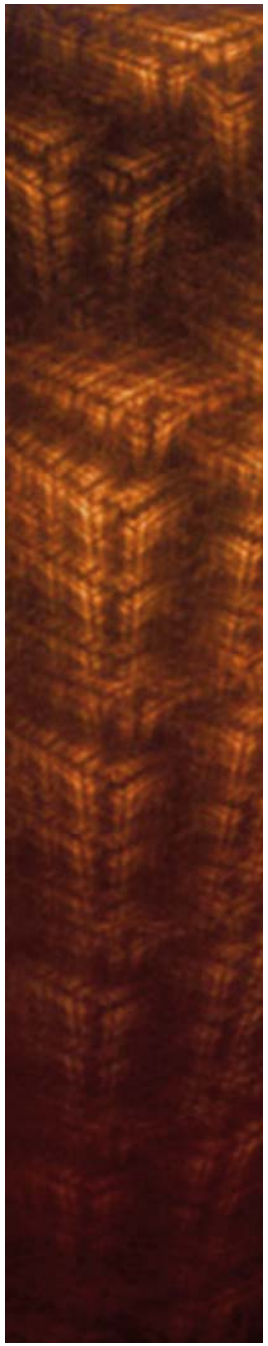


La controvertida microplasticidad del magnesio policristalino

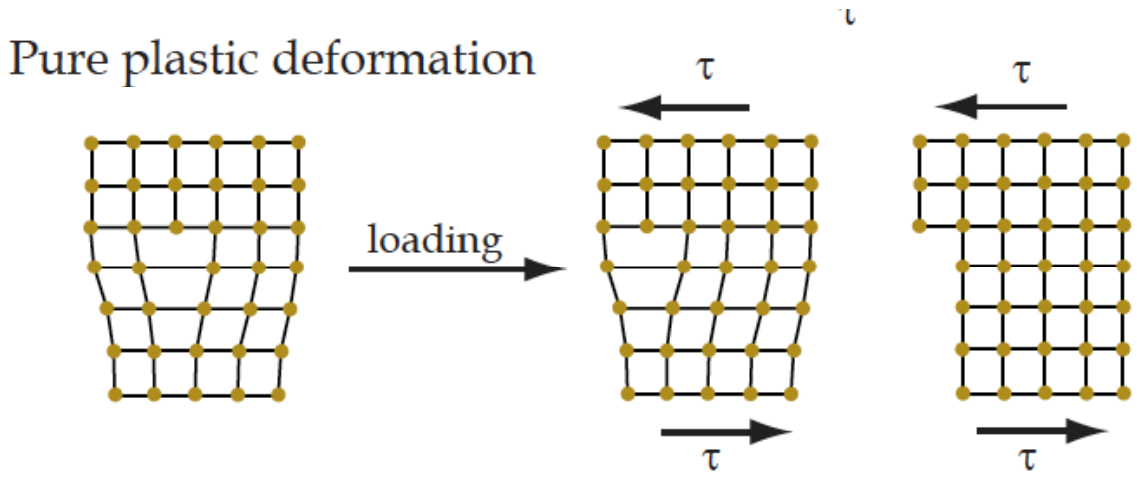
Teresa Pérez-Prado
IMDEA Materiales

Micrografía Carmen Cepeda-Jiménez

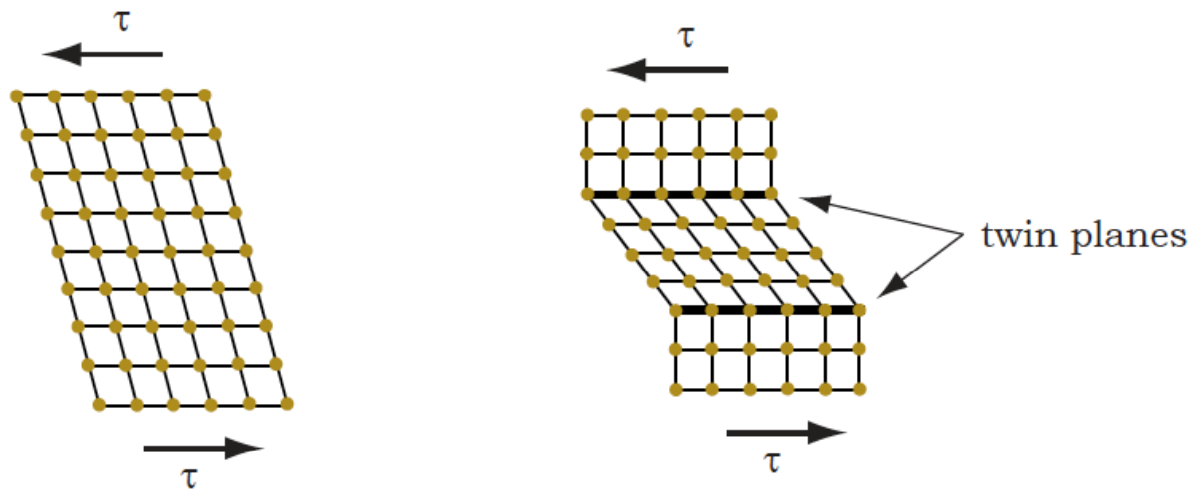
50 Aniversario de la Revista de Metalurgia, CENIM 2015

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

Deslizamiento de dislocaciones

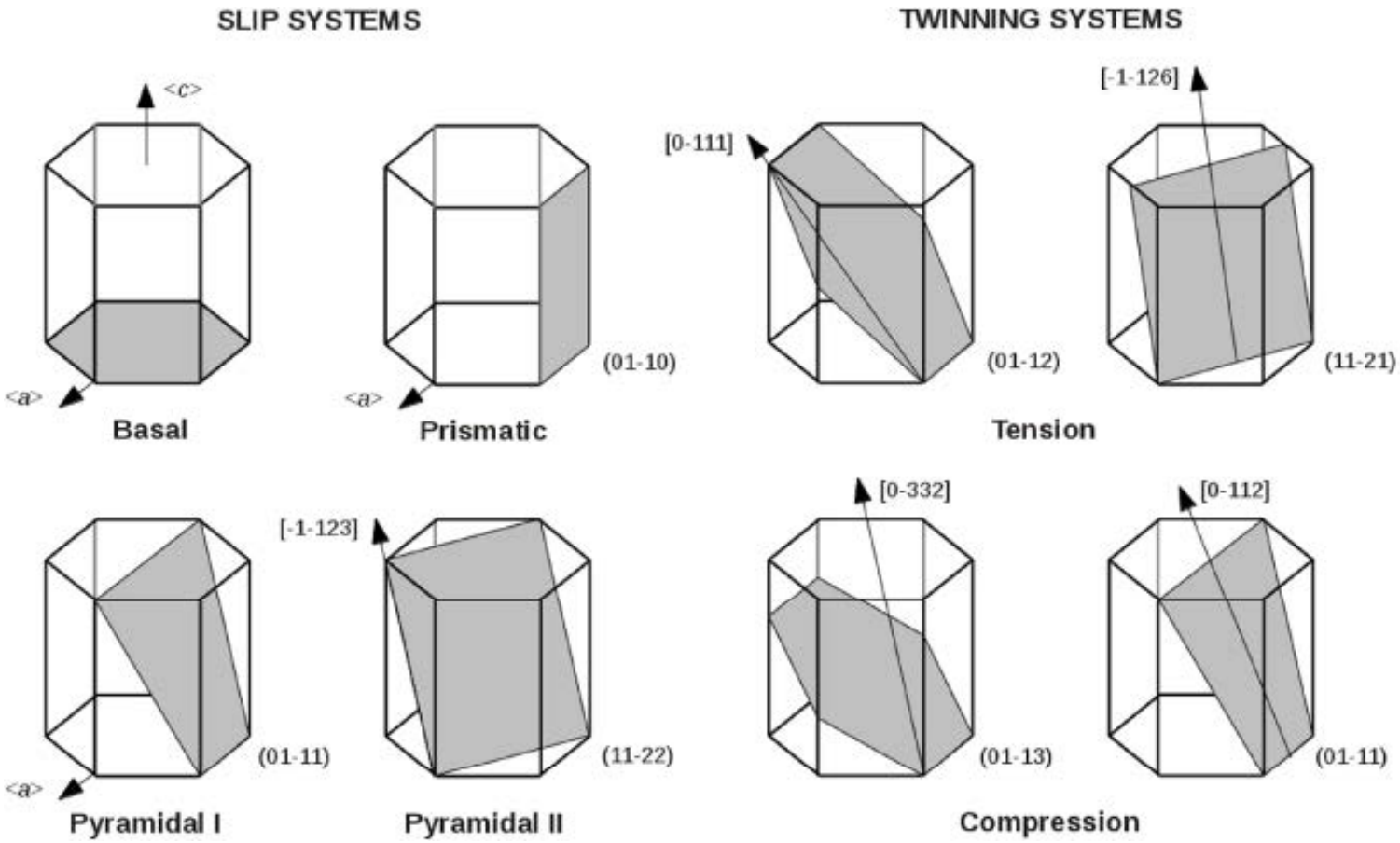


Maclado



Micromechanical modelling of deformation of hcp metals, S. Graff, Helmholtz Gesellschaft, 2008

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

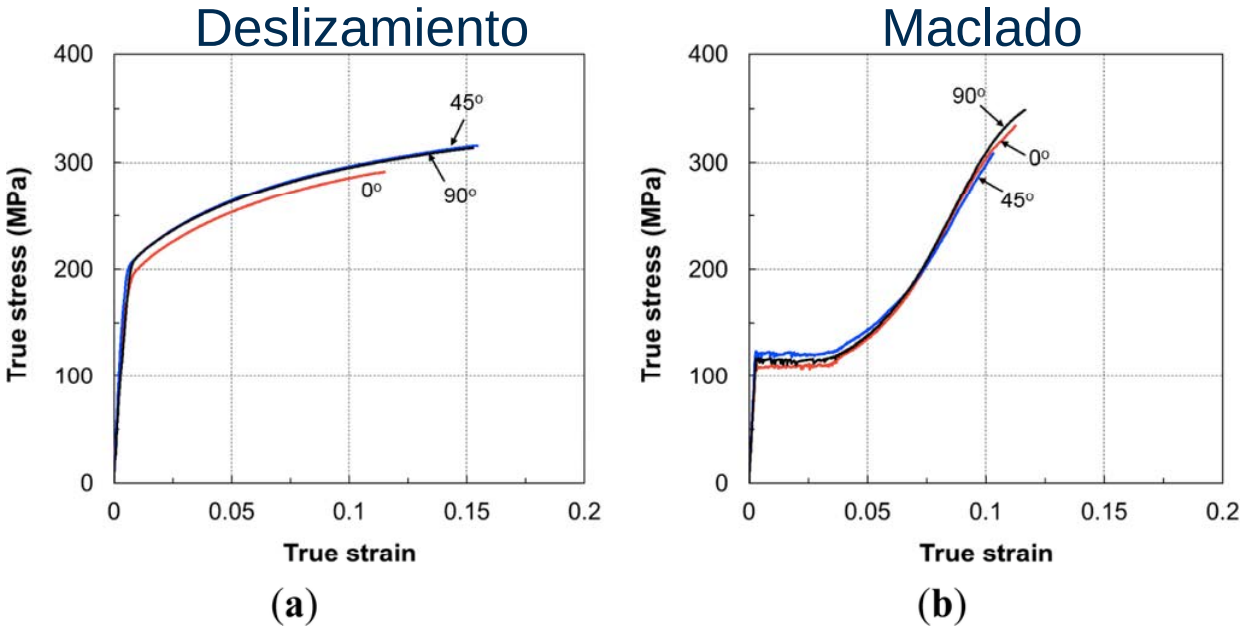


Sistemas de deslizamiento y maclado en magnesio

Advances in wrought magnesium alloys. Ed. by C. Bettles and M. Barnett. Cambridge: Woodhead publishing;2012.

