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Title: Zirconium Deformation Behavior: Insights from EBSD Measurements

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Los Alamos
NATIONAL LABORATORY

Zirconium Deformation Behavior: Insights from EBSD Measurements

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The deformation of crystal-bar zirconium was investigated as a function of strain and strain rate through electron back-scattered diffraction (EBSD) characterization. The resultant data provided spatially resolved information on microstructure and texture evolution, individual twin system activity, and subsequent strain partitioning between twinned volume and parent grains. A range of deformation conditions was represented through quasi-static compression, 4-point beam bend tests at room and cryogenic temperature, and Taylor cylinder impact experiments. Effects from the interplay between slip and twinning deformation modes on anisotropic plasticity are considered in order to address the apparent trend toward isotropy at high rates. The role of various length scales on deformation behavior will be considered, along with the implications of these length scales on the assumptions typically invoked for plasticity modeling.

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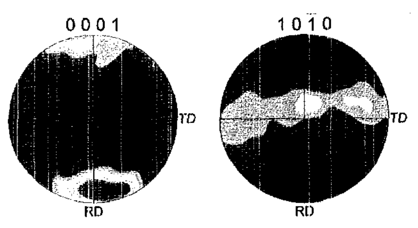
Introduction

- Deformation modes at room and cryogenic temps.
  - Prismatic slip $\{10\bar{1}0\}\langle\bar{1}2\bar{1}0\rangle$
  - $\{10\bar{1}2\}\langle\bar{1}011\rangle$ Tensile (// c-axis) twin
  - $\{11\bar{2}2\}\langle\bar{1}\bar{1}23\rangle$ Compressive twin
  - $\{11\bar{2}1\}\langle\bar{1}\bar{1}26\rangle$ Tensile twin
- Zr good hcp candidate for study ⟶ ductility combined with manageable number of slip and twin systems.
- ***Texture evolution*** and resultant ***Plastic anisotropy*** affected by twin reorientation.
- EBSD provides mesoscale perspective with twin system characterization.
- Previous work by Reed-Hill, Tenckhoff, Salinas Rodriguez.

Zr Samples as f($\dot{\varepsilon}$)

- Quasi-static (10^{-3} s^{-1})
  - Tension
  - Wire-Drawn
  - Compression
- Hopkinson Bar (2-3 x 10^{3} s^{-1})
  - Tension
  - Compression
- Taylor Cylinder Impact (~ 10^{4} s^{-1})
  - 243 m/s
  - 101 m/s
  - Goal: Explain anomalous plastic response in Taylor cylinder samples.

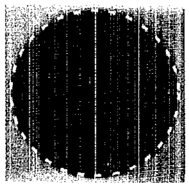
Initial Texture



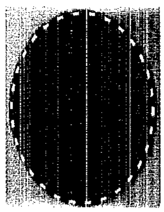
- Clock-rolled and recrystallized crystal-bar Zr plate
- In-plane samples

Profiles of r-θ Plane in Compression as $f(\dot{\varepsilon})$

Quasi-static 298K

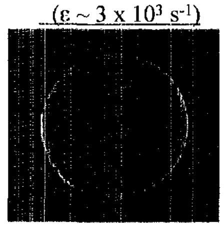


Through-thickness
r = 1.59

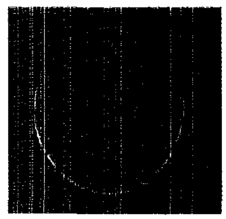


In-plane
r = 11.2

Hopkinson Bar
($\dot{\varepsilon} \sim 3 \times 10^3\ s^{-1}$)

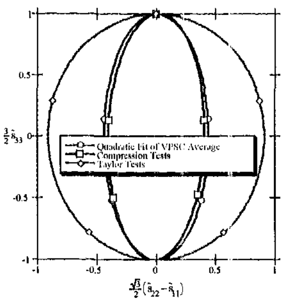


298K Through-thickness
r = 1.05

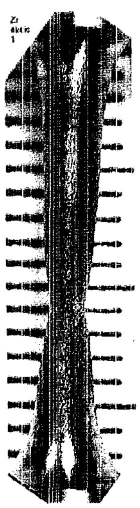


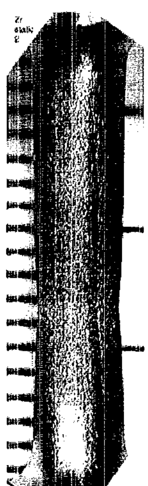
298K In-plane
r = 1.92

Taylor Cylinder

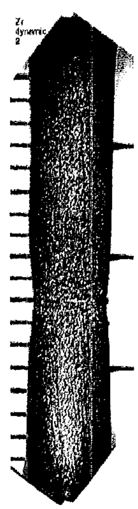


In-Plane Tension at QS and HB Rates



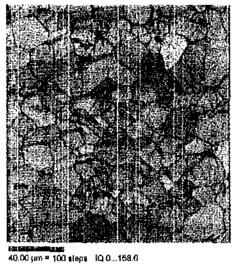


2 mm

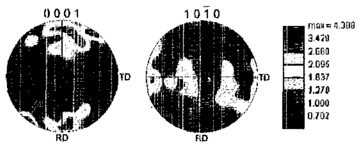


$0.001\ s^{-1}$ $1100\ s^{-1}$

Quasi-static, 9% Compression



{10$\bar{1}$2}<10$\bar{1}$1> T
{11$\bar{2}$2}<11$\bar{2}$3> C
{11$\bar{2}$1}<11$\bar{2}$6> T



