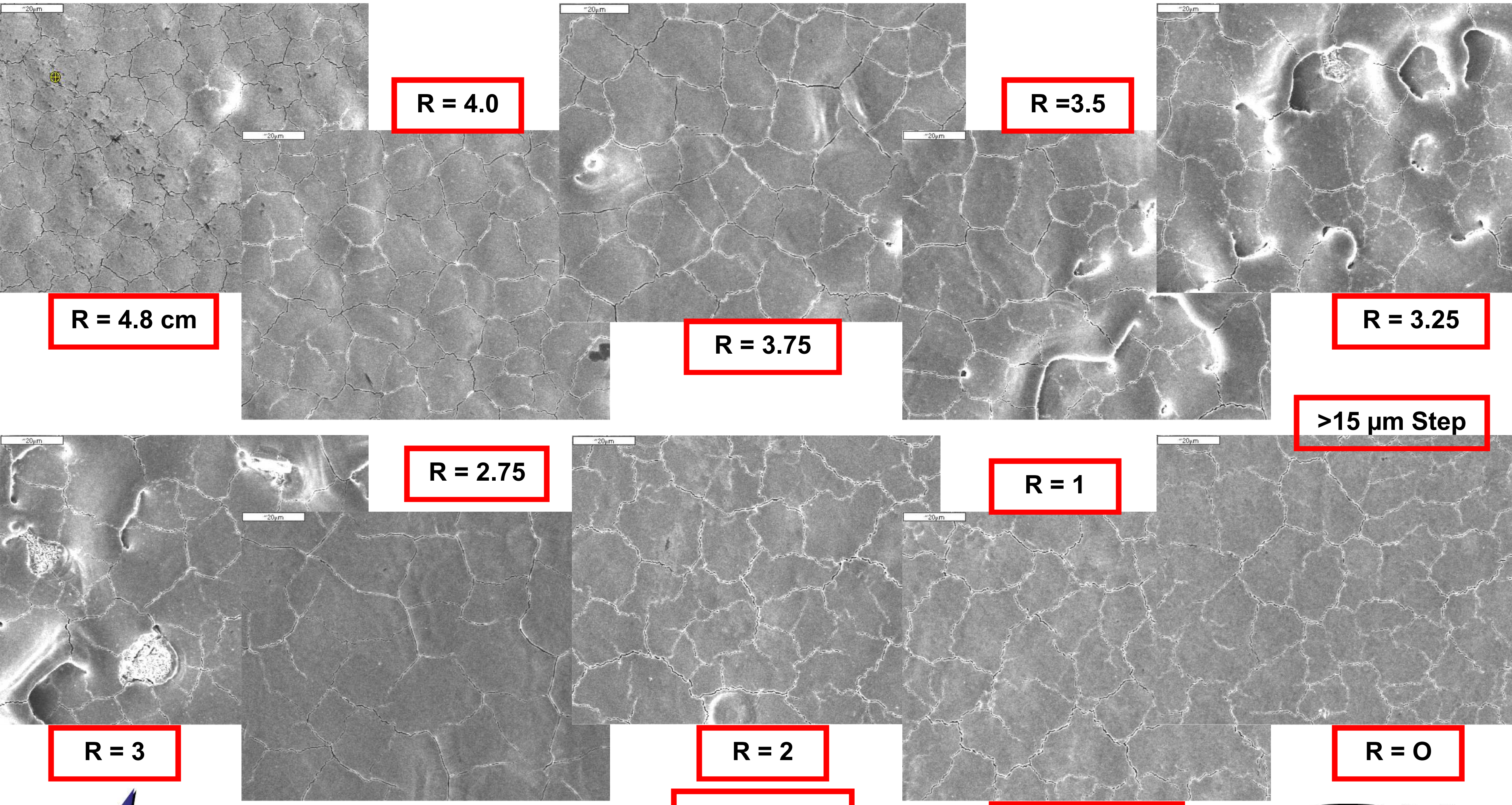




- Two each W-0.5%TiC (H) and PM Tungsten (Snead) samples exposed in fluence range from melting to above ablation threshold (per pulse).
- Sample melt leads to much higher roughness (R_a reaches 2.5 μm for WTiC, 9.5 μm for PM W)
- Roughness reduced beyond ablation threshold, but 15 μm (WTiC) to > 35 μm (PMW) material removed after 400 pulses