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

Deslizamiento vs. maclado



AZ31, 25°C, 10^{-3} s^{-1}, Nguyen et al. Materials , 2014

Advances in wrought magnesium alloys. Ed. by C. Bettles and M. Barnett. Cambridge: Woodhead publishing;2012.

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

MONOCRISTALES

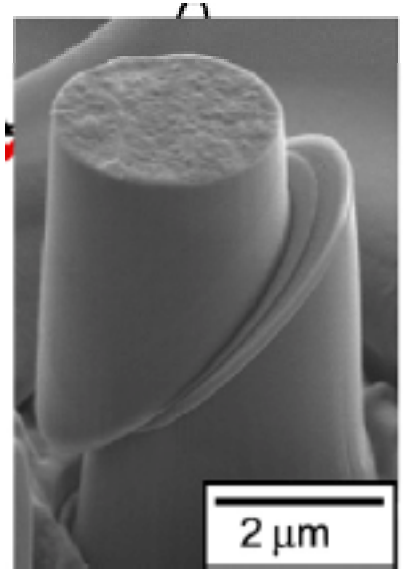
Maclado:
Textura, baja T,
alta velocidad de deformación

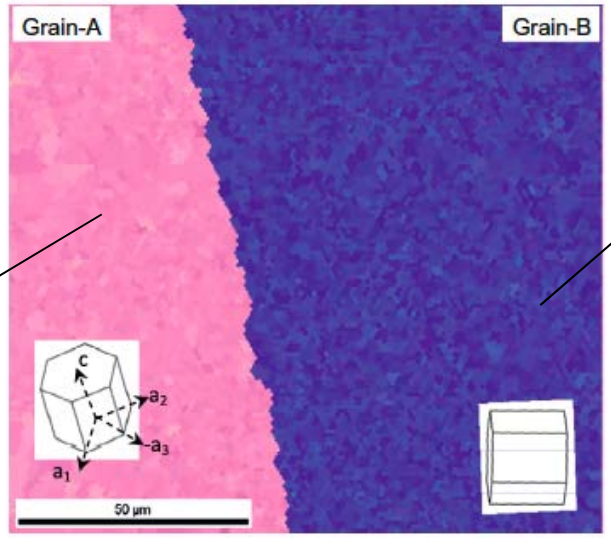
Deslizamiento:
Textura, alta T,
baja velocidad de deformación

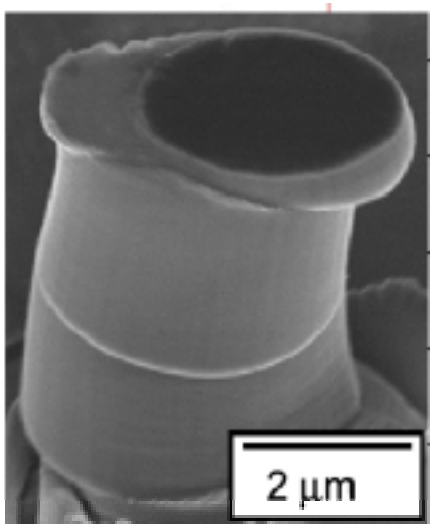
COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

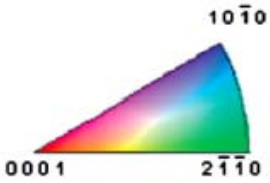
Mg monocristalino, 25°C, 10^{-3} s^{-1}

INFLUENCIA DE LA TEXTURA





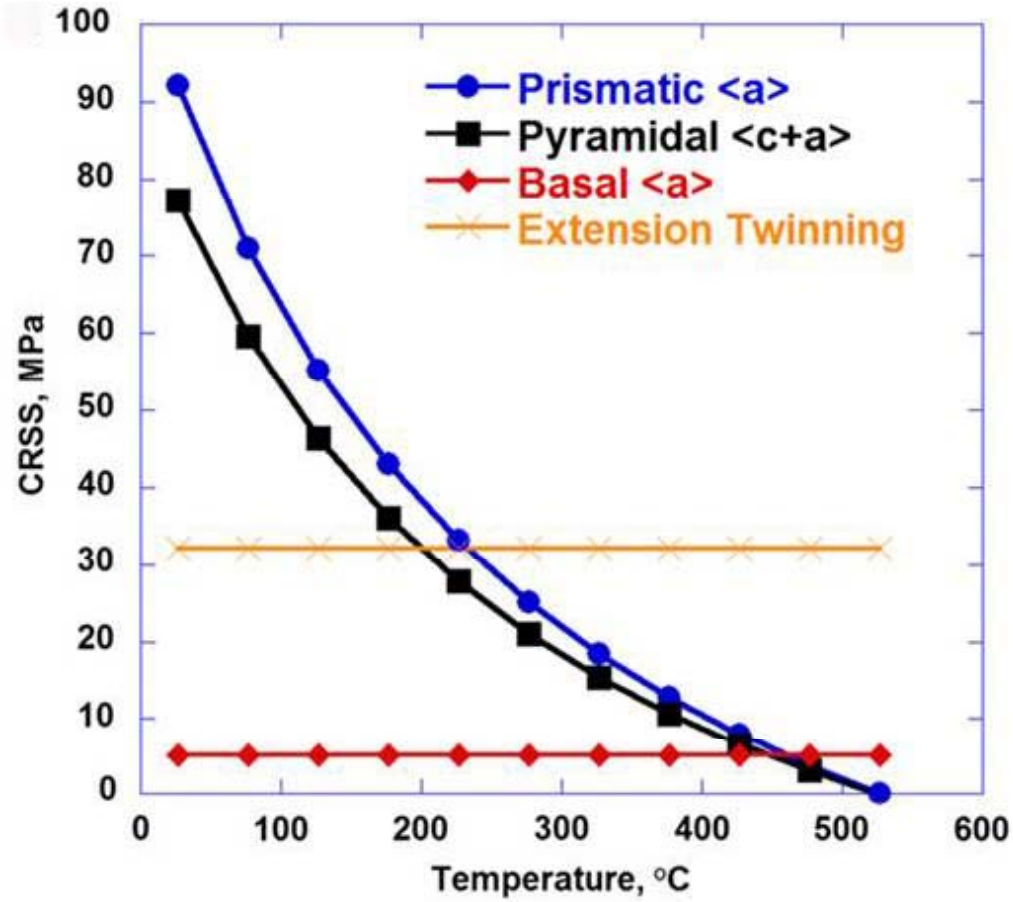




K. Eswar Prasad, K. Rajesh, U. Ramamurty, Acta materialia 65 (2014) 316

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

INFLUENCIA DE LA TEMPERATURA

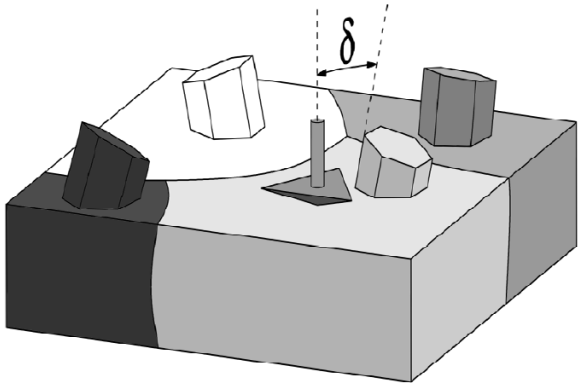


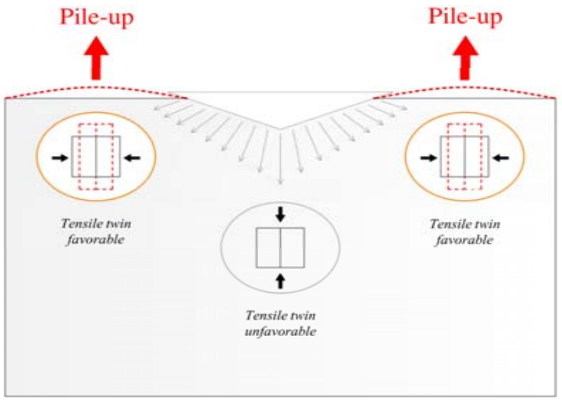
M.R. Barnett. Metall Mater Trans 34A (2003)1799

Advances in wrought magnesium alloys. Ed. by C. Bettles and M. Barnett. Cambridge: Woodhead publishing;2012.