- Very little twin fraction, little reorientation
- Slip accommodates majority of deformation

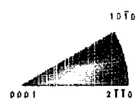
Quasi-static, 13% Compression

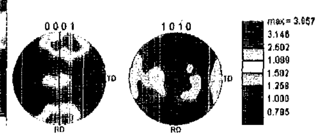
Image Quality/Twin Bdy Map

Twin Bdy Key

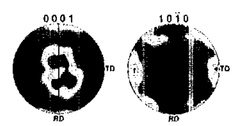
{10$\bar{1}$2}<10$\bar{1}$1> T
{11$\bar{2}$2}<11$\bar{2}$3> C
{11$\bar{2}$1}<11$\bar{2}$6> T

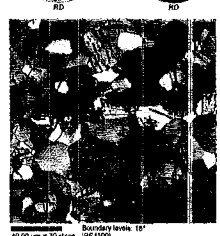
- Although favorably oriented for slip, fine tensile twins prevalent.
- Modest reorientation





Crystal Direction Map wrt CA





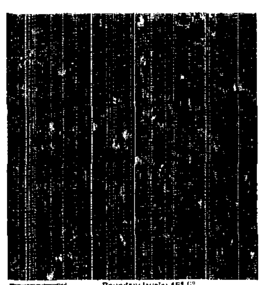
ND = Radial Dir.

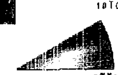
Taylor Factor Map

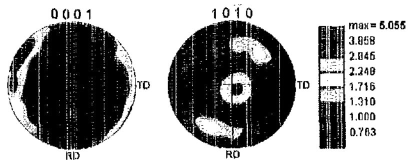
Taylor Factor Scale

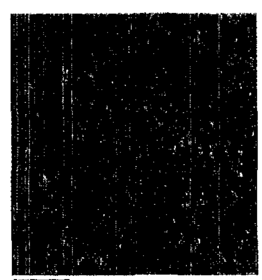
- Taylor factor map contrasts regions by relative resistance to yield by prismatic slip, as a function of orientation and strain path.
- Initial tensile twins reorient into less favorable deformation by slip.

Tensile, Quasi-static, 298K





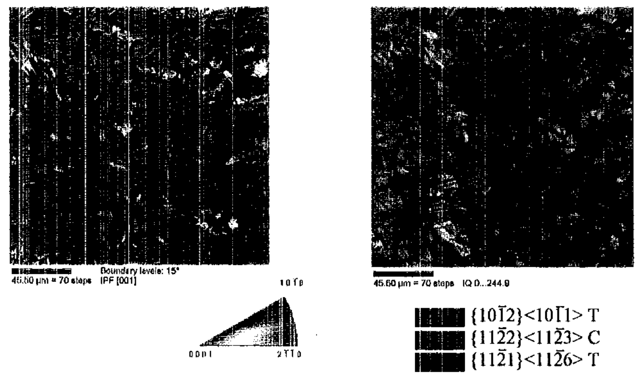


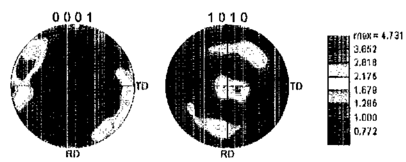


- $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
- $\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
- $\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T

- $\langle 10\bar{1}0\rangle$ // tensile axis texture
- Little twin activity, no compressive twins

Tensile, Quasi-static, 76K





- <10$\bar{1}$0> // tensile axis texture
- {1122} compressive twins active

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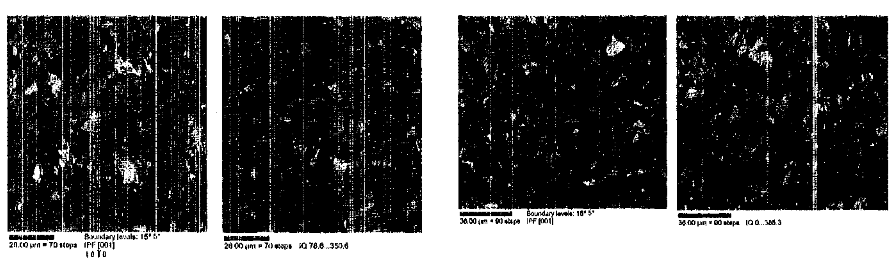
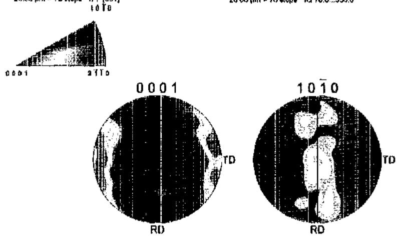
Wire-drawn, ε = 21%, 40%

