Mechanical Behaviour of Materials

PII. Crystal plasticity (1):

Slip-Induced Deformation

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PII. Crystal plasticity:

(1) Plastic deformation and dislocations

(2) Twin

(3) Yielding

(4) Simulations

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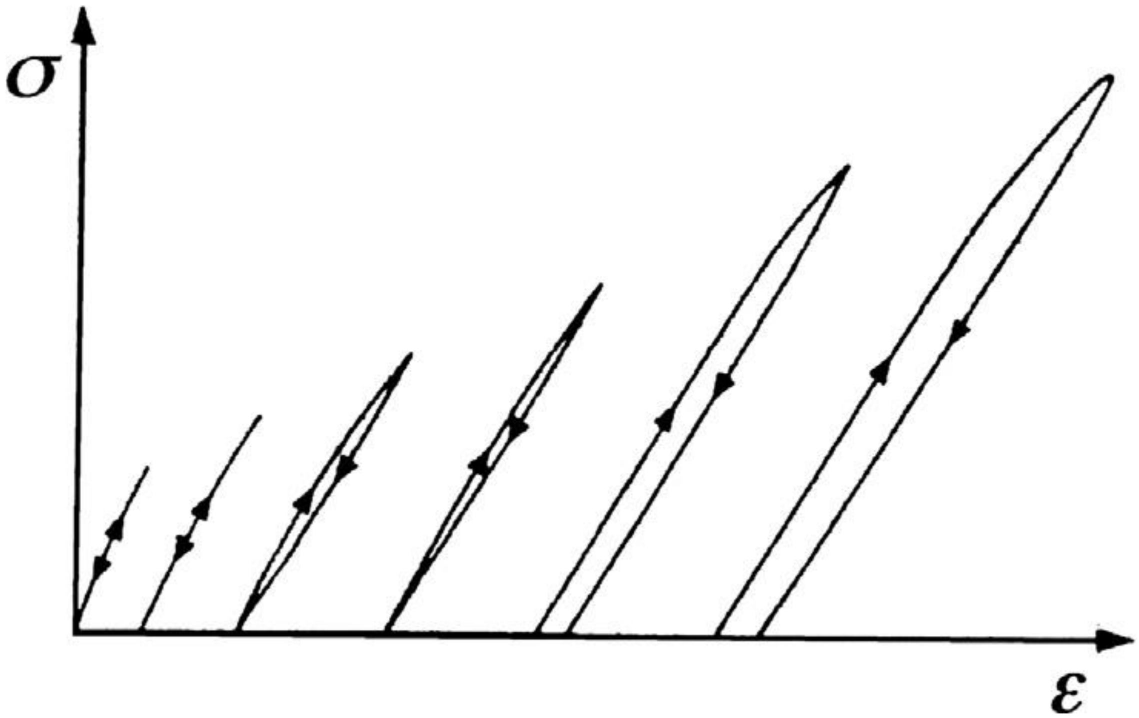
1. Plastic Deformation and Dislocations
2. Schmid's factor and Taylor factor
3. Lattice rotation

Key points of slip

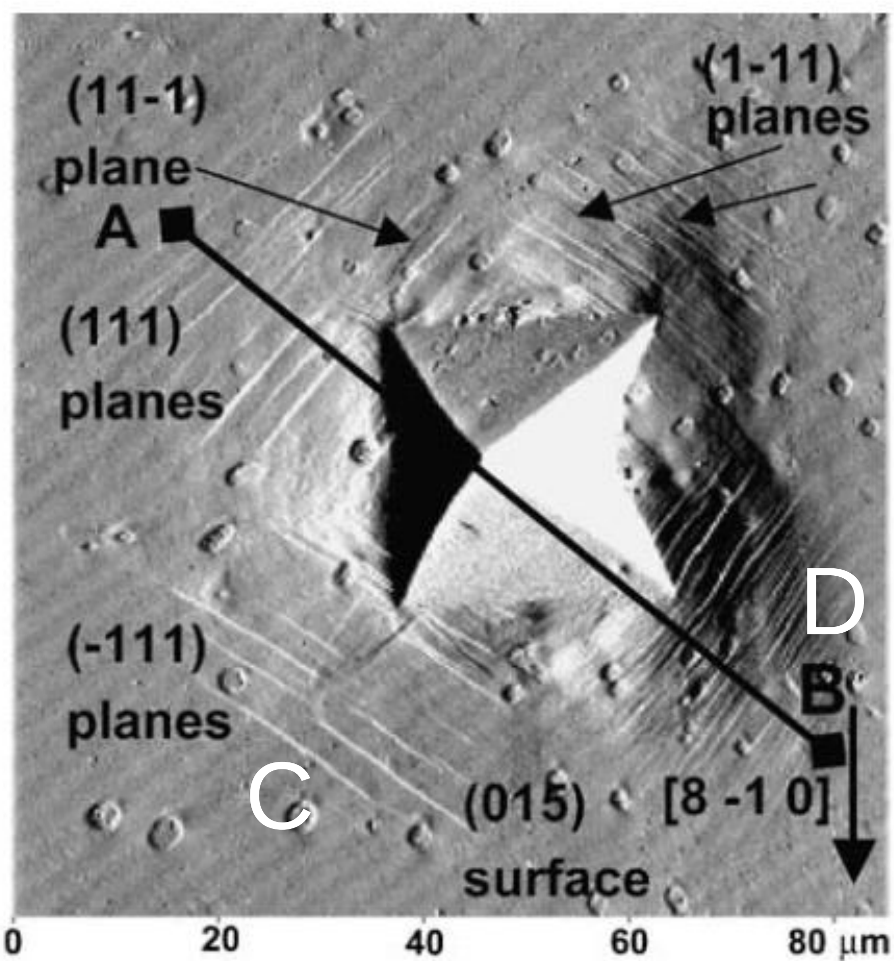
The first response is called elastic (see Figure) and corresponds to an unequivocal relationship between stress and strain.As previously seen for crystalline materials, in the limit of small strains, this relation is linear according to Hooke's law. The elastic stage corresponds to a distortion of the atomic bonds and is entirely reversible. This stage is followed by a deformation stage, called "anelastic", for which no permanent strain exists after unloading.

In addition, the transition between elastic, anelastic and plastic stages is generally very gradual, so that the critical stress for macroplasticity is often conventionally defined at a given plastic strain, typically 2 x 10^{-3}.