- Similar behavior for Mo, Cu, Nb. Ablation steps exceeding 35 μm observed (> 900Å/pulse removed)
- BIG surprise: W25Re. Hardly ANY roughening.
- (LEFT): ‘fingers’ protruding from W shield

Nitrogen Beam

SEMs, W0.5%TiC (H), S4.8 to BEAM CENTER: Same roughness at both extremes, 15 µm Step at R = 1 cm (400 pulses)

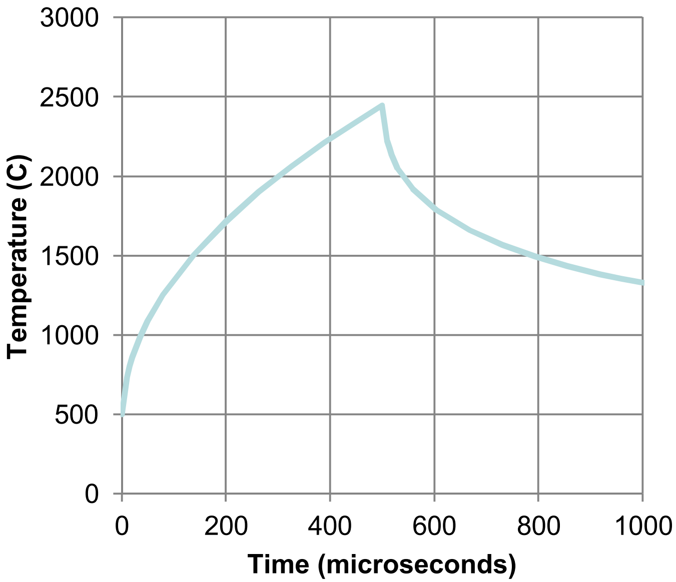


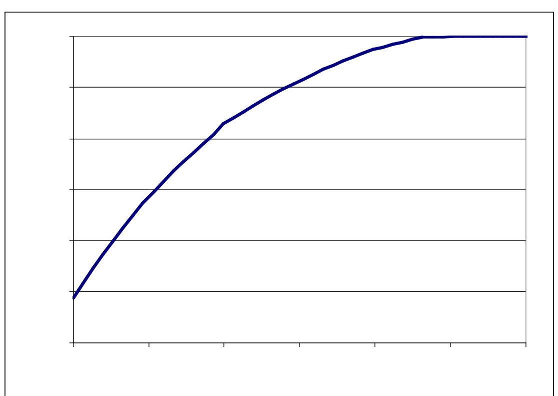
1000X Mag All Images

Stress Modeling (Jake Blanchard)