ε = 21% ε = 40%





ND = Axial

- Curly microstructure analogous to bcc
- Deformation intensified near boundaries to accommodate compatibility
- Insignificant twinning

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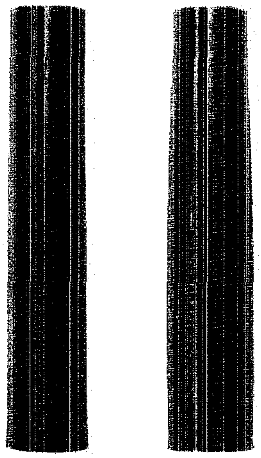
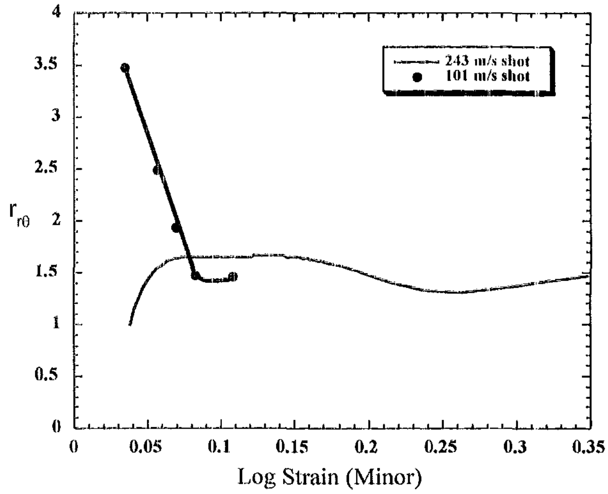
Taylor Cylinder r-values



101 m/s   243 m/s

- Dramatic difference in anisotropy in r-θ plane with axial position for 101 m/s sample.



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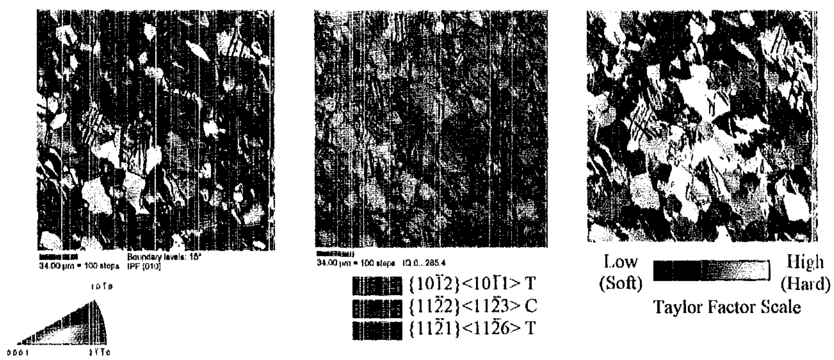
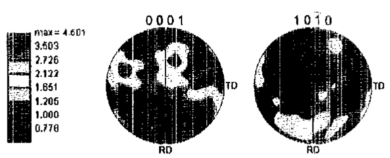
243 m/s, Near Tail





- Significant reorientation has extended to tail end of cylinder.

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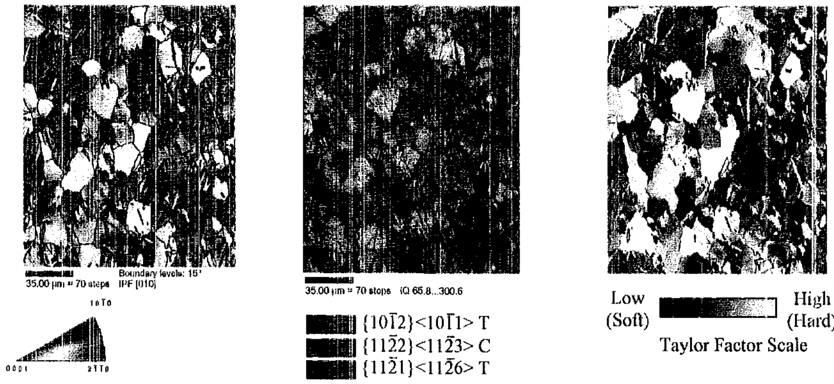
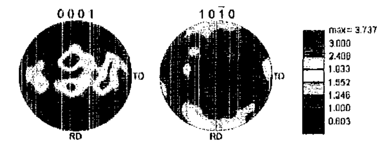
243 m/s, 5 mm from tail





- Stable orientation, <0001> ~20° from CA, nearly established only 5 mm from tail.
- Subsequent deformation occurs in reoriented structure.