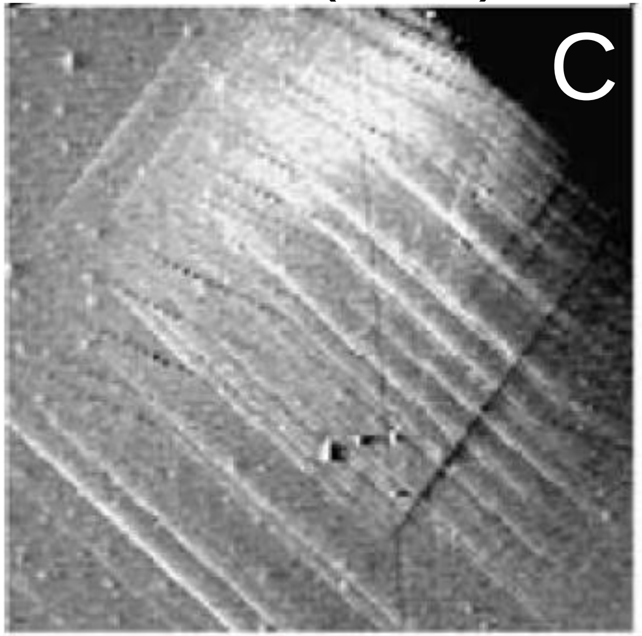


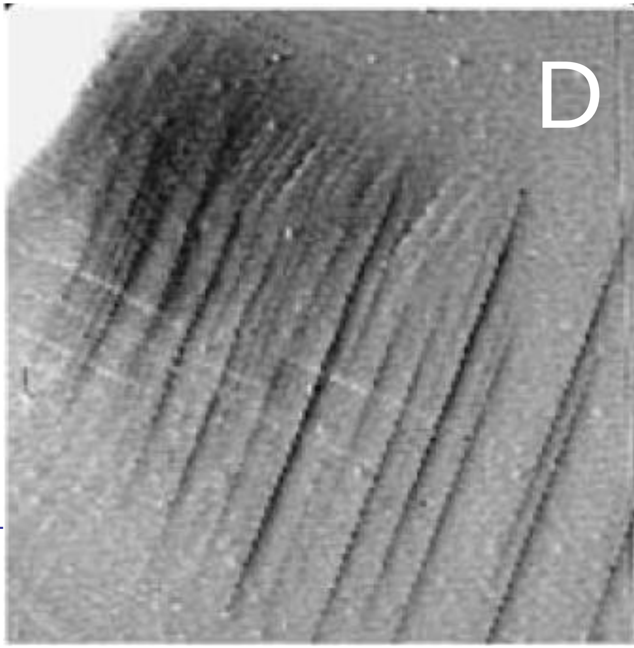
Different deformation stages of a crystalline material

AFM images of slip step pattern around indentations in (1 0 0)



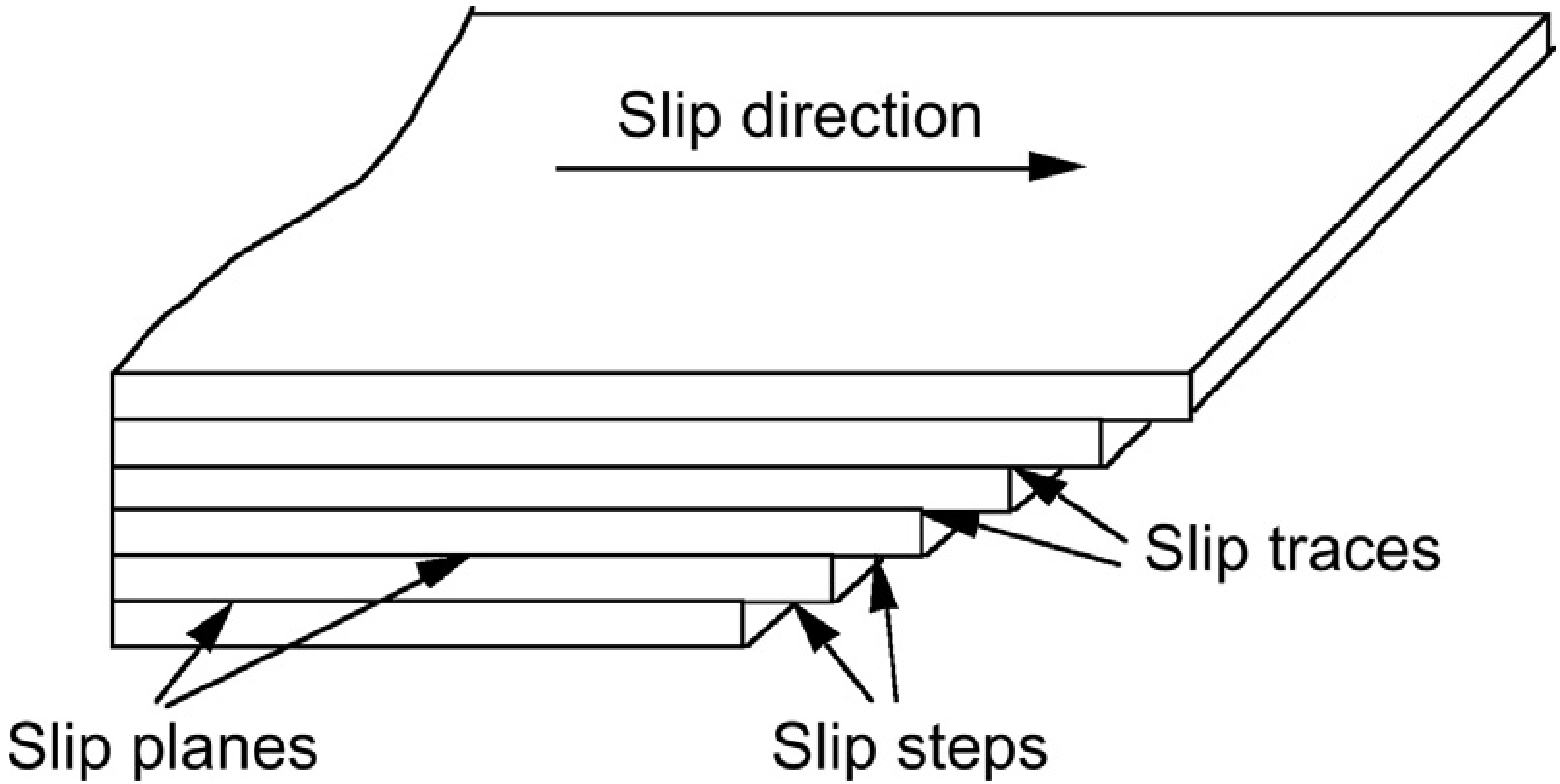
Scripta Materialia 49 (2003) 1055–1060





Surface relief during plastic deformation

It is clearly observed that plastic deformation is accompanied by the appearance of lines. These lines, together with the surface relief, suggest that plastic deformation occurs by the shearing of the sample along planes, with large regions that have slipped past each other (see figure).