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

MG MONOCRISTALINO: INFLUENCIA DE LA TEMPERATURA

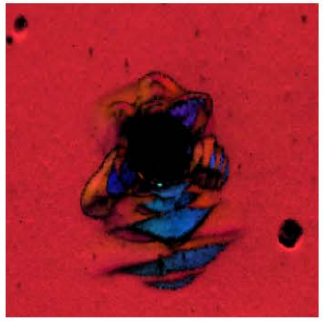


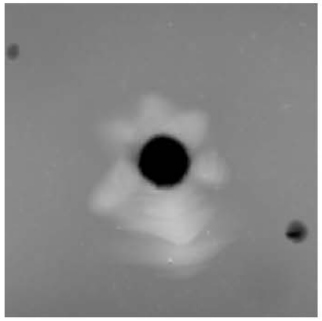


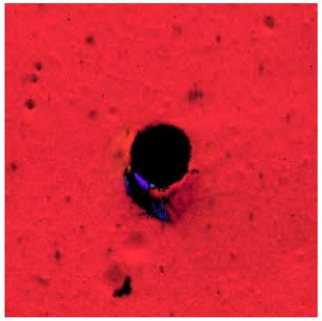
RT | **300 ºC**

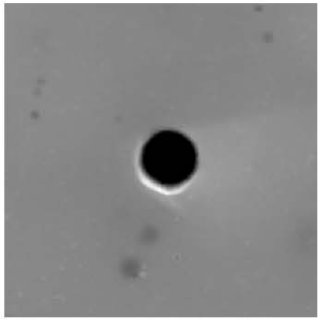
EBSD | AFM | EBSD | AFM

δ = 7º





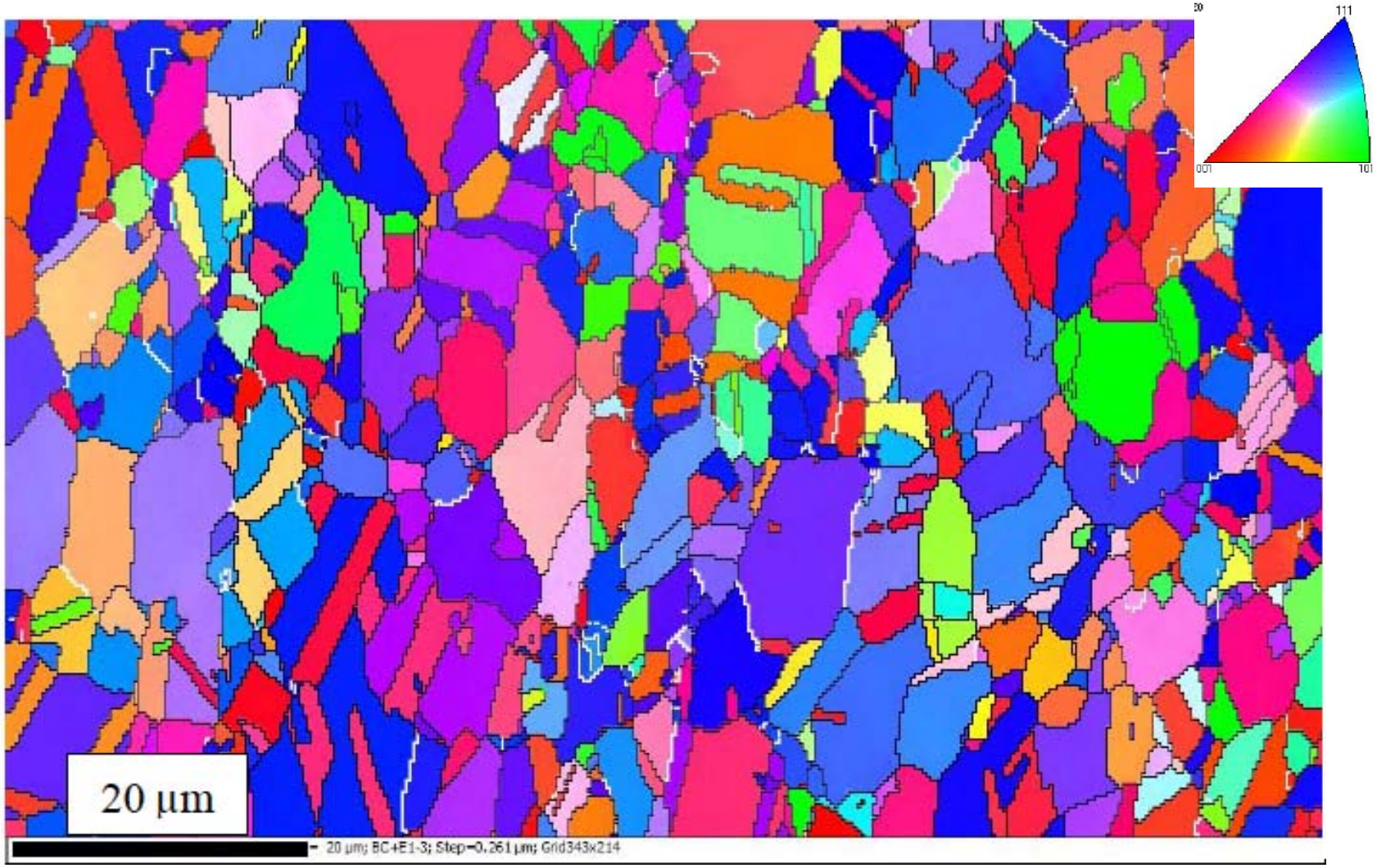




Sánchez-Martín, Zambaldi, Pérez-Prado, Molina-Aldareguia, Scripta Mater 2015

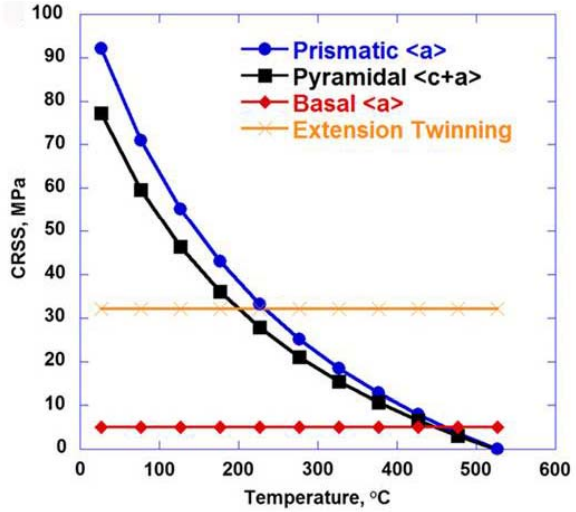
COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

PROBLEMA NO RESUELTO EN POLICRISTALES



COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

PROBLEMA NO RESUELTO EN POLICRISTALES



M.R. Barnett. Metall Mater Trans 34A (2003)1799

$$\left(\frac{CRSS_{non\text{-}basal}}{CRSS_{basal}}\right) =$$

50+
(Single crystal)

2-10
(Modelos de plasticidad Cristalina (VPSC))

Advances in wrought magnesium alloys. Ed. by C. Bettles and M. Barnett. Cambridge: Woodhead publishing; 2012

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

PROBLEMA NO RESUELTO EN POLICRISTALES

Dispersión en las constantes Hall-Petch

Materials	Processing condition	Loading path	Grain Size (μm)	σ_o (MPa)	k_σ (MPa mm$^{1/2}$)
AZ31	Rolling	Tension (in-plane)	16–40	60	10.5
AZ31	Rolling	Tension //RD	5–25	45	10.1
AZ31	Single rolling	Tension //RD	5–17	89	7.3
AZ31	Rolling	Tension //RD	5–21	131	7.9
AZ31	Rolling	Tension //RD	2–55	122	6.6
AZ31	Rolling	Tension //RD	13–140	88	8.9
AZ31	Rolling	Tension //TD	13–140	115	8.6
AZ31	Extrusion and drawing	Tension //ED	3.5–12	120	5.0
AZ31	Extrusion	Tension //ED	2.5–8	80	9.6
AZ31	Extrusion	Compression //ED	3–11	22	12.3
AZ31	FSP	Tension //AD	2.6–6.1	10	5.1
AZ31	ECAP	Tension //ED	5–32	30	5.4
AZ31	ECAP	Tension //ED	6–22	50	10.8
AZ31	ECAP	Tension //ED	9–22	10	10.3
AZ31	ECAP	Tension //ED	2–8	30	5.7

Wang, Choo, Acta Mater 2014

COMPETICIÓN ENTRE EL DESLIZAMIENTO DE DISLOCACIONES Y EL MACLADO

PROBLEMA NO RESUELTO EN POLICRISTALES

Controvertido efecto del tamaño de grano en el maclado

La actividad del maclado decrece con el tamaño de grano

Barnett MR, Keshavarz Z, Beer AG, Atwell D. Acta Mater 2004; 52:5093 (AZ31, extruded, 3-23 μm).
Dobron P, Chmelik F, Yi S, Parfenenko K, Letzig D, Bohlen J. Scripta mater 2011;65:424. (AZ31, hydrostatic extrusion, 1-10 μm)
Jain A, Duygulu O, Brown DW, Tomé CN, Agnew SR. Mater Sci Eng A 2008;486-545. (AZ31, rolled, 13-140 μm).
Li J, Xu W, Wu X, Ding H, Xia K. Mater Sci Eng A 2011;528:5993. (Pure Mg, ECAP, 0.8-980 μm). **d= 2.7 μm**
Choi HJ, Kim Y, Shin JH, Bae DH. Mater. Sci. Eng. A 2010;527:1565. (60 nm-120 μm, hot extrusion of BM powders). **d= 1 μm**

La fracción de volumen de maclado es independiente del tamaño de grano

Ghaderi A, Barnett MR. Acta mater 2011;59:7824. (AZ31, extruded, 5-55 micras).
Muránsky O, Barnett MR, Carr DG, Vogel SC, Oliver EC. Acta mater 2010; 58:1503. (ZM20, extruded, 17-114 micras)

La probabilidad de encontrar una macla en un grano no depende del tamaño de grano

Beyerlein IJ, Capolungo L, Marshall PE, McCabe RJ, Tomé CN. Phil Mag 2010;90:2161-2190. (Pure Mg, hot rolled, 4-80 micras)

Se ha observado maclado en Mg-10at.%Ti procesado por molienda mecánica con d=33 nm!!
X.L. Wu, K.M. Youssef, C.C. Kock, S.N. Mathaudu, L.J. Kekskés, Y.T. Zhu, Scripta Mater. 64 (2011) 213

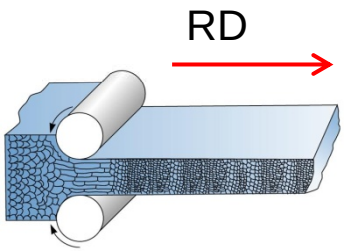
OBJETIVO

Entender la transición entre maclado y deslizamiento cristalográfico en magnesio policristalino

PROCEDIMIENTO EXPERIMENTAL

Material de partida: Mg puro (Helmholtz-Zentrum Geesthacht)

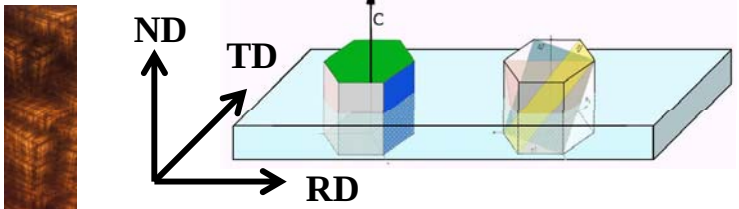
Procesado:

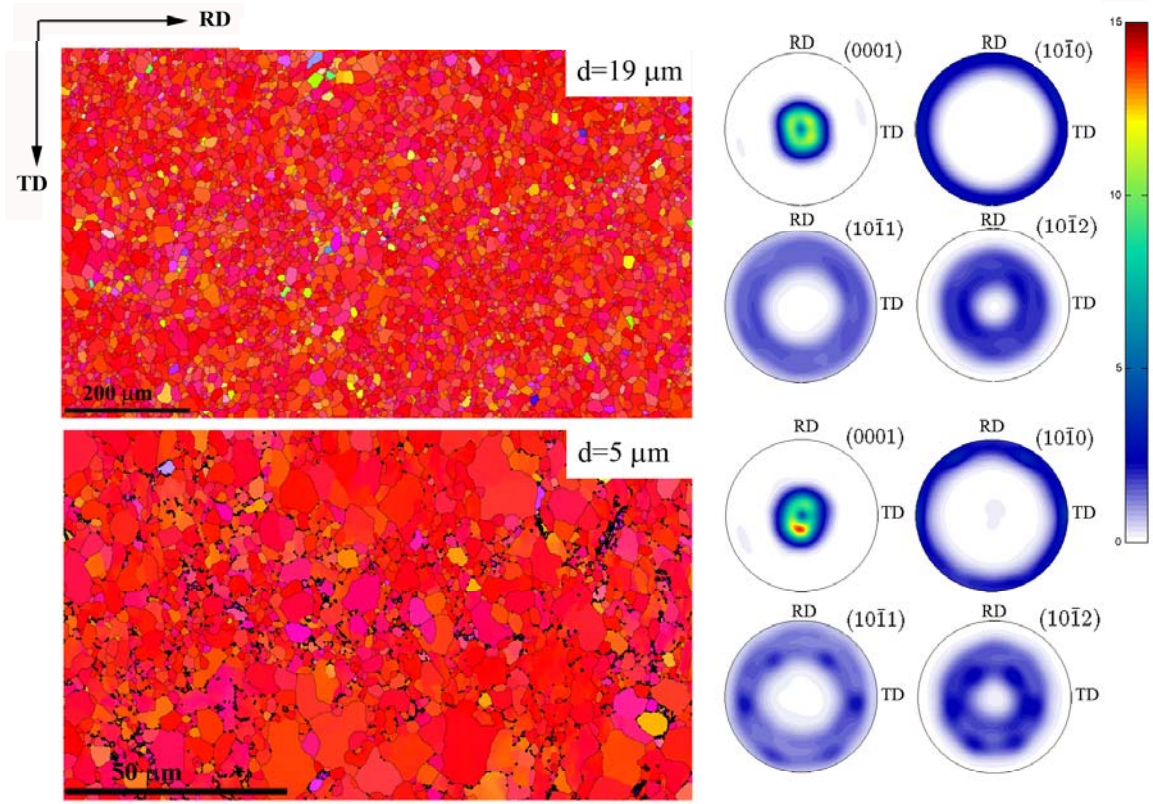


- Laminación en caliente: 200ºC (3 passes, 50% reduction)
- Tratamiento térmico:

1. 300ºC for 5 min (d=19 μm)
2. 150ºC for 10 min (d=5 μm)

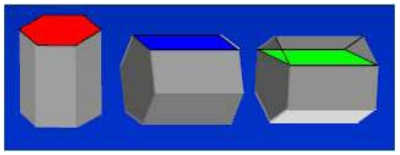
POLICRISTALES DE MG





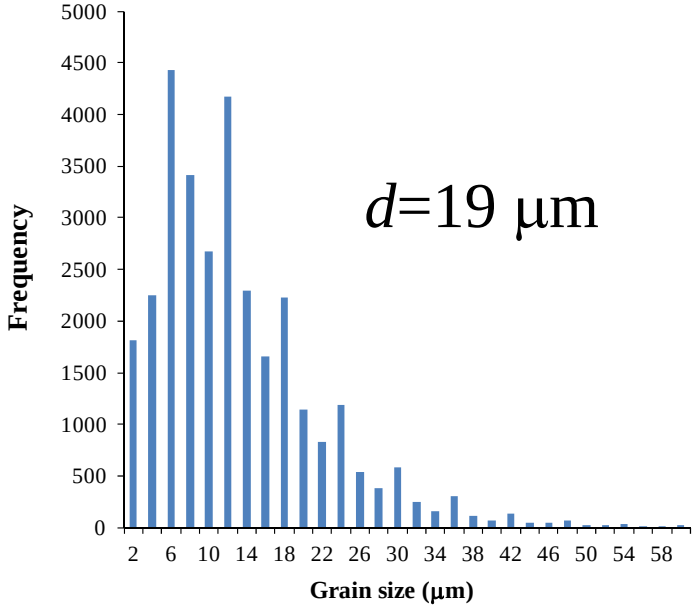
EBSD color code

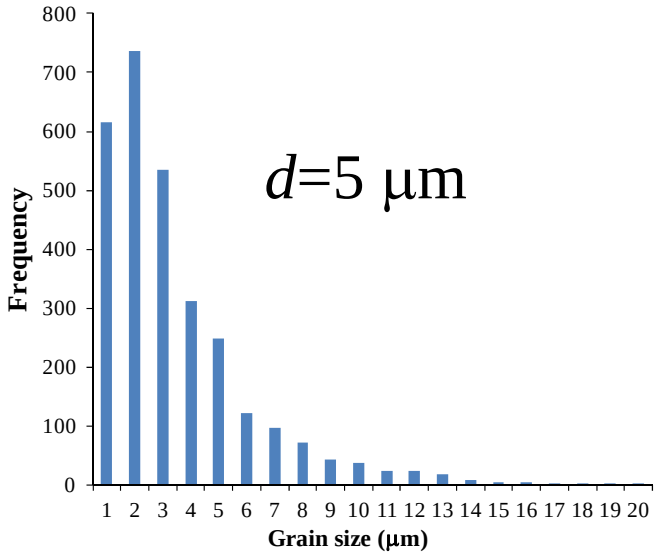
$(0001)\ (10\bar{1}0)\ (2\bar{1}\bar{1}0)$



Cepeda-Jiménez et al. Acta Mater 2015

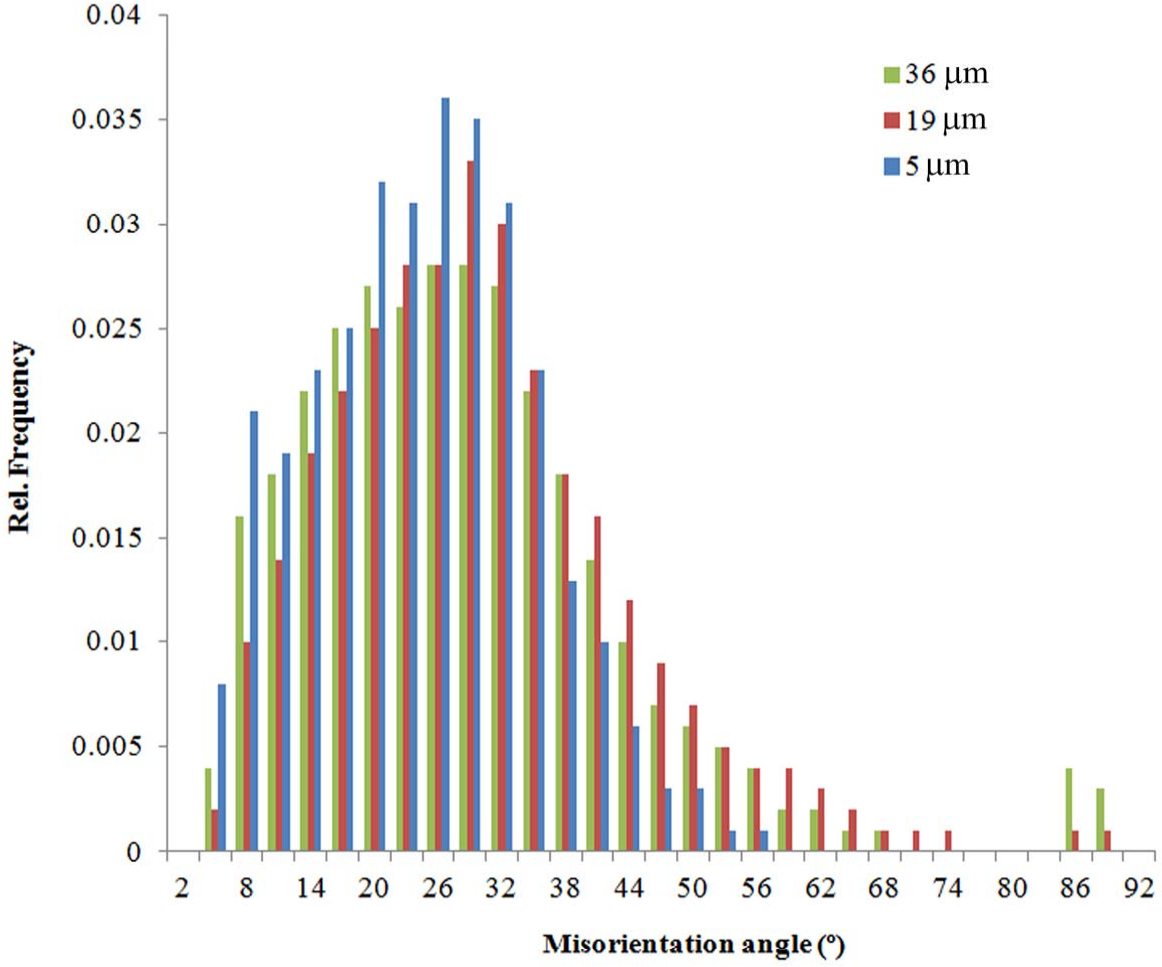
POLICRISTALES DE MG





Cepeda-Jiménez et al. Acta Mater 2015

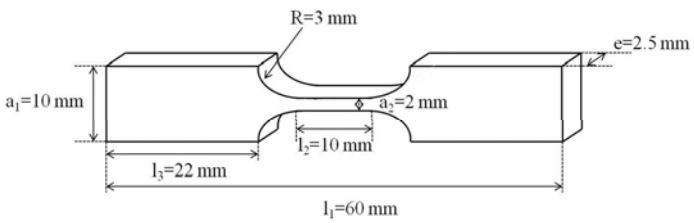
POLICRISTALES DE MG



Cepeda-Jiménez et al. Acta Mater 2015

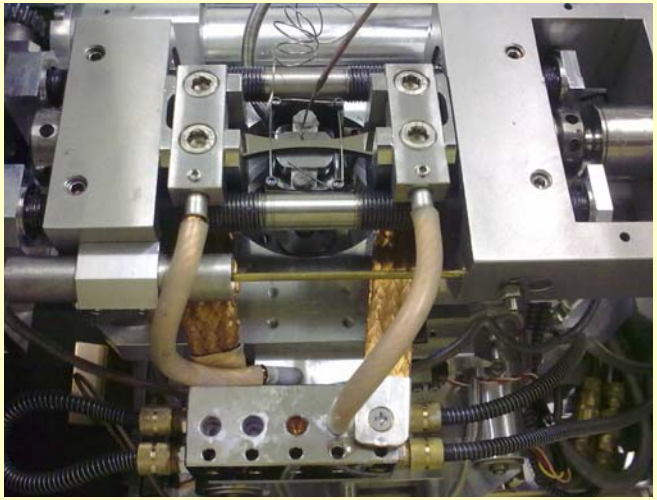
PROCEDIMIENTO EXPERIMENTAL

RD; tensile axis



Compresión: RT, 150 and 250ºC
10^{-3} y 10^{-5} s^{-1}

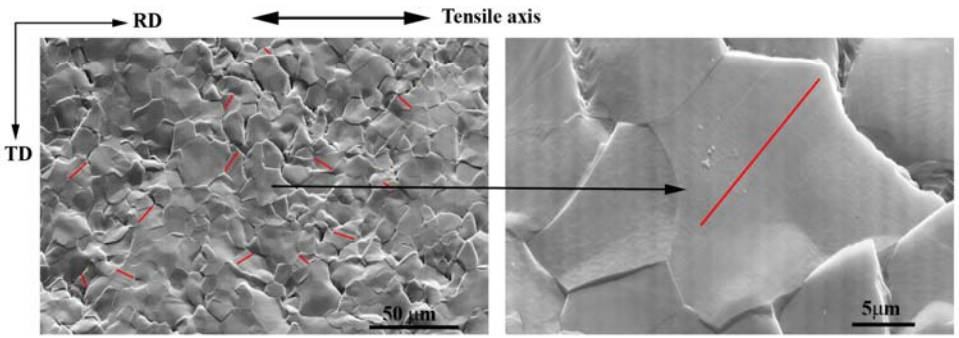
SEM



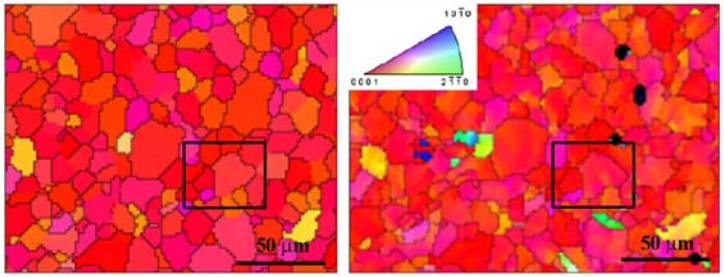
La baja presión evita la oxidación de la superficie pulida

PROCEDIMIENTO EXPERIMENTAL

Análisis de trazas asistido por EBSD

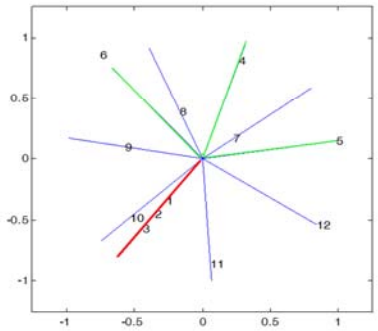


Slip trace observation on SEM micrographs



EBSD maps before and after tensile test

	Slip system	Schmid Factor
1	(0 0 0 1) [-2 1 1 0]	0.1171
2	(0 0 0 1) [-1 2 -1 0]	0.3169
3	(0 0 0 1) [-1 -1 2 0]	0.1998
4	(0 1 -1 0) [2 -1 -1 0]	0.3007
5	(1 0 -1 0) [1 -2 1 0]	0.1301
6	(-1 1 0 0) [1 1 -2 0]	0.4308
7	(1 1 -2 2) [-1 -1 2 3]	0.1911
8	(-1 2 -1 2) [1 -2 1 3]	0.4764
9	(-2 1 1 2) [2 -1 -1 3]	0.0533
10	(-1 -1 2 2) [1 1 -2 3]	0.0120
11	(1 -2 1 2) [-1 2 -1 3]	0.1923
12	(2 -1 -1 2) [-2 1 1 3]	0.0517