THE UNIVERSITY of WISCONSIN MADISON

Fracture Modeling: Comparison of Tungsten exposed to IFE and MFE ELM Conditions



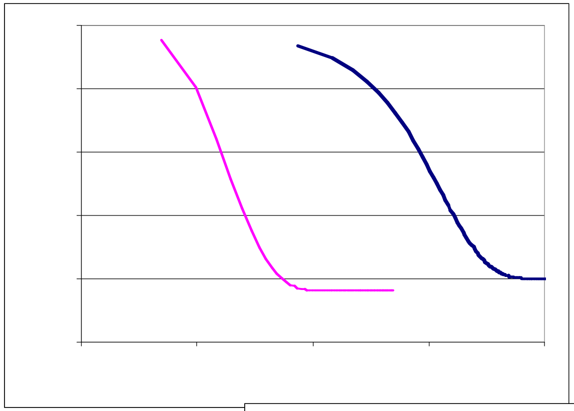


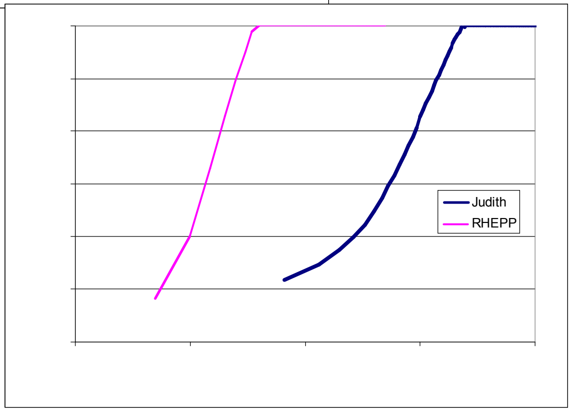
- 3 mm Tungsten on ferritic steel exposed to single heat pulse. Fluence: 0.7 MJ/m^2 over 500 μsec. $T_{initial}$ = 500C, Tungsten properties from ITER Material Properties Handbook.
- Heat deposited at surface
- (Top Left): Surface temp reaches ~2500C
- (Bottom Left): Plastic Strain reaches 1%, gradient to >250 μm depth

Materials Modification Laboratory

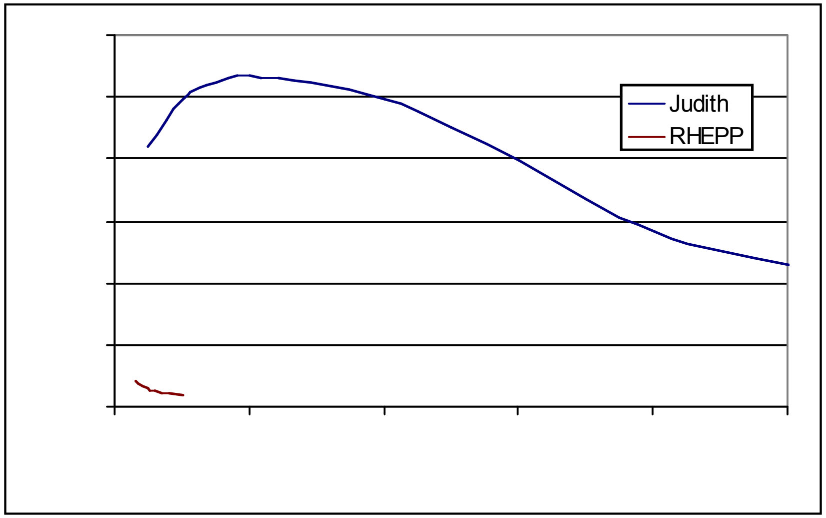
Sandia National Laboratories

Unlike RHEPP heating, the ELM-like pulse produces fracture stresses at the fatigue crack threshold after one pulse





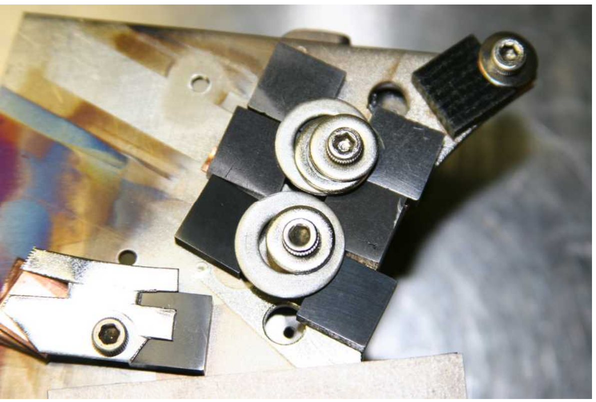
- (Top Left) RHEPP pulses with fluence chosen to reach same surface maximum temperature - 2500C
- (Mid Left) Plastic Strain Curves: Both effects MUCH deeper for the ELM case
- Bottom: Stress Intensity for the 'ELM' case at 25 MPA-m$^{0.5}$ - at fatigue cracking threshold for tungsten (20-40 MPA-m$^{0.5}$). RHEPP at ~ 2 MPA-m$^{0.5}$
- This could explain why RHEPP thermomechanical effects take hundreds of pulses to develop.