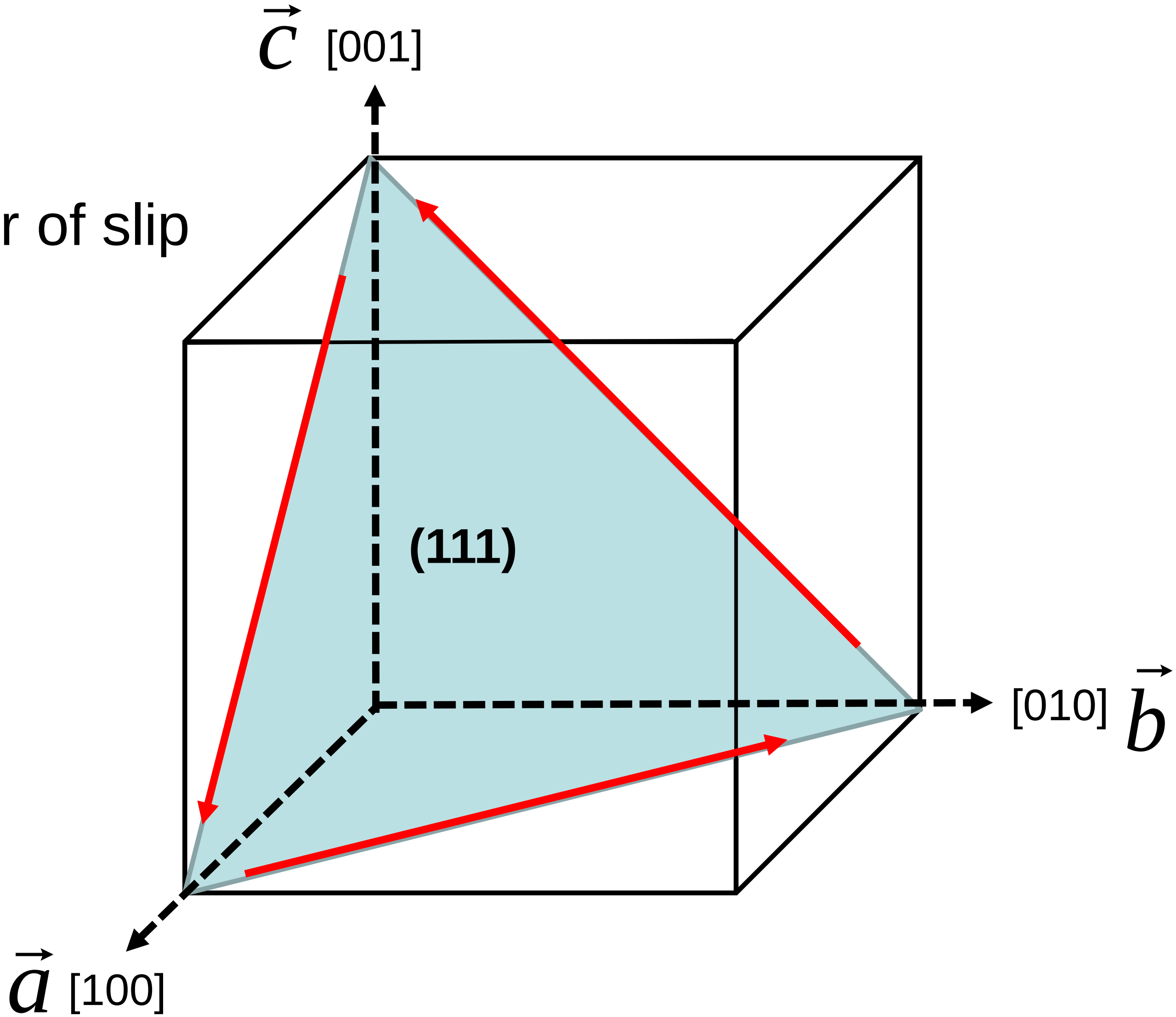


Cited from D. Rodney and J. Bonneville, ch06, (2015)

Surface relief during plastic deformation-cont.

Examples of fcc metals:
γ-Fe, Al, Cu, Ni, Ag

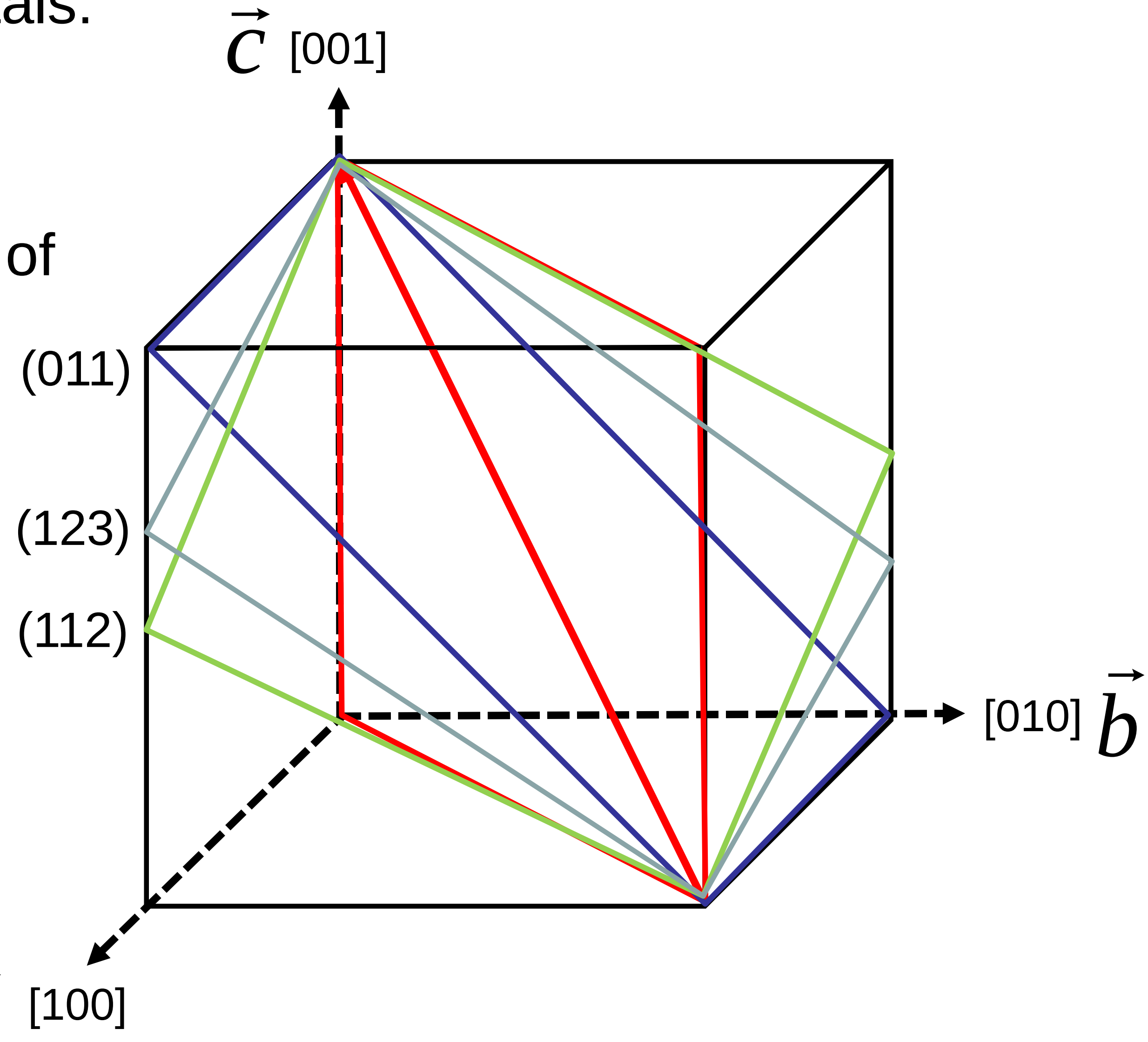
Slip system/number of slip System:
{111}<110>/12



Slip systems in FCC metals

Examples of bcc metals:
α-Fe, Mo, W

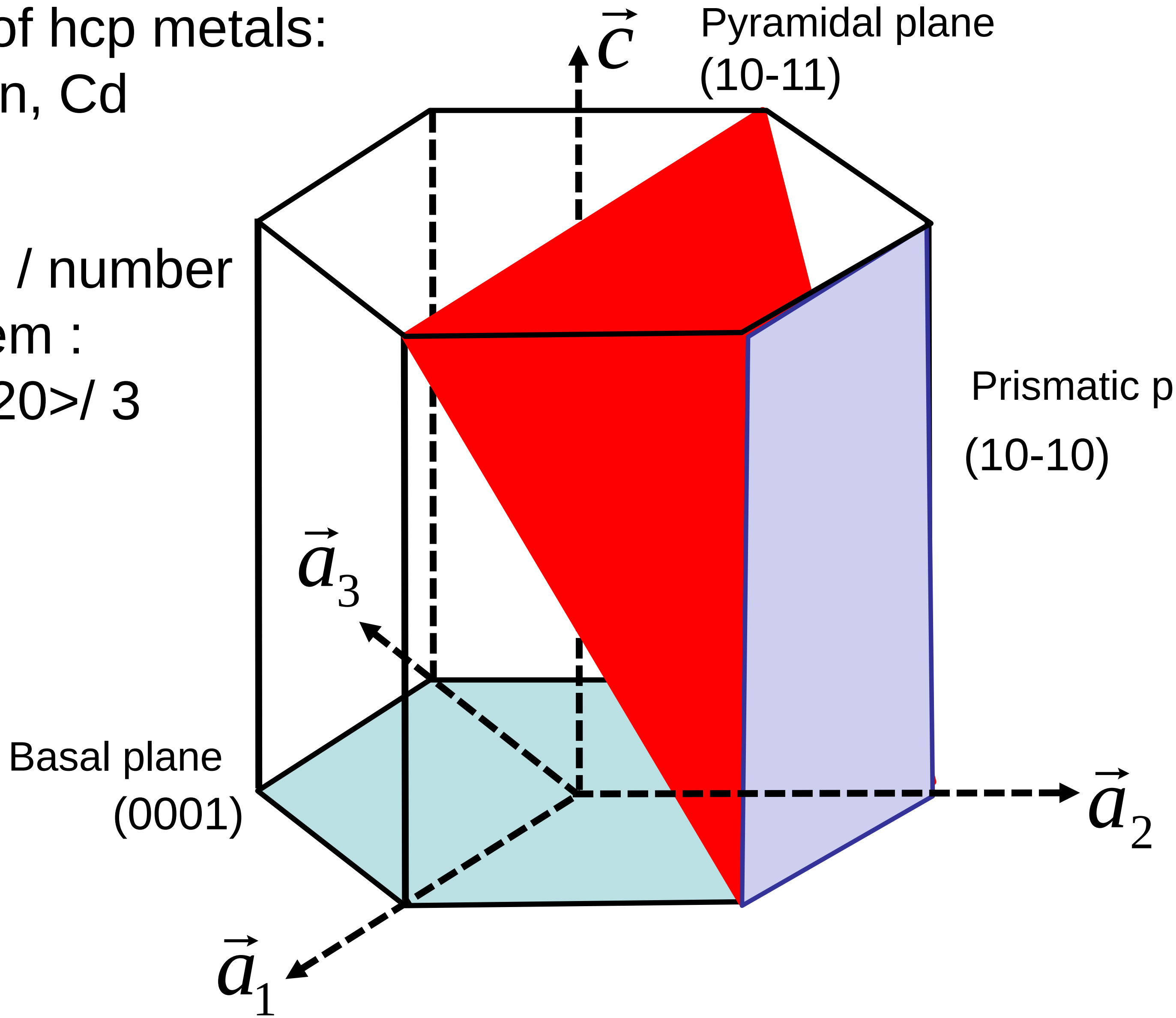
Slip system/ number of slip system:
{110}<111>/12
{112}<111>/12
{123}<111>/24