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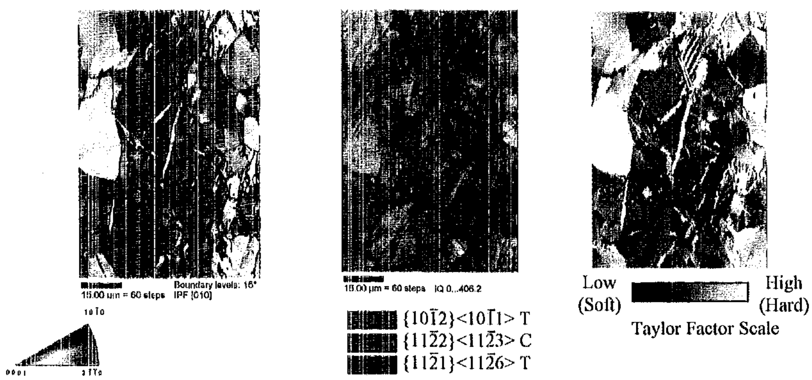
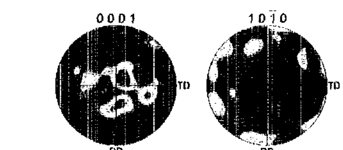
243 m/s, z = 5 mm





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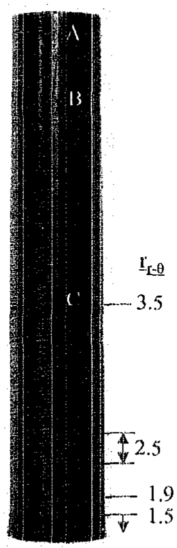
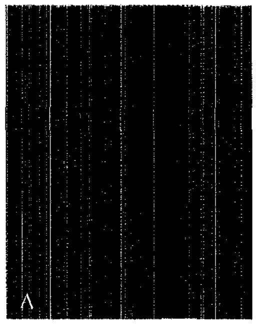
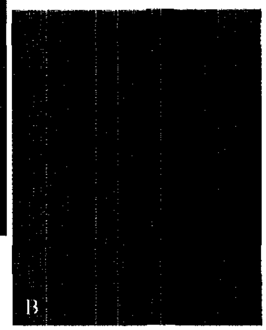
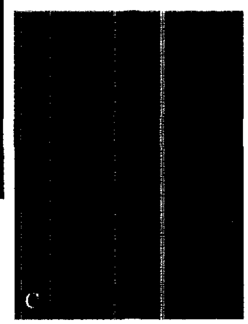
Micrographs from 101 m/s Zr Taylor









- Twin activity evident at very small strains
- Monotonic increase in twin activity with axial position

20 μm

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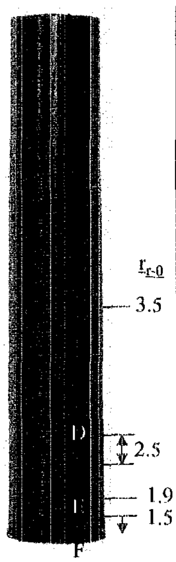
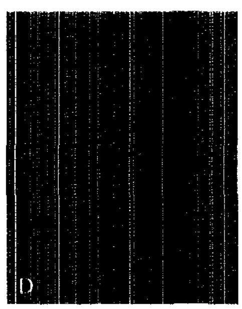
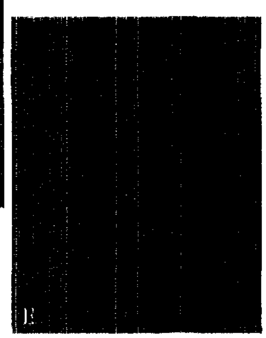
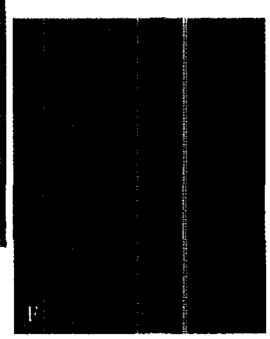
Micrographs from 101 m/s Zr Taylor









- Difficult to resolve twins at larger strains
- Some grains appear to be devoid of twins

20 μm

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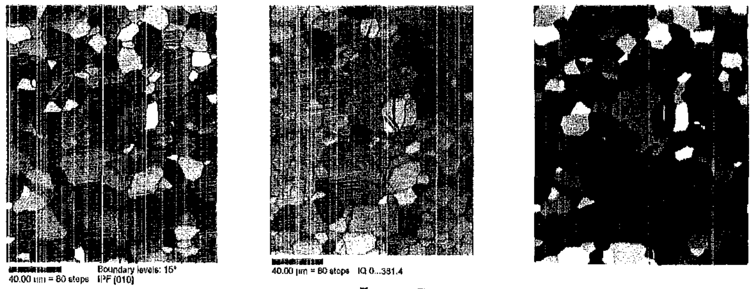
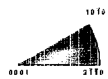
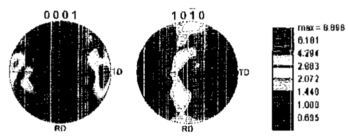
101 m/s, z = 36 mm