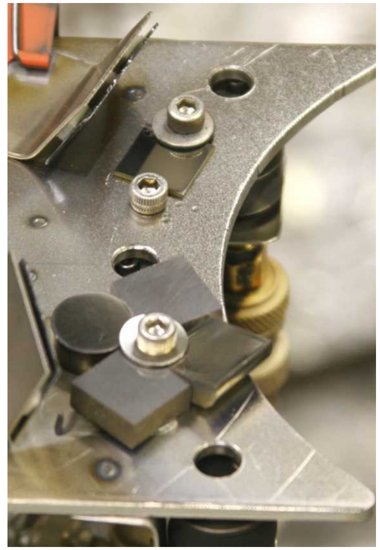


Carbon and Velvet Materials

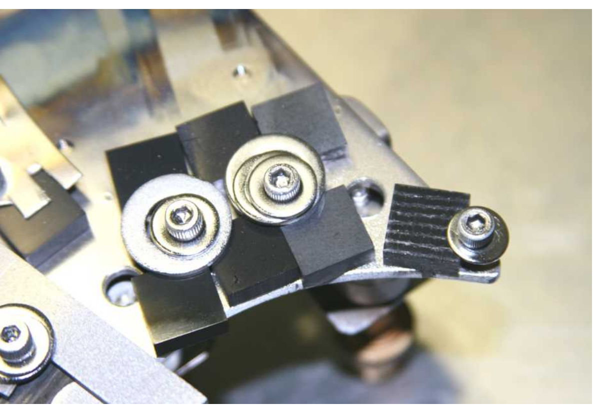
Several carbon samples from Juelich exposed to 400 pulses @ 1-1.25 J/cm2: All lose less mass than PM tungsten