Pencil glide in an BCC Crystal

Examples of hcp metals:
α-Ti, Mg, Zn, Cd

Slip system / number of slip system :
{0001}<11-20>/ 3

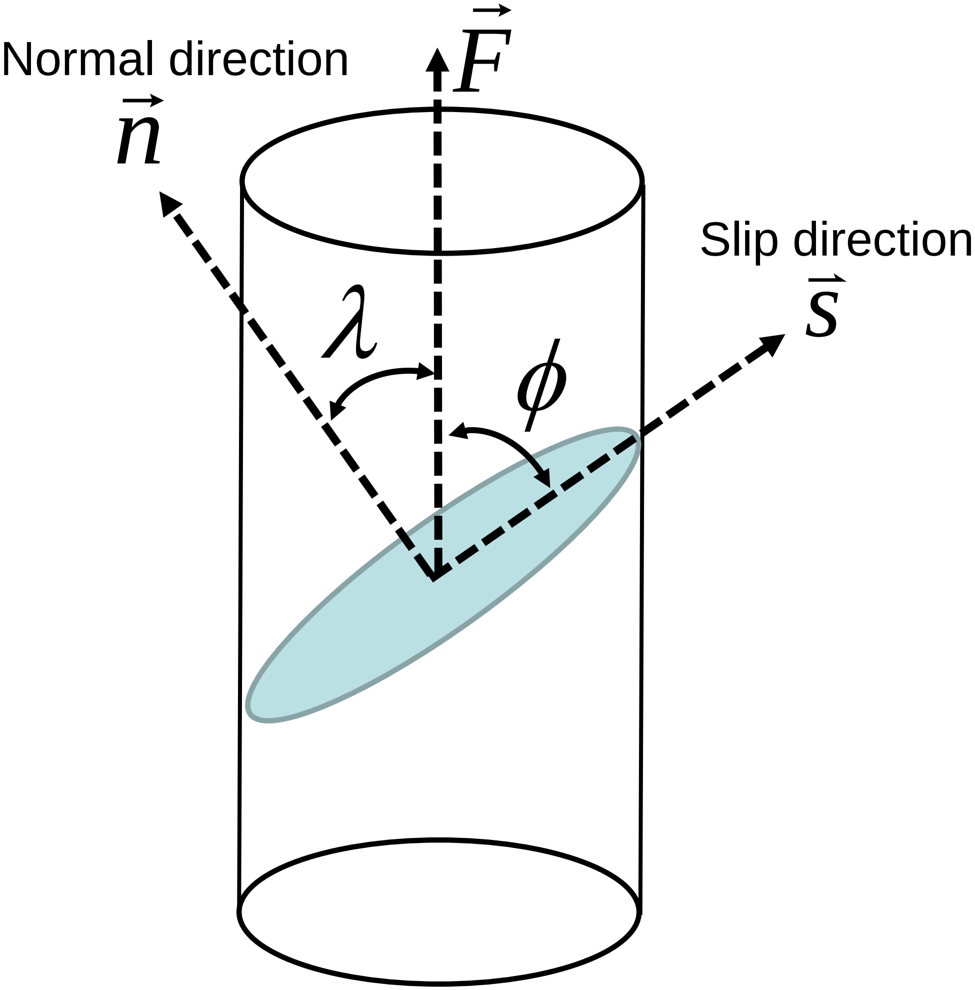


Slip systems in HCP metals

metal	c/a ratio	preferred slip system	purity	$\langle a \rangle$ basal CRSS (MPa)	$\langle a \rangle$ prism CRSS (MPa)
Cd	1.886	$\langle a \rangle$ basal	99.996	0.2	
Zn	1.856	$\langle a \rangle$ basal	99.999	0.2	
ideal	1.633			hard sphere model	
Mg	1.624	$\langle a \rangle$ basal	99.996	0.8	
Co	1.623	$\langle a \rangle$ basal			
Re	1.615	$\langle a \rangle$ basal		9.0	16.5
Zr	1.593	$\langle a \rangle$ prism	99.98	>24	6.4
Ti	1.588	$\langle a \rangle$ prism	99.95	92	23.5
Ru	1.582	$\langle a \rangle$ prism	99.92		20.6
Hf	1.581	$\langle a \rangle$ prism	98.6		20
Be	1.568	$\langle a \rangle$ basal	99.	2.3	14.7

T.B. Britton, F.P.E. Dunne, A.J. Wilkinson. Proc. R. Soc. A 471 (2015) 20140881.