Orientation data input into a MATLAB code and slip system selection

Basal slip- Active deformation mechanism

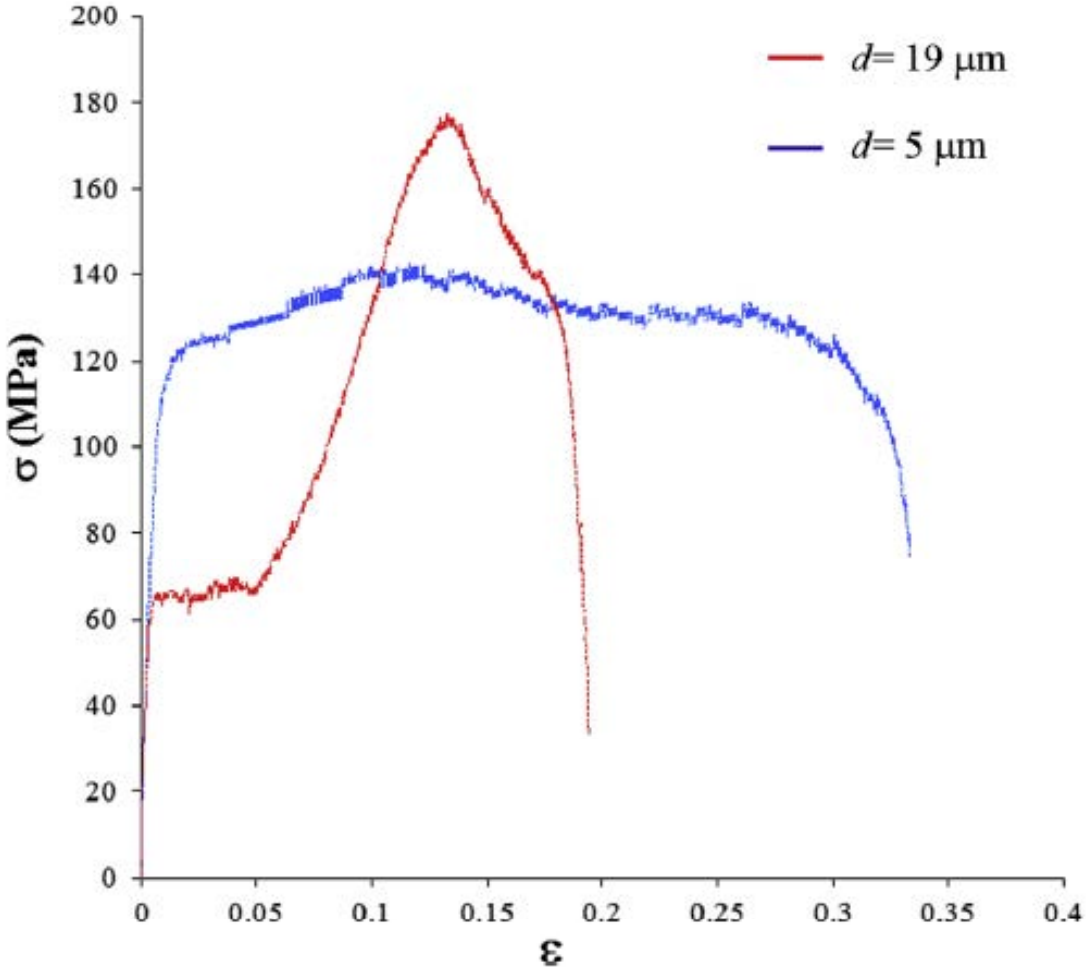
T.R. Bieler *et al* Int. J. Plasticity 25 (2009) 1655

PROCEDIMIENTO EXPERIMENTAL

Grain size	T (ºC)	Strain rate (s^{-1})	Number of slip traces
d=19 μm	50	10^{-3}	158
	50	10^{-4}	
	50	10^{-5}	119
	150	10^{-3}	154
	250	10^{-3}	76
d=5 μm	50	10^{-3}	139