Samples mounted (3, HI and LO) before Start, Beam Center off to Right



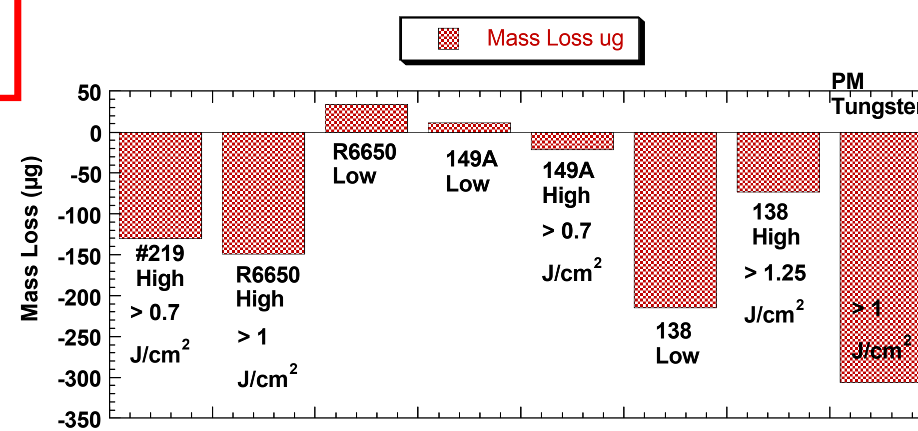


(Above) REFERENCE PM Tungsten between screws



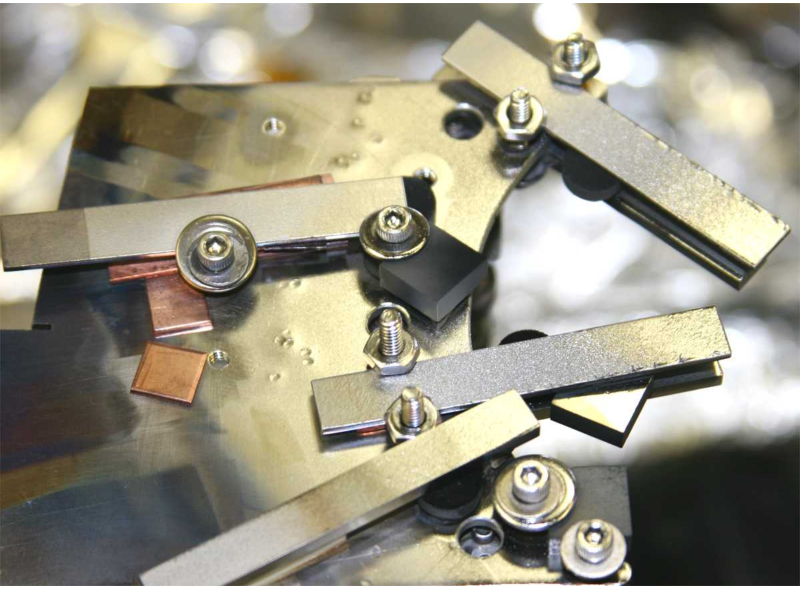
(Above) After 400 shots

- Several C samples exposed at HI (above) PM W 1 J/cm^2 level, and LO (below), as per picture at left.
- Samples:
  - 219 - CFC, PITCH/PAN fibers, HI only
  - R6650 - isotopic fine grain graphite
  - 149A - Ti-doped RGTi from Russia
  - 138 - unidirectional perp CFC (MFC1) from Japan
- All these lost LESS mass at LO and HI than PM W after 400 pulses (below)
- Mass GAIN below due to Cu contamination due to Beam. Not known why 138 HI lost less mass than 138 Lo.



MAP Nitrogen

Higher Fluence exposure of Juelich Carbons: Beyond 1.3 J/cm^2 fluence/pulse leads to significant mass loss



Samples mounted for higher fluence compared to C400 (Below). Tungsten shields extend towards beam center (right)

- **Samples**:
  - R6650 Repeat at 1.3 - 1.5 J/cm^2
  - Pyrolytic Graphite cut perpendicular to C-Planes: 2 - 4 J/cm^2
  - 149A - Repeat at 1.5 - 2 J/cm^2
- **Results:**
  - R6650 roughened from 0.18 to 3 μm, 2 μm step even at 1.3 J/cm^2 (50Å ablative loss/pulse)
  - Pyrolytic: almost 4 μm step at 2 J/cm^2, beyond measurement ability at 4 J/cm^2
  - 149A: roughened from 0.15 to 0.6 μm, mass loss likely but not confirmed

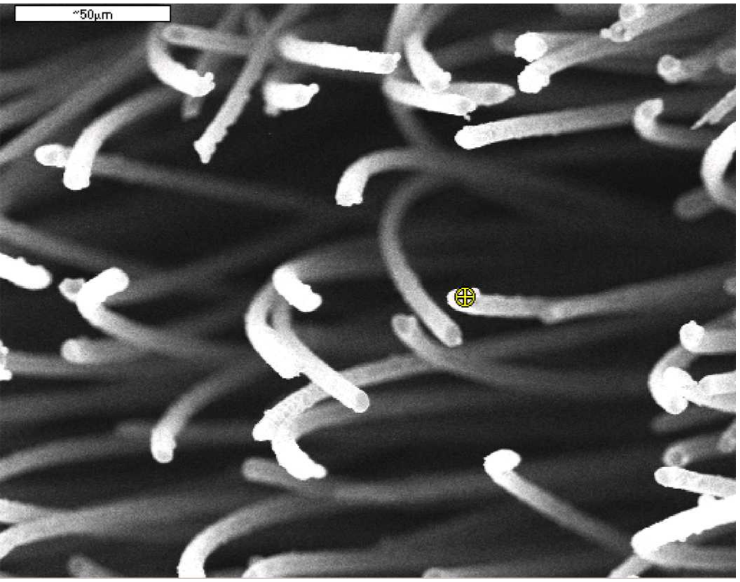
Earlier C400 Series (from Previous Slide)