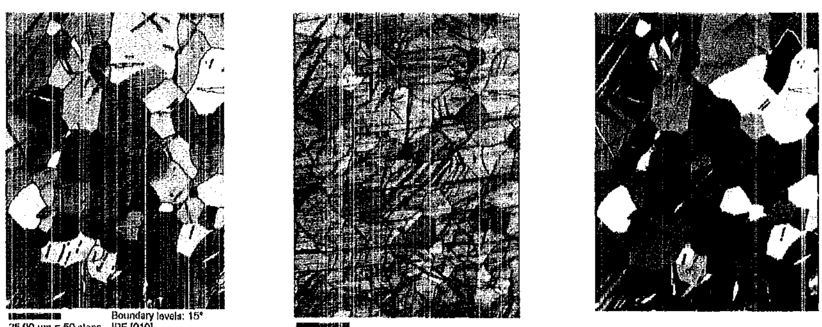
$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}\bar{6}\rangle$ T

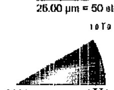
Low (Soft) — High (Hard)
Taylor Factor Scale



- Twins present at strains on order of 1%.

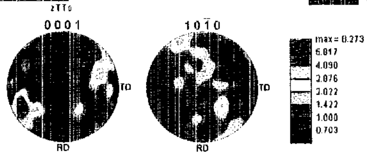
101 m/s, z = 35 mm





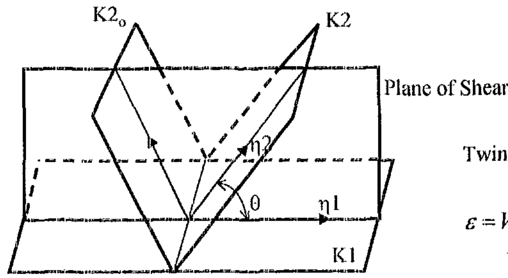
$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}\bar{6}\rangle$ T

Low (Soft) — High (Hard)
Taylor Factor Scale



- Twinning progresses rapidly by ~ 2% strain.
- $\{10\bar{1}2\}$ tensile twin dominant.

Deformation Twin Strain Contribution



Twin Shear = $\frac{\text{Shear displacement}}{\text{Twin width}} = \gamma = 2\cot\theta$

$$\varepsilon = V \cdot \gamma \cdot \mu$$

V = Volume fraction twinned
μ = Schmid factor

- Twinning contribution to deformation relatively small compared to slip
- However, may be important at small strains
  Need information on volume fraction twinned

e.g. If V = 50% and μ averages 0.4 for the activated twins, twinning can completely account for following ε:

System	γ	ε%
{1012}<1011> T	0.167	3.3
{1122}<1123> C	0.225	4.5
{1121}<1126> T	0.63	12.6

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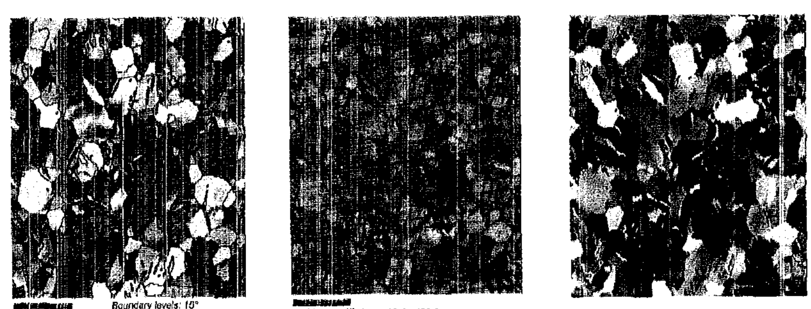
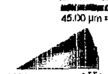
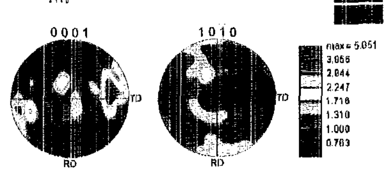
101 m/s, z = 22 mm





$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T

Low (Soft) — High (Hard)
Taylor Factor Scale



- At ~7% strain, tensile twins begin to noticeably affect texture.
- Texture evolution at quasi-static rates and comparable strains much less due to less twinning.