Slip plane in terms of c/a ratio in HCP metals



$$\tau_{ns} = \frac{F\cos\lambda}{A_1} = \frac{F}{A}\cos\phi\cos\lambda$$

$$A_1 = A/\cos\phi$$

$$\tau_{ns} = \sigma_z \cos\phi\cos\lambda$$

$$\tau_c = \pm\sigma_z \cos\phi\cos\lambda$$

$$m = \cos\phi\cos\lambda$$

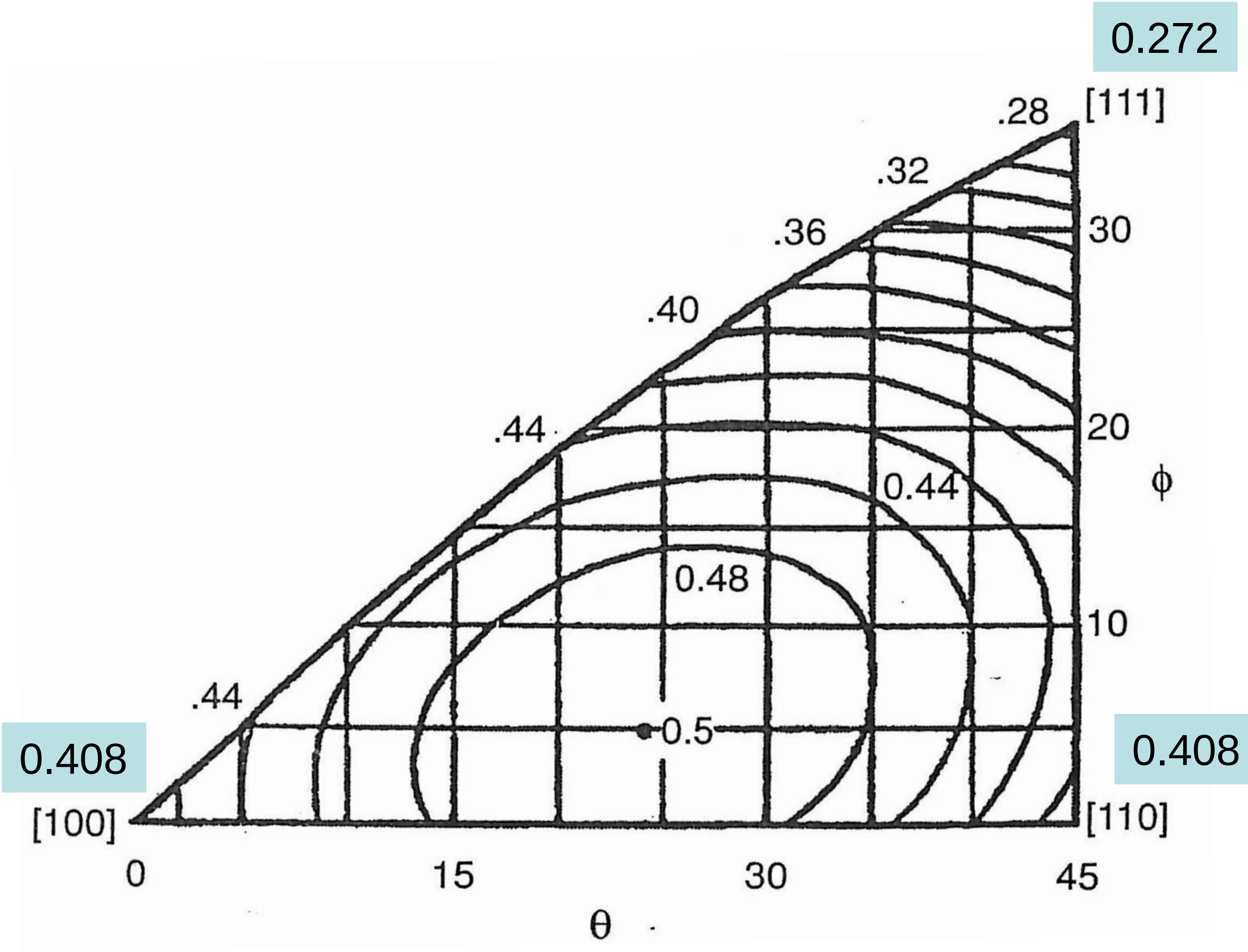
(Schmid factor)

Schmid's law: slip begins when the shear stress on a slip system reaches a critical value τ_c, called the critical resolved shear stress.