RHEPP-1 Surface Roughening

Tungsten-coated Carbon Velvet survives 1600 pulses amazingly well

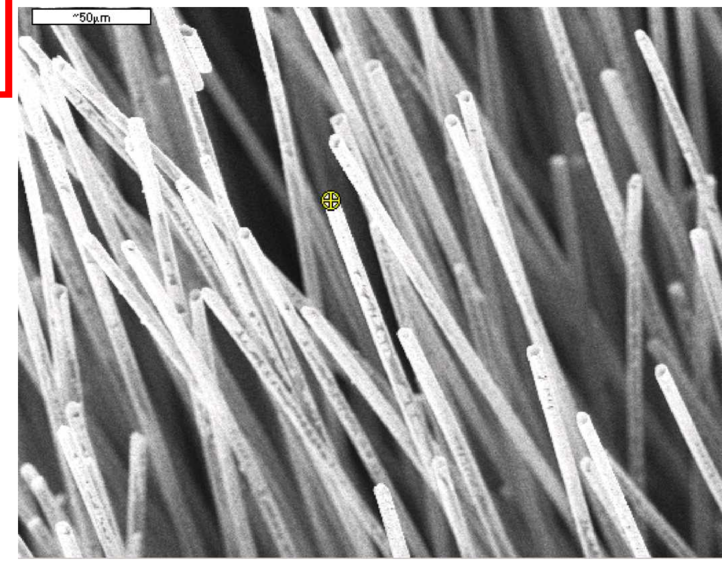
From T. Knowles, ESLI

Carbon PAN fibers w/ 1.6 µm W coating, 2% areal coverage



(RIGHT)
520C (nominal), 1600 pulses, 1.5 J/cm^2/pulse

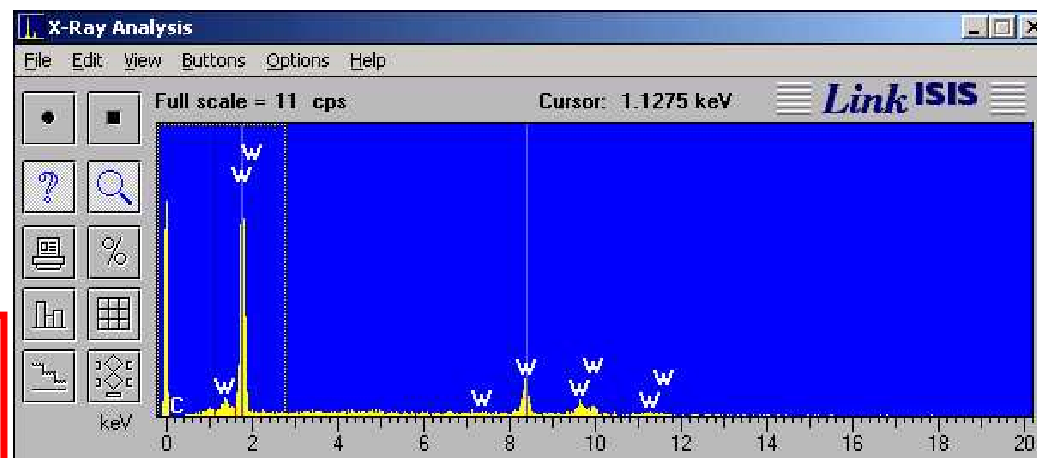
NOTE: W remaining on tips (see below) and sides



(ABOVE)
RT @ ~ 2.8 J/cm^2, 1600 pulses

NOTE: bent tips, flat ends have W removed, rounded ends still have W

This reinforces recent JUDITH result: Mechanical strength of PAN fibers may more than make up for their lower Thermal Conductivity compared to PITCH



EDS scan of tip (cross): W rich