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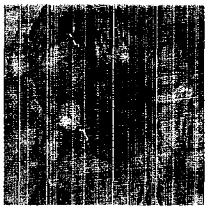
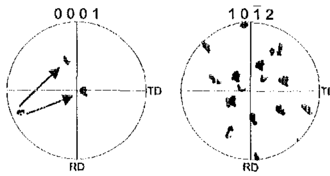
Reorientation from {10$\bar{1}$2} Tensile Twins

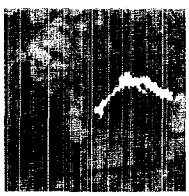


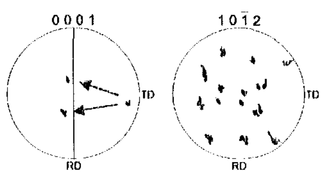


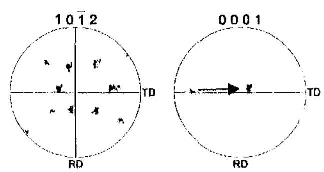
- 85° reorientation of basal pole
- Subsequent growth and deformation produce massive globular twinned regions, accelerated texture evolution.
- {10$\bar{1}$2} shows large tolerance for incoherent growth.

ND = Axial
RD = Major Radial Axis
TD = Minor Radial Axis

Reorientation from {10$\bar{1}$2} Tensile Twins

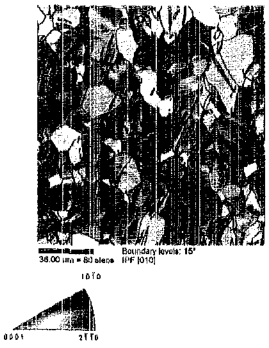






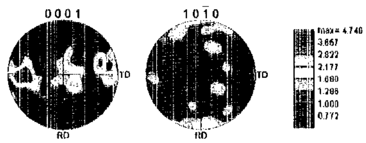
ND = Axial
RD = Major Radial Axis
TD = Minor Radial Axis

101 m/s, z = 14 mm



$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T

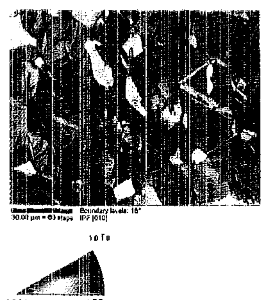
Low (Soft) — High (Hard)
Taylor Factor Scale



Los Alamos

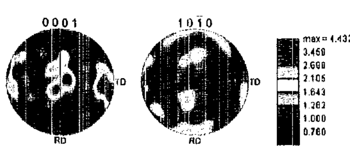
TMS Sp_00

101 m/s, z = 11 mm



Low (Soft) — High (Hard)
Taylor Factor Scale

$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T



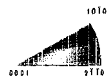
Los Alamos

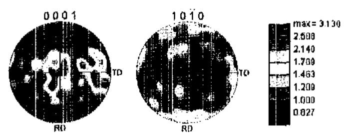
TMS Sp_00

101 m/s, z = 8 mm

{10$\bar{1}$2}<10$\bar{1}$1> T
{11$\bar{2}$2}<11$\bar{2}$3> C
{11$\bar{2}$1}<11$\bar{2}$6> T

Low (Soft) — High (Hard)
Taylor Factor Scale





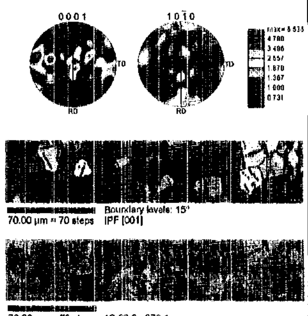
- Compressive twin activity begins, reorients grains to more favorable slip position.

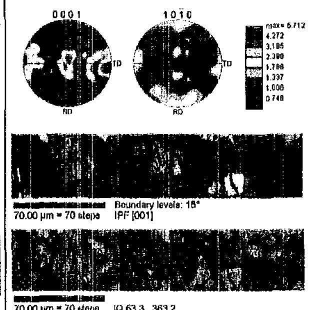
101 m/s Taylor, Transition Region

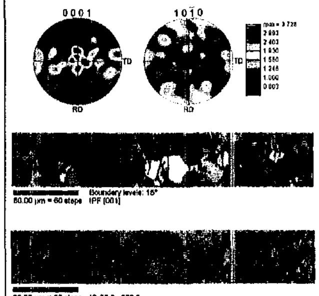
4 mm from Impact interface — 2 mm from Impact interface

r = 2.1 — r = 1.5

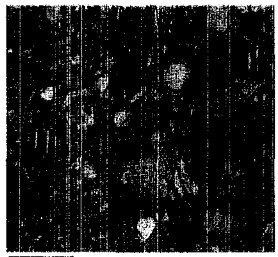
High-r Transition Region | Mid-Transition Region | Low-r Transition Region

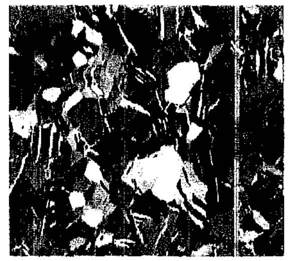




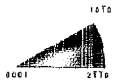


101 m/s, z = 4 mm

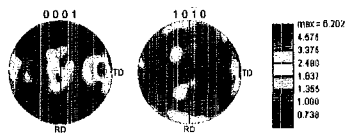




Low (Soft) — High (Hard)
Taylor Factor Scale

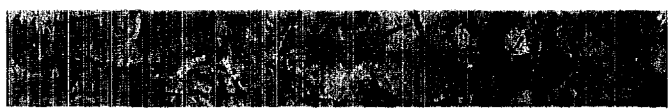


$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T



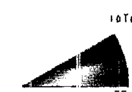
- $\{11\bar{2}1\}$ tensile twins observed as stress increases.