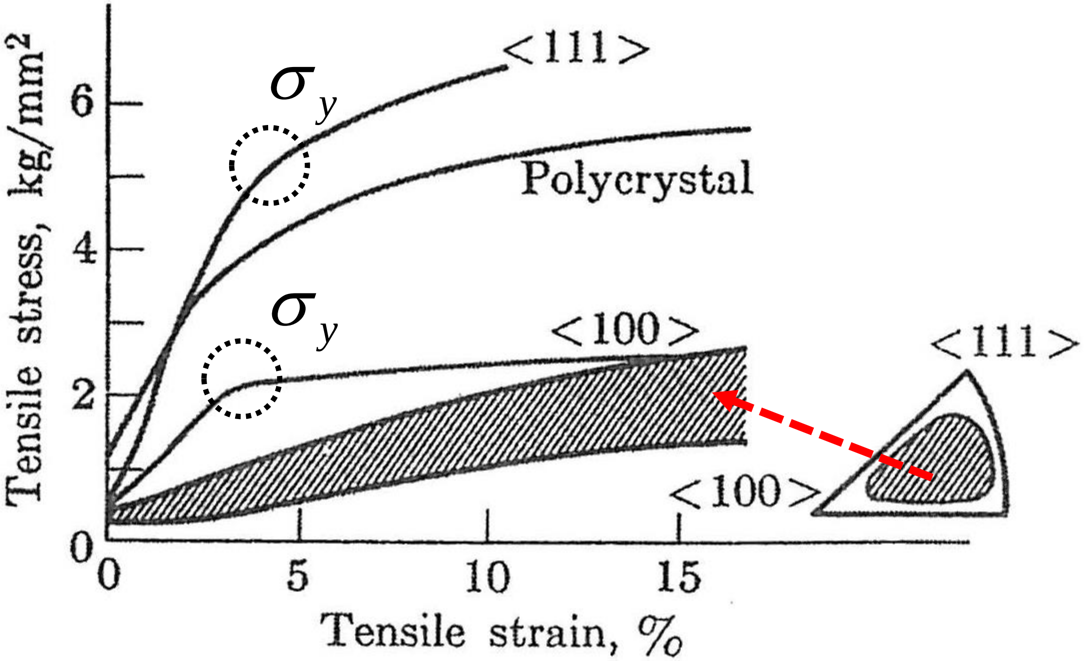
$$\tau_{ns} = \pm\tau_c$$

In tensor (index) form:
$\tau = b_i\, \sigma_{ij}\, n_j$

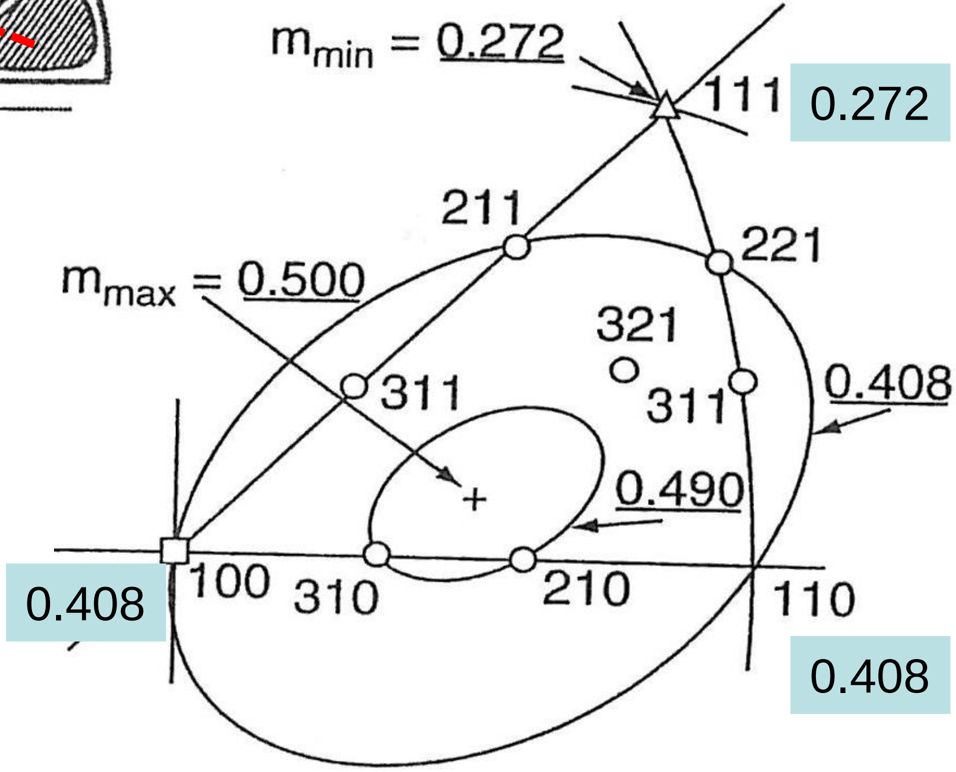
Schmid's Law



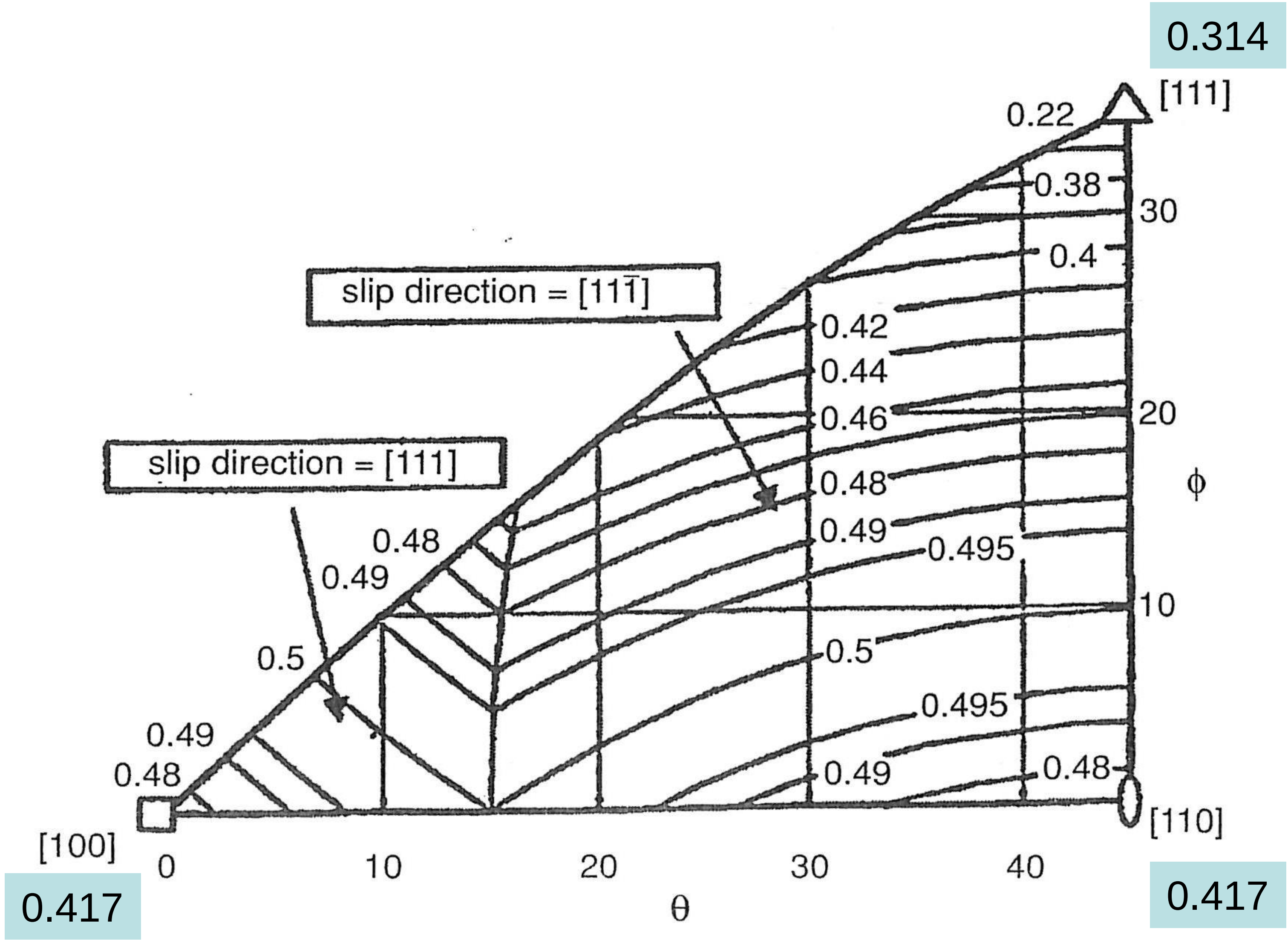
Schmid factor for FCC metals



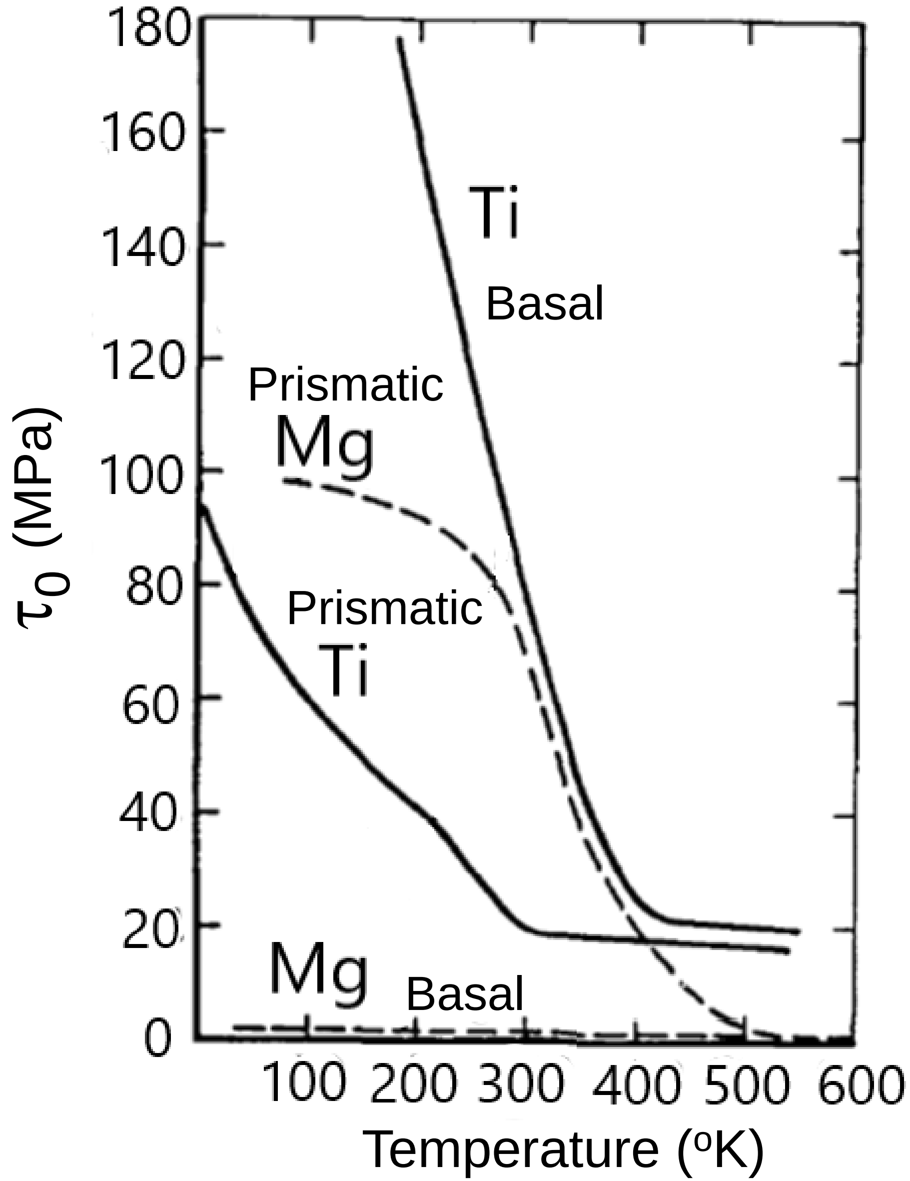
From U.F. Kocks, Acta Met. 8 (1960)