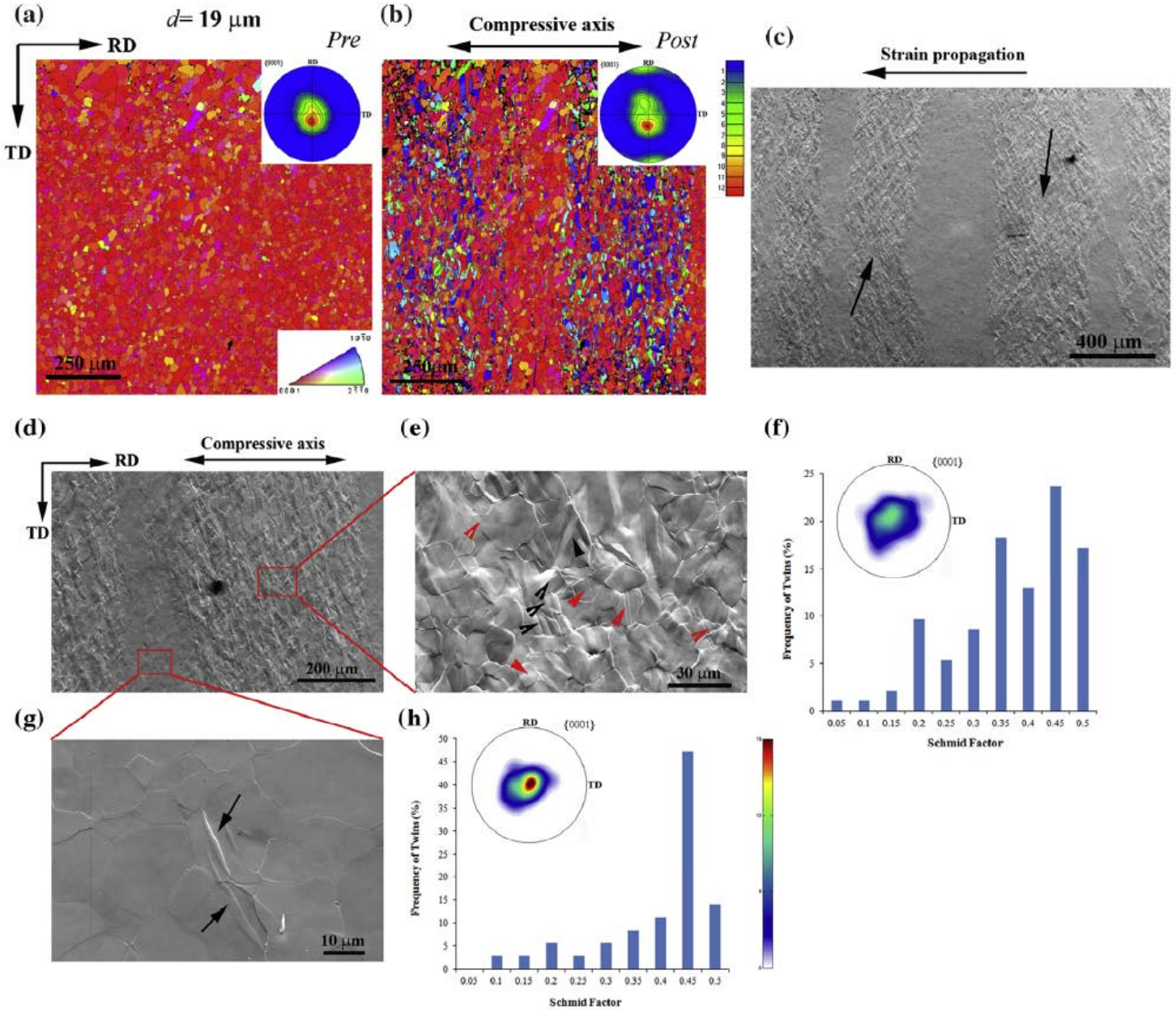
Cepeda-Jiménez et al. Acta Mater 2015

Mg puro, temperatura ambiente, 10^{-3} s^{-1}

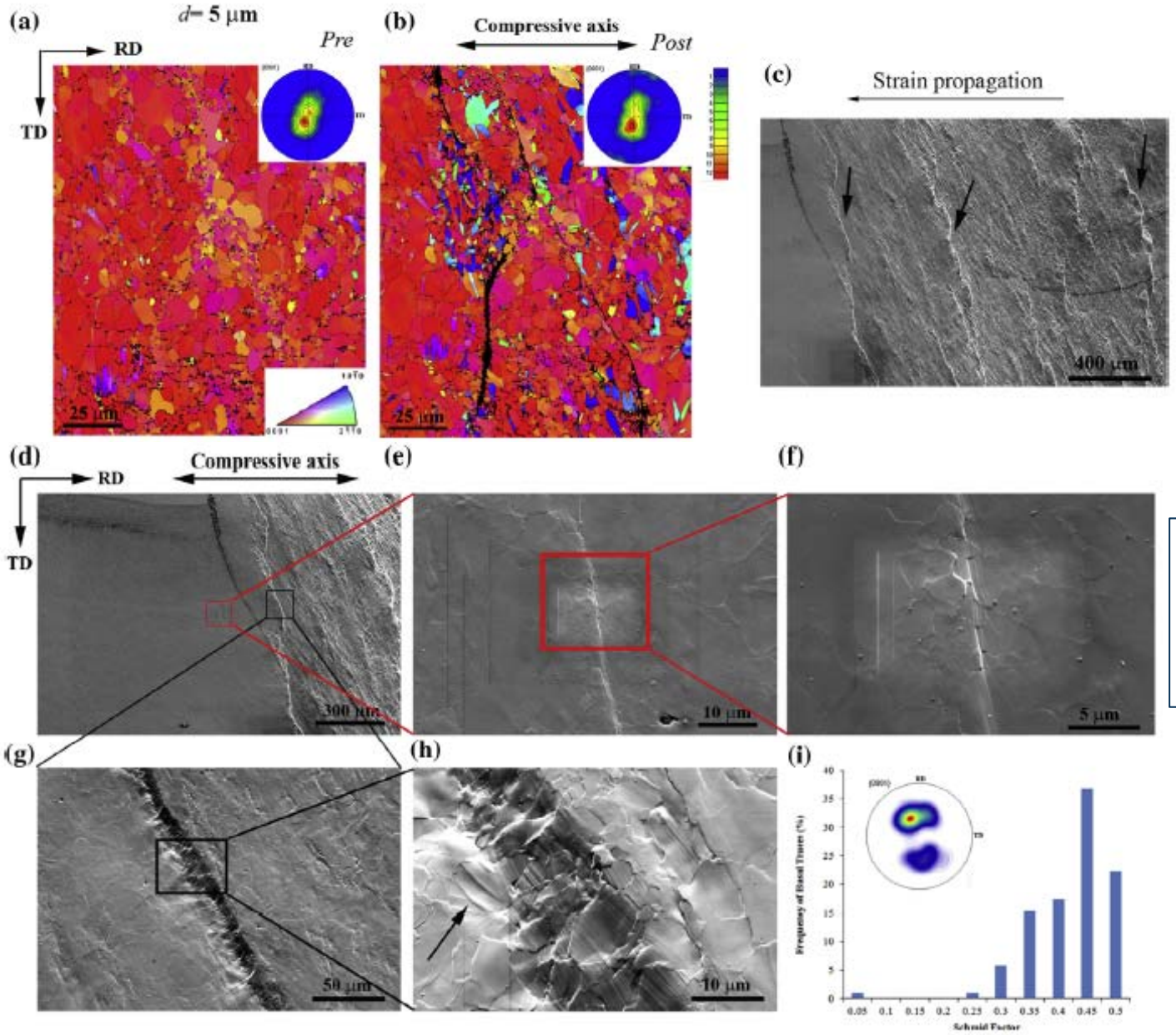


Cepeda-Jiménez et al. Acta Mater 2015

Mg puro, temperatura ambiente, 10^{-3} s^{-1}, 19 μm



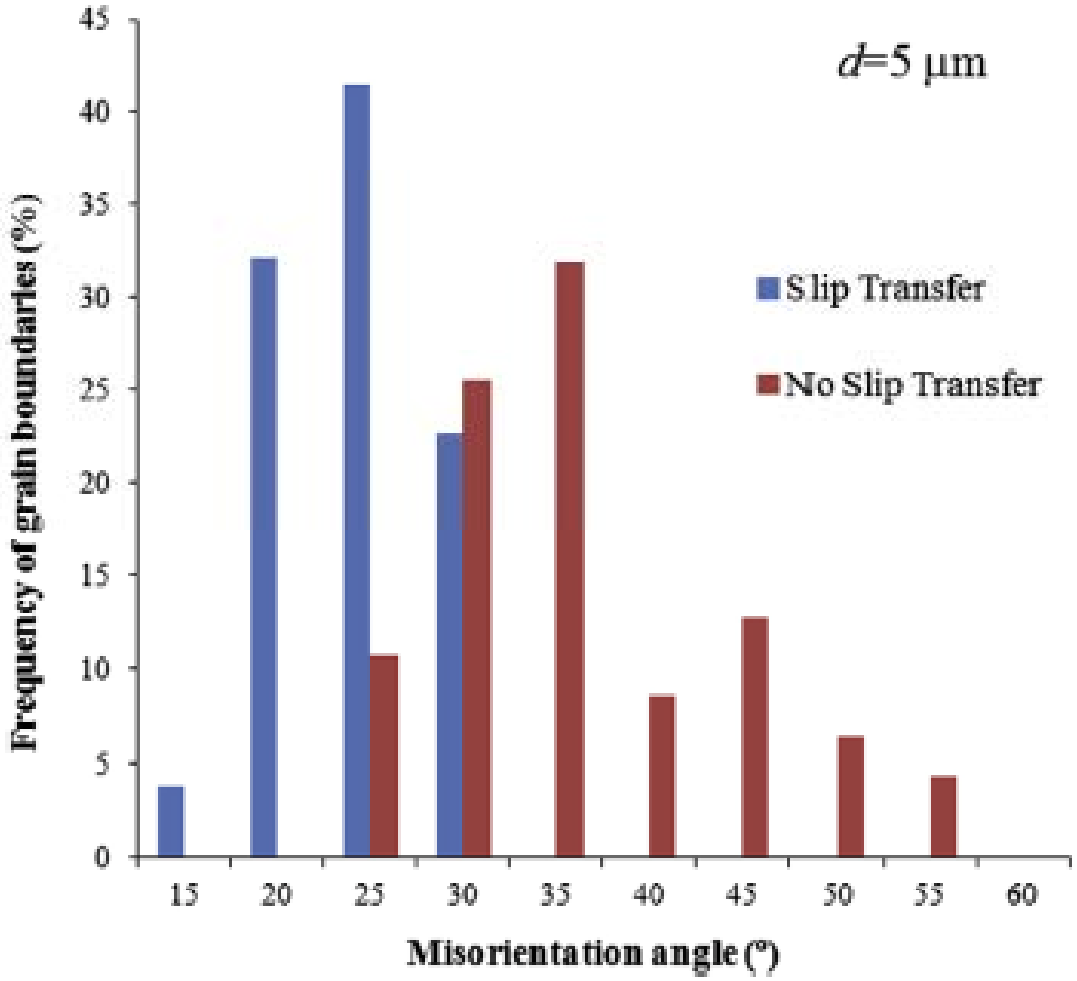
Mg puro, temperatura ambiente, 10^{-3} s^{-1}, 5 μm



139 traces
73% basal
13% prismatic
14% <c+a>

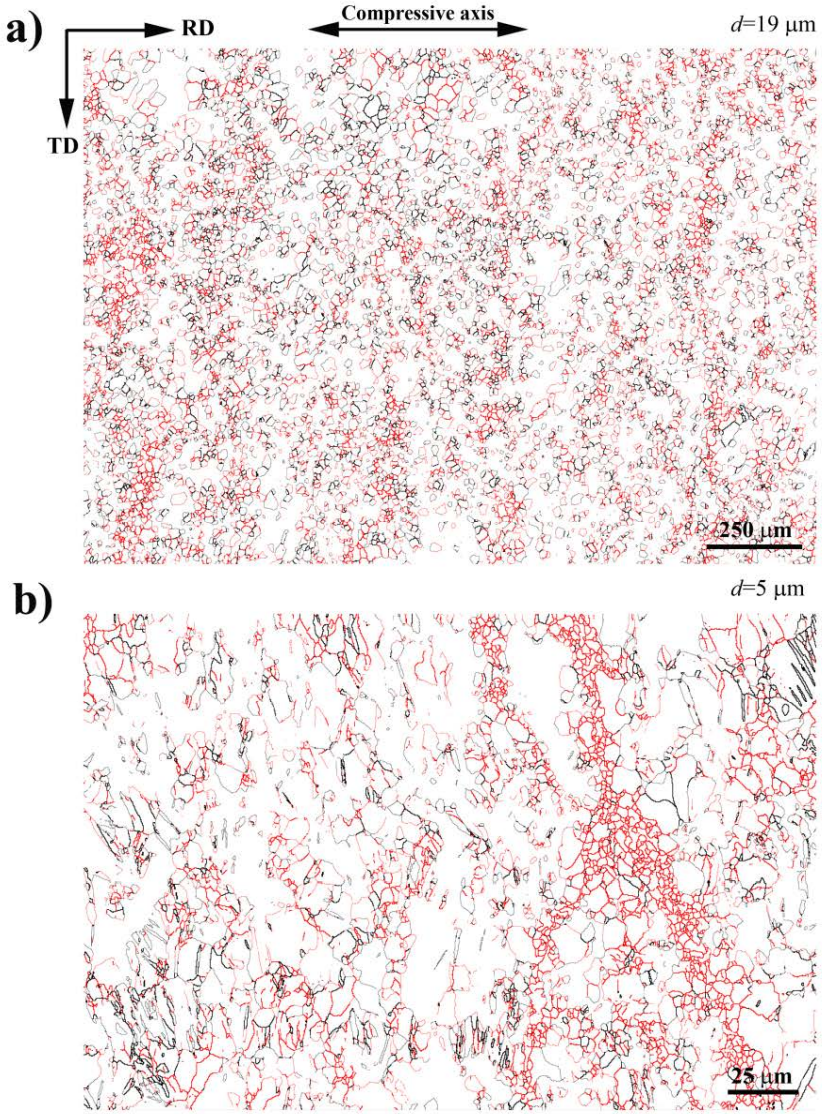
Mg puro, temperatura ambiente, 10^{-3} s^{-1}, 5 μm

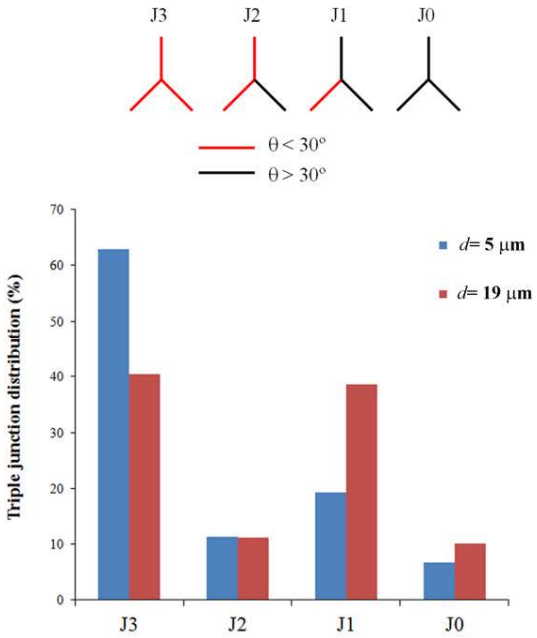
θ_{th}=30°



Cepeda-Jimenez et al. Acta Mater 2015

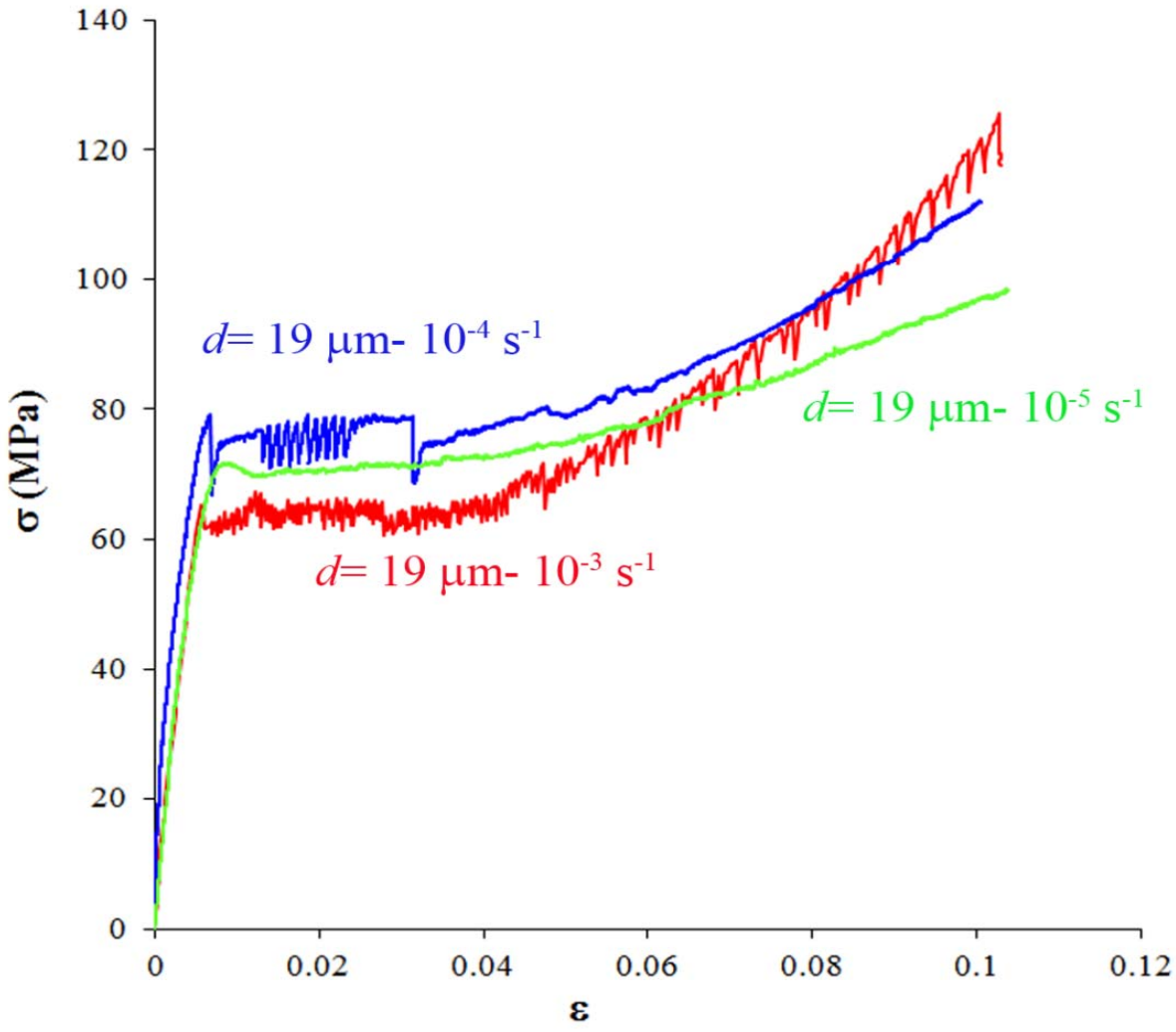
Mg puro, temperatura ambiente, 10^{-3} s^{-1}