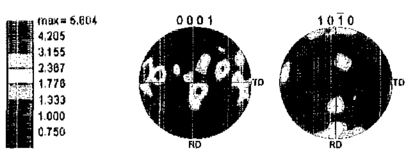
101 m/s, z = 4 mm



80.00 µm = 80 steps IQ 61.6...379.1

80.00 µm = 80 steps Boundary levels: 15°
IPF [001]



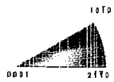


101 m/s, z = 2 mm

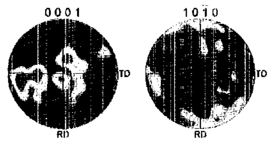
30.00 µm = 60 steps Boundary levels: 15° IPF [001]

30.00 µm = 60 steps IQ 0...370.0

Low (Soft) High (Hard)
Taylor Factor Scale



{10$\bar{1}$2}<10$\bar{1}$1> T
{11$\bar{2}$2}<11$\bar{2}\bar{3}$> C
{11$\bar{2}$1}<11$\bar{2}\bar{6}$> T



- Some regions show massive {10$\bar{1}$2} twins.
- r-value transitioned to that observed throughout 243 m/s sample by this position.

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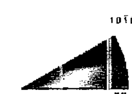
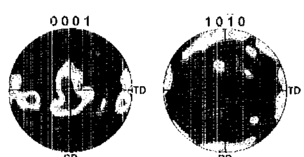
TMS_Sp_00

101 m/s, z = 2 mm

60.00 µm = 60 steps IQ 63.7...359.8

60.00 µm = 60 steps Boundary levels: 15° IPF [001]

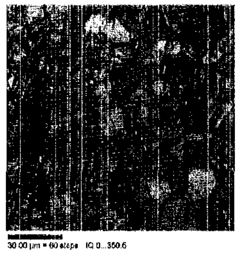


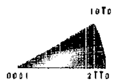


Los Alamos

TMS Sp_00

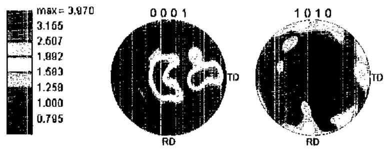
101 m/s, z = 1 mm





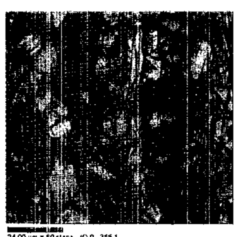
$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T

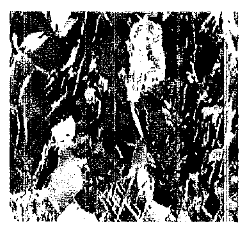
Low (Soft) — High (Hard)
Taylor Factor Scale

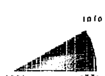


- Texture now nearly fiber about axial direction.
- Results in little r-θ anisotropy.

101 m/s, z = 100 μm

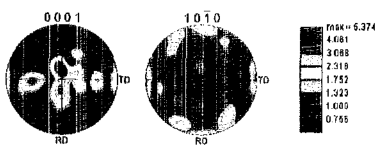






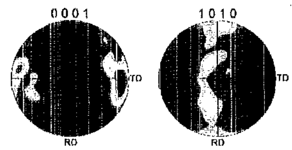
$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T

Low (Soft) — High (Hard)
Taylor Factor Scale

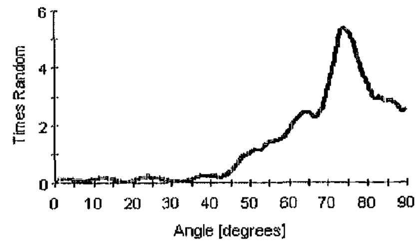


- Slip deformation has obliterated misorientation relationship for many twin boundaries.

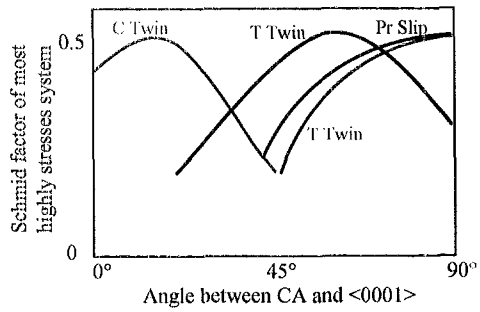
Basal Pole Distribution *vs.* Preferred Deformation Mode