Stress-strain curves for polycrystalline and single crystal Al

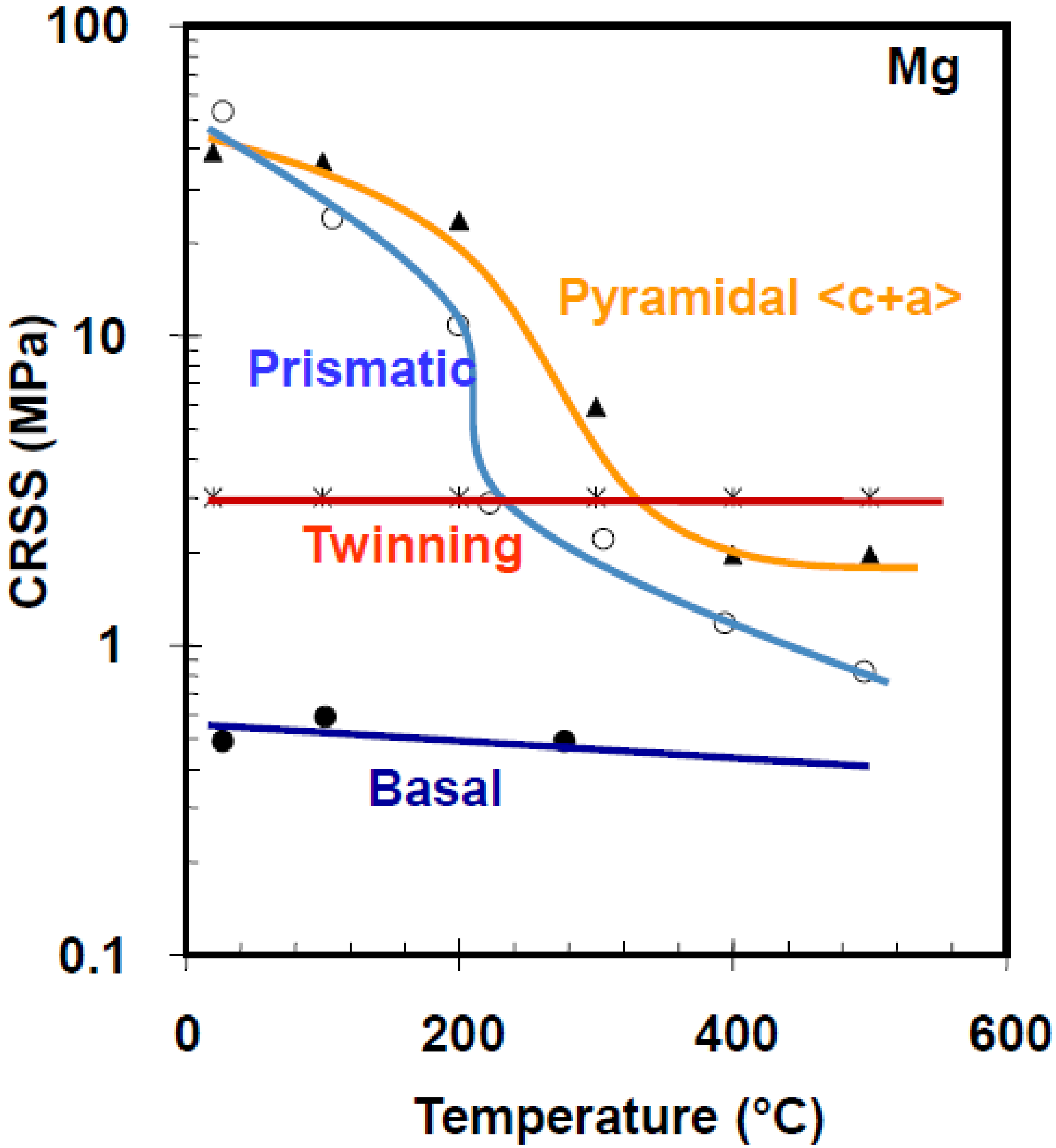


Schmid factor for BCC metals on <111>-pencil glides



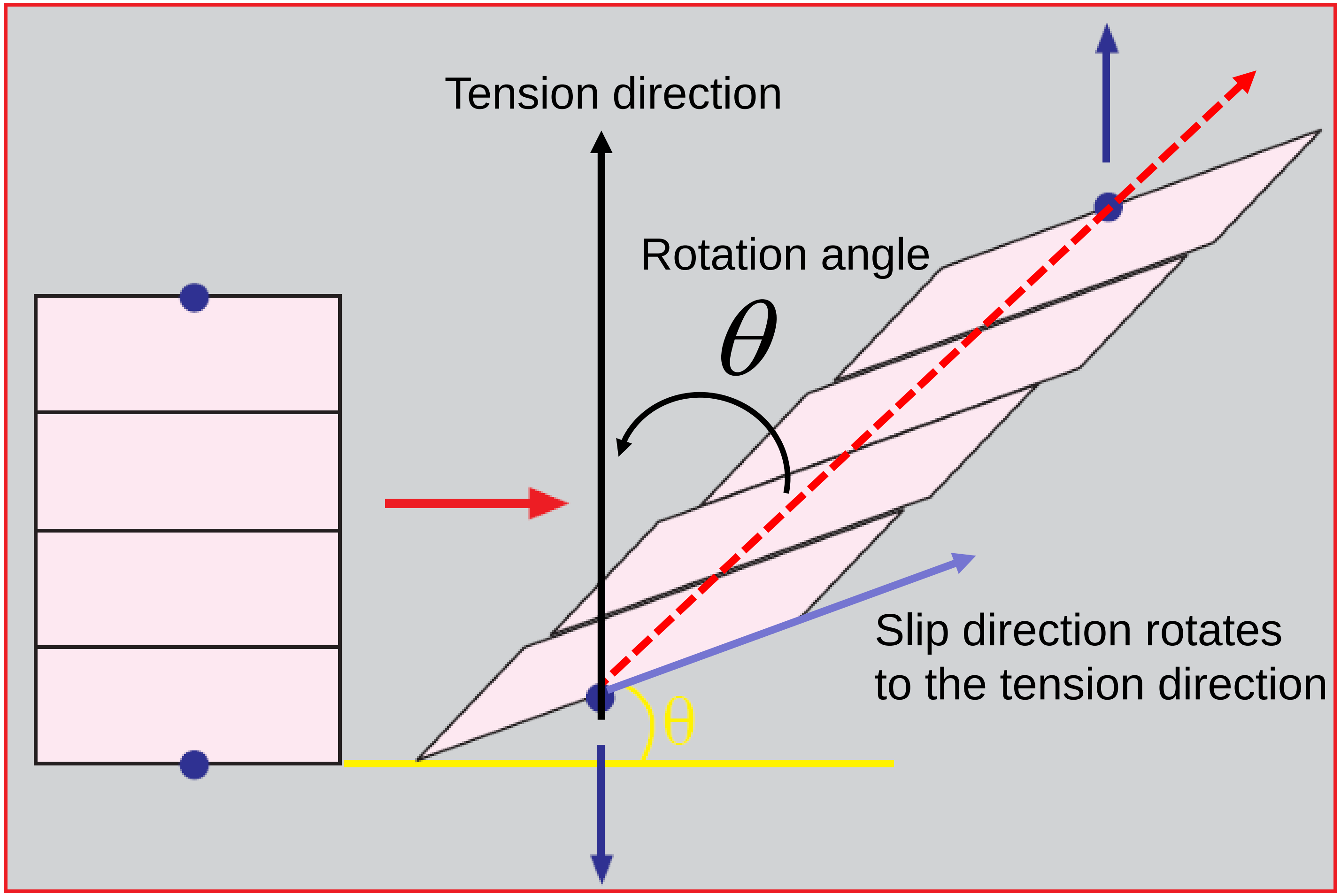
P.G. Partirdge, The crystallography and deformation modes of hexagonal close-packed metals, metal Review,1967:12:169