Cepeda-Jiménez et al. Acta Mater 2015

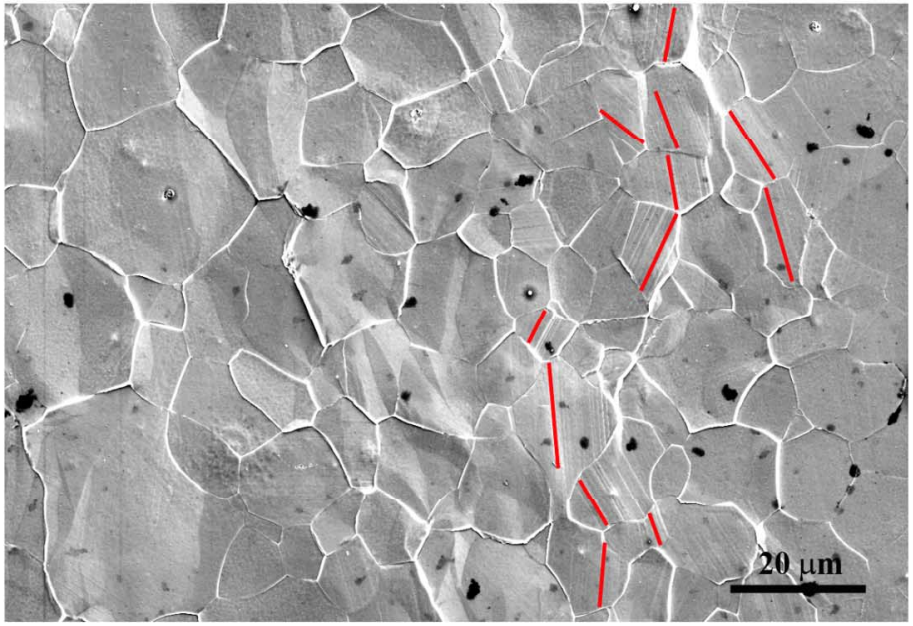
Mg puro, 19 μm, temperatura ambiente



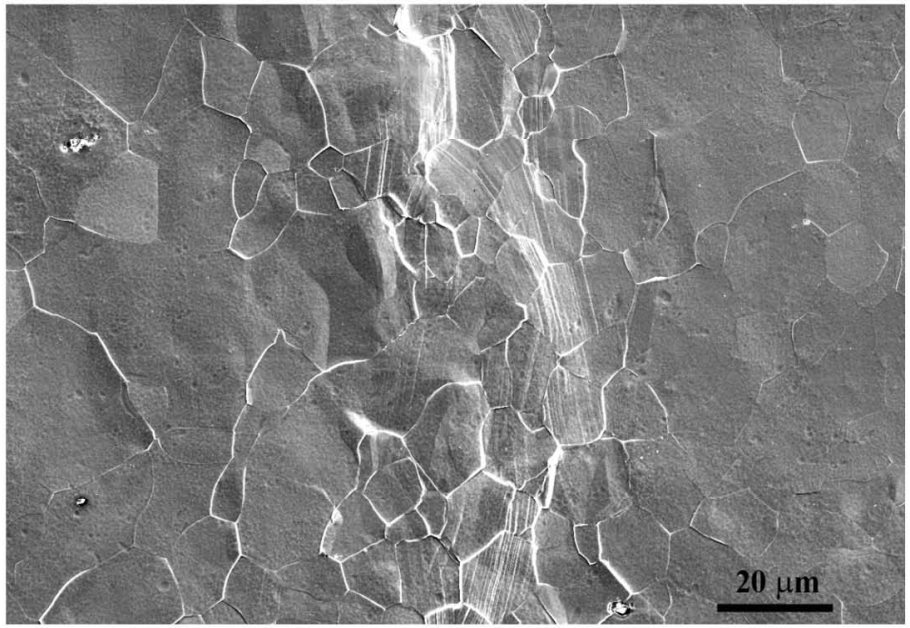
Cepeda-Jiménez et al. Acta Mater 2015

Mg puro, 19 μm, temperatura ambiente

a) d= 19 μm- 10^{-4} s^{-1}



b) d= 19 μm- 10^{-5} s^{-1}



119 traces
91% basal
6% prismatic
3% <c+a>

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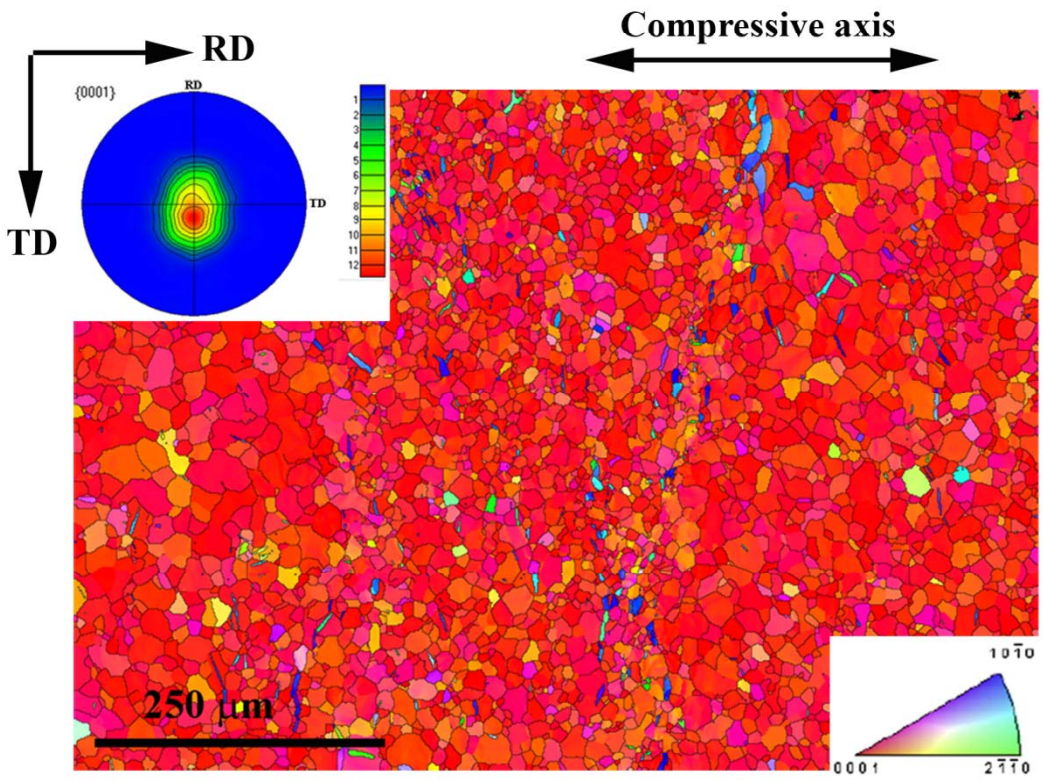
Mg puro, 19 μm, temperatura ambiente, 10^{-5} s^{-1}



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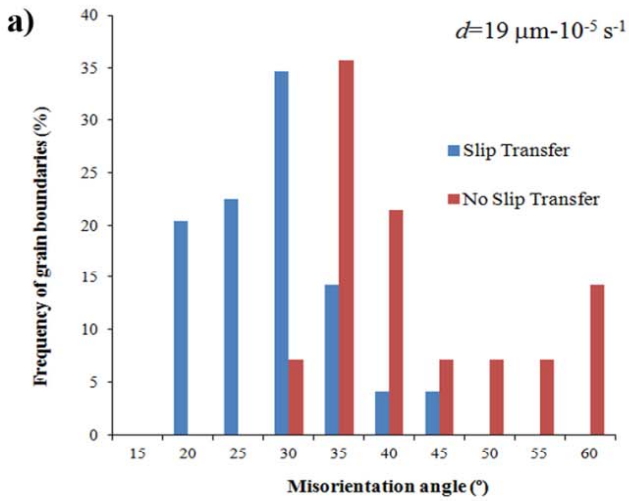
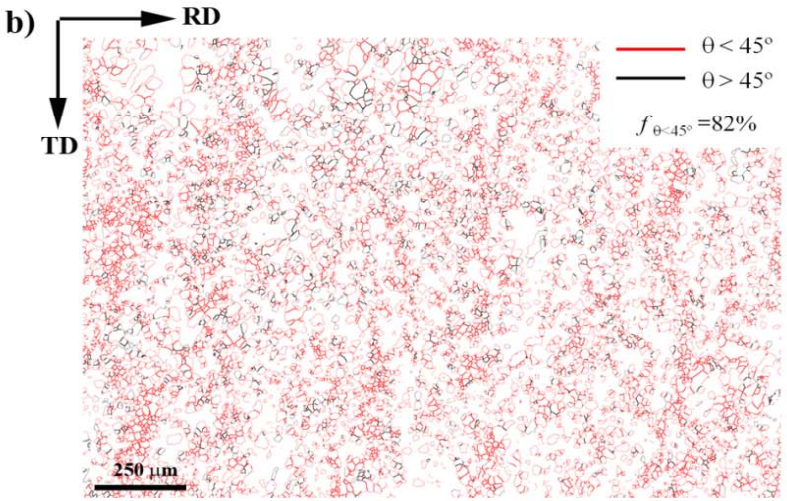
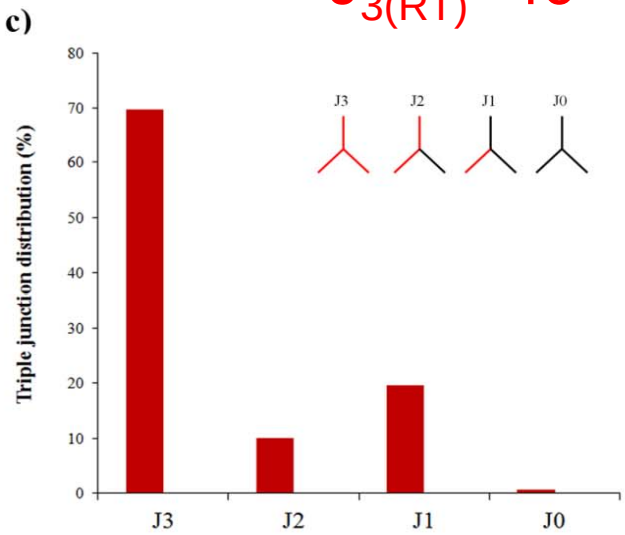
Mg puro, 19 μm, temperatura ambiente, 10^{-5} s^{-1}