101 m/s, z = 36 mm

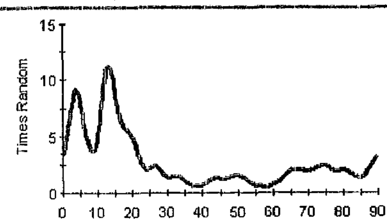


$\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ T
$\{11\bar{2}2\}\langle 11\bar{2}3\rangle$ C
$\{11\bar{2}1\}\langle 11\bar{2}6\rangle$ T
Prismatic slip

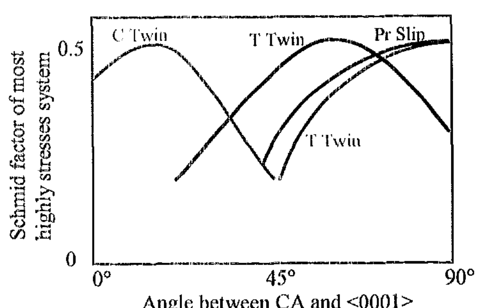


101 m/s Basal Pole Distribution

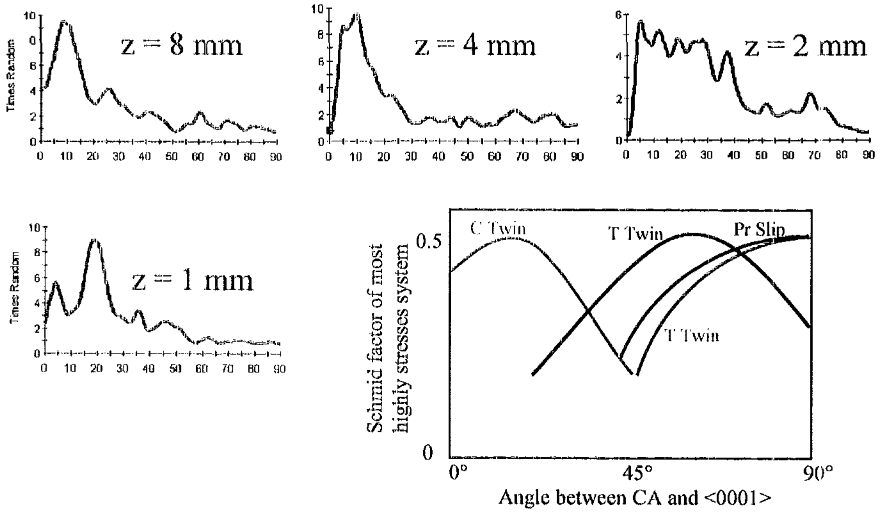
z = 21 mm



z = 11 mm



101 m/s Basal Pole Distribution



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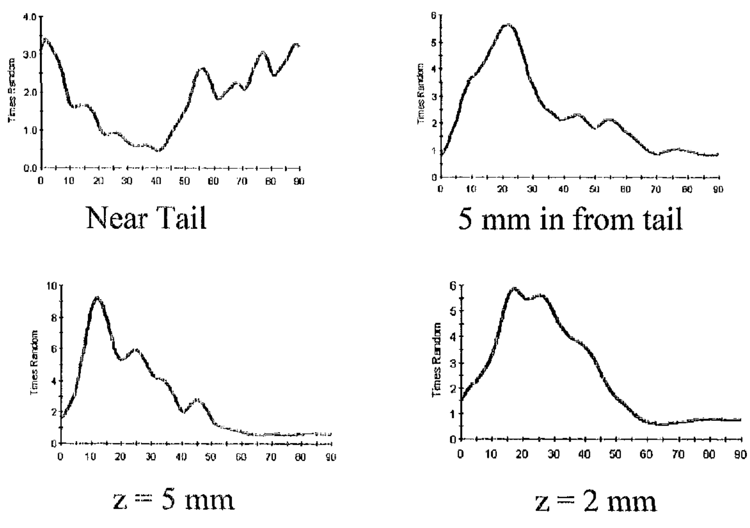
TMS_Sp_00

243 m/s Basal Pole Distribution



Los Alamos

TMS_Sp_00

Conclusions

- Compressive strain and high rates lead to significant $\{10\bar{1}2\}$ tensile twin fraction, despite texture favorably oriented for slip.
  - Rate sensitivity of prismatic slip increases CRSS relative to twin
  - In tension, for same orientation, $\{11\bar{2}2\}$ activation stress relatively higher, resulting in less twin reorientation.
- Increased twinning results in accelerated weakening of r-θ plane texture → less subsequent plastic anisotropy than anticipated.
- Microstructural evolution masked in 243 m/s Taylor sample due to large strain throughout cylinder.
- Twinning less active at quasi-static rates.
  - Texture evolution primarily due to slip, much more gradual than twinning
  - Greater plastic anisotropy from slip in sharply r-θ textured structure
  - Anisotropy directionally sensitive at Hopkinson-bar rates
    - Compressive twins in tension less active than tensile twins in comp.
    - Less twin reorientation in tension leads to greater plastic anisotropy

Los Alamos

TMS_99_00