CRSS of basal and prismatic slips in hcp crystals

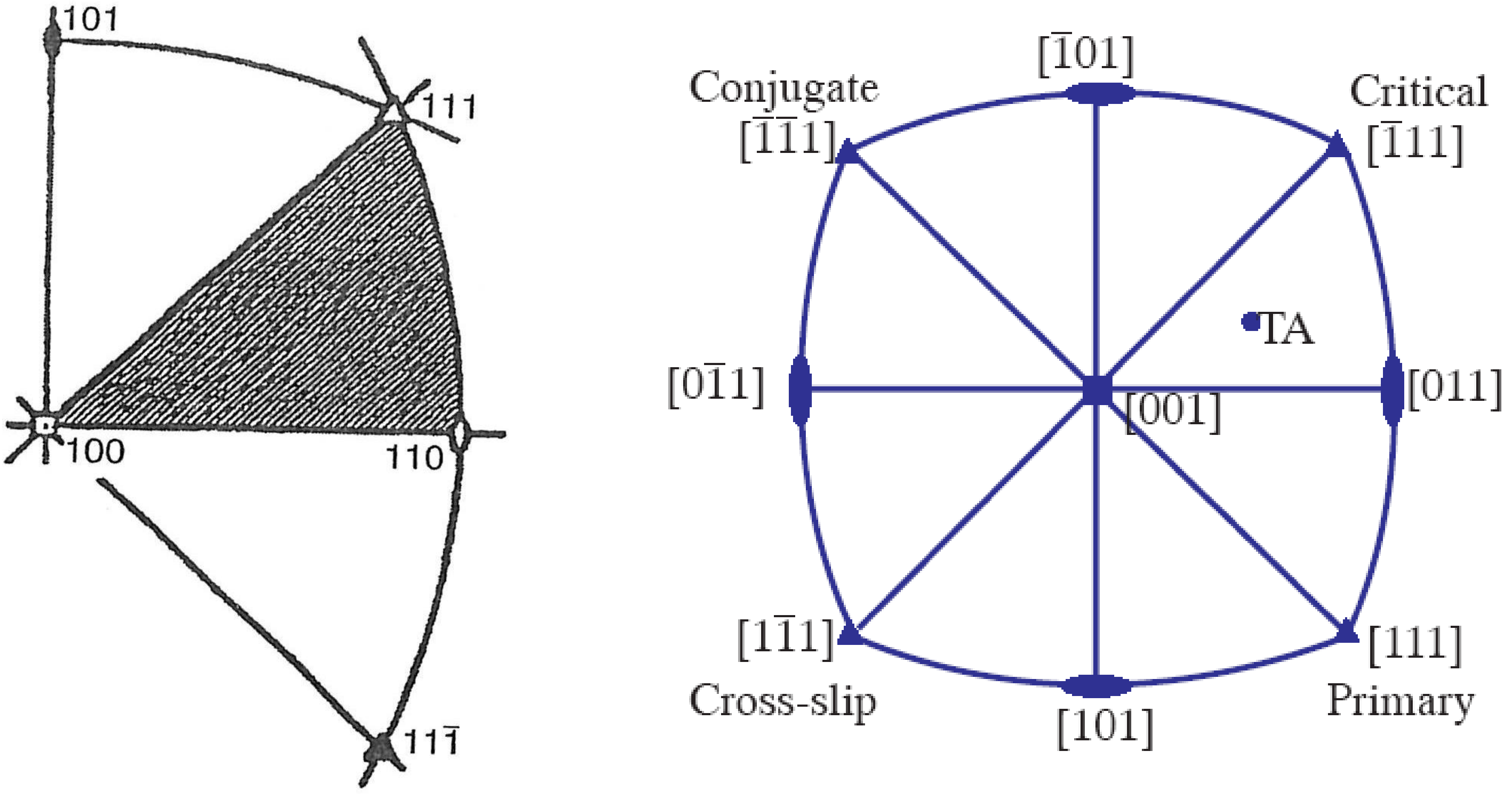


Barnett et al. (2002)

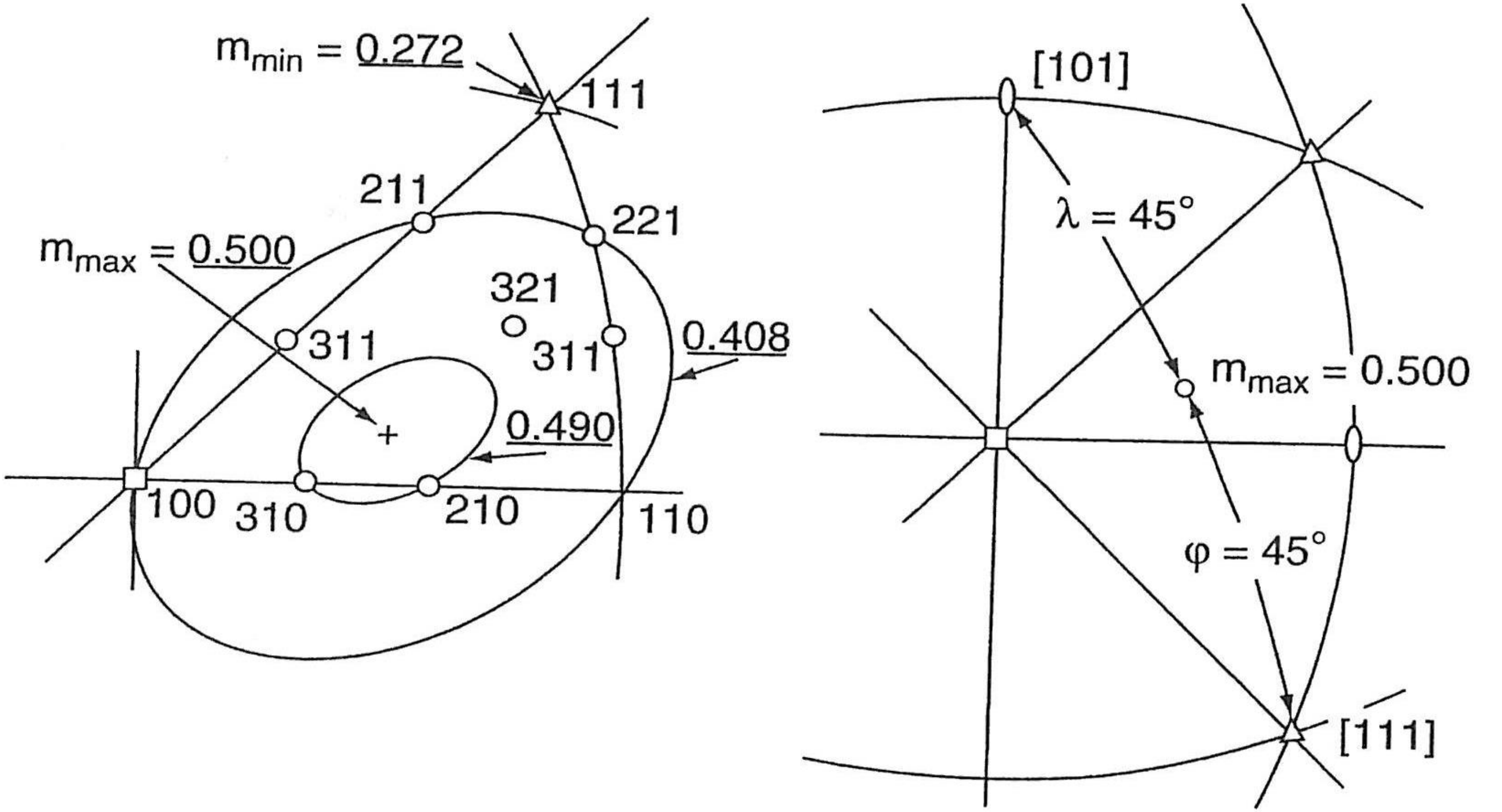
CRSS of basal and prismatic slips in hcp crystals