θ_{th}=45°

$J_{3(RT)}$=40





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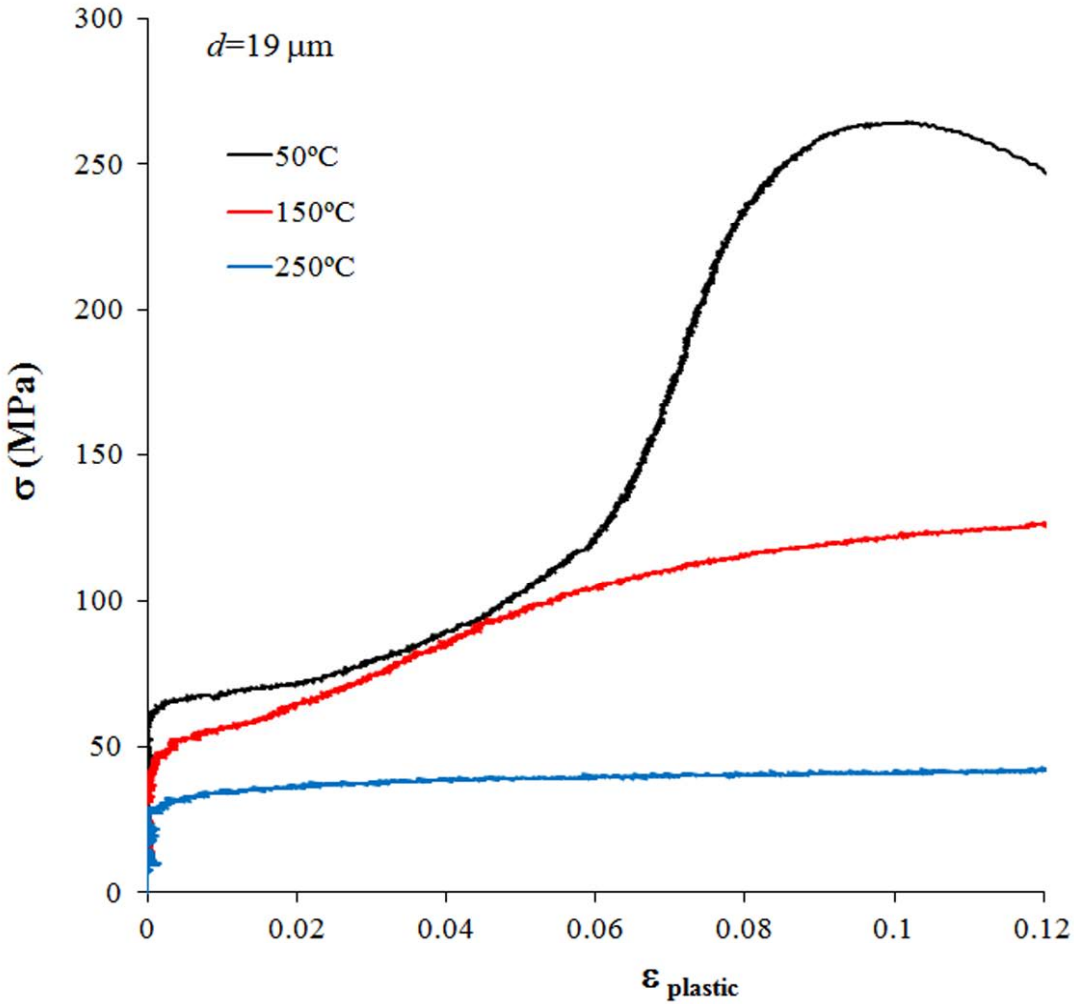
Mg puro, 19 μm, 10^{-3} s^{-1}



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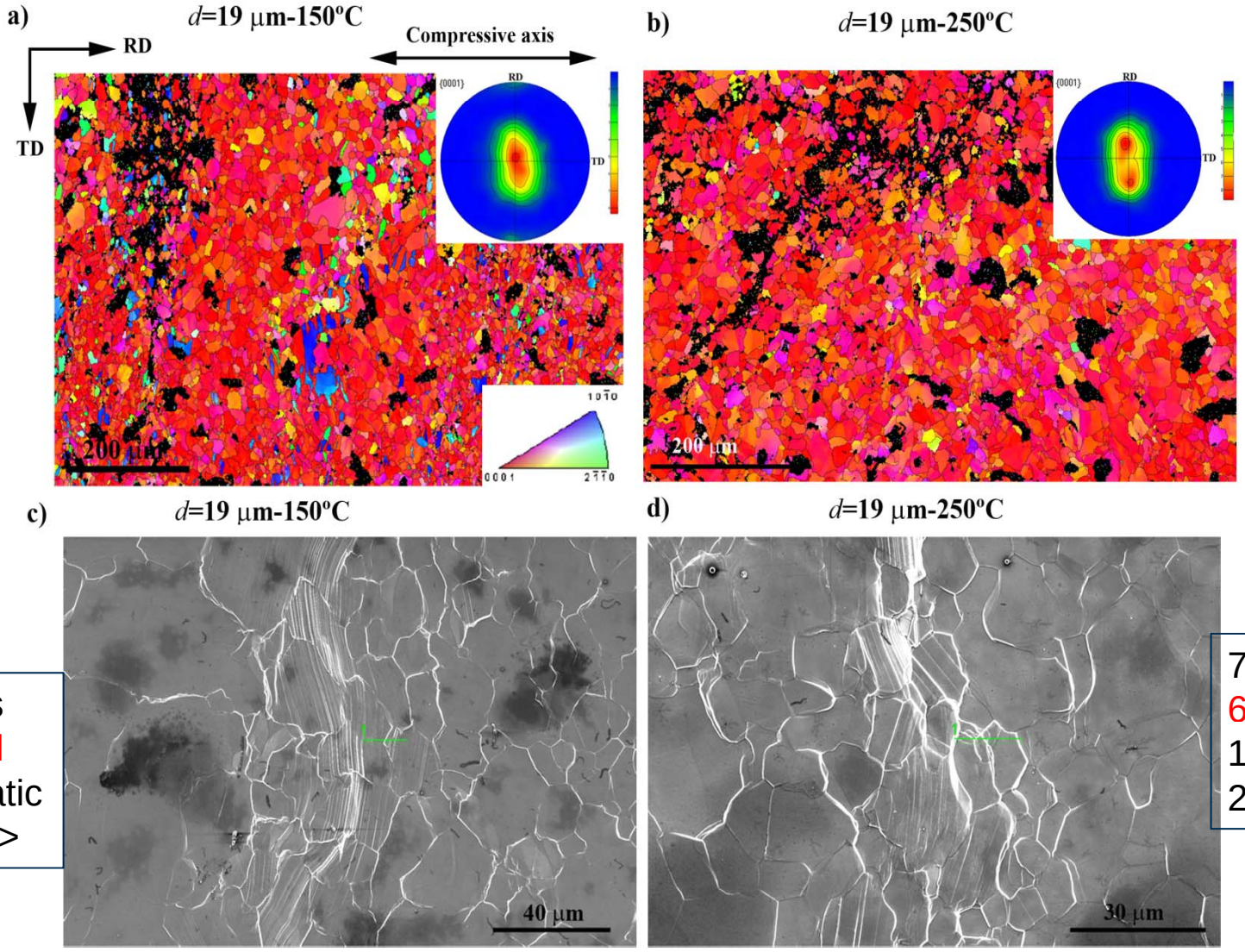
Mg puro, 19 μm, 10^{-3} s^{-1}



154 traces
78% basal
8% prismatic
14% <c+a>

76 traces
61% basal
13% prismatic
26% <c+a>

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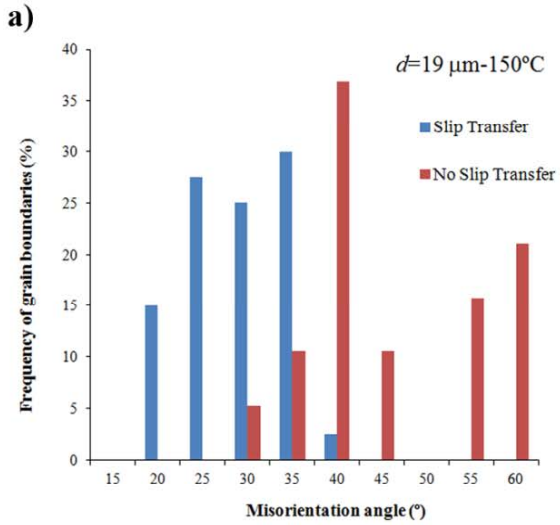
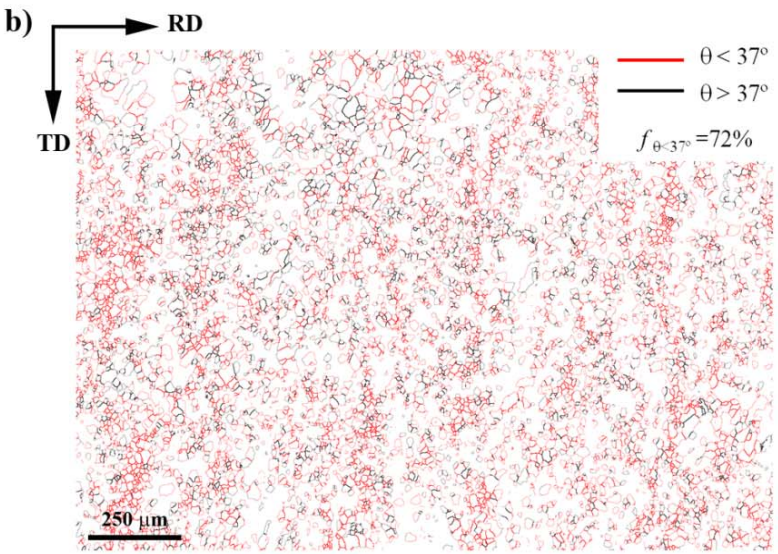
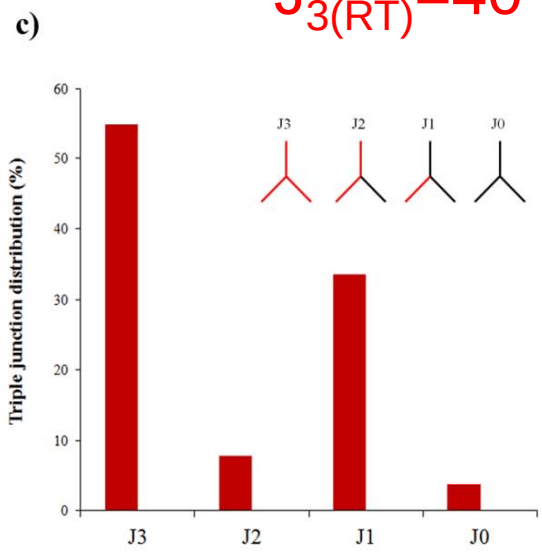
Mg puro, 19 μm, 150°C, 10^{-3} s^{-1}



θ_{th}=37°>30°



$J_{3(RT)}$=40



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Mg puro, 19 μm

Desorientación crítica para la transferencia del basal

Mg puro	RT	150°C
10^{-3} s^{-1}	30°	37°
10^{-5} s^{-1}	45°	

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CONCLUSIONES

- Cuando decrece el tamaño de grano, aumenta la temperatura o disminuye la velocidad de deformación, se produce una transición de maclado a DESLIZAMIENTO BASAL.

- La transición está relacionada con una mejora de la conectividad entre granos bien orientados para el deslizamiento basal.

- La topología de la red de fronteras de grano, así como la naturaleza de dichas fronteras y la distribución espacial de las orientaciones juegan un papel decisivo en la selección de los mecanismos de deformación dominantes en policristales de Mg puro.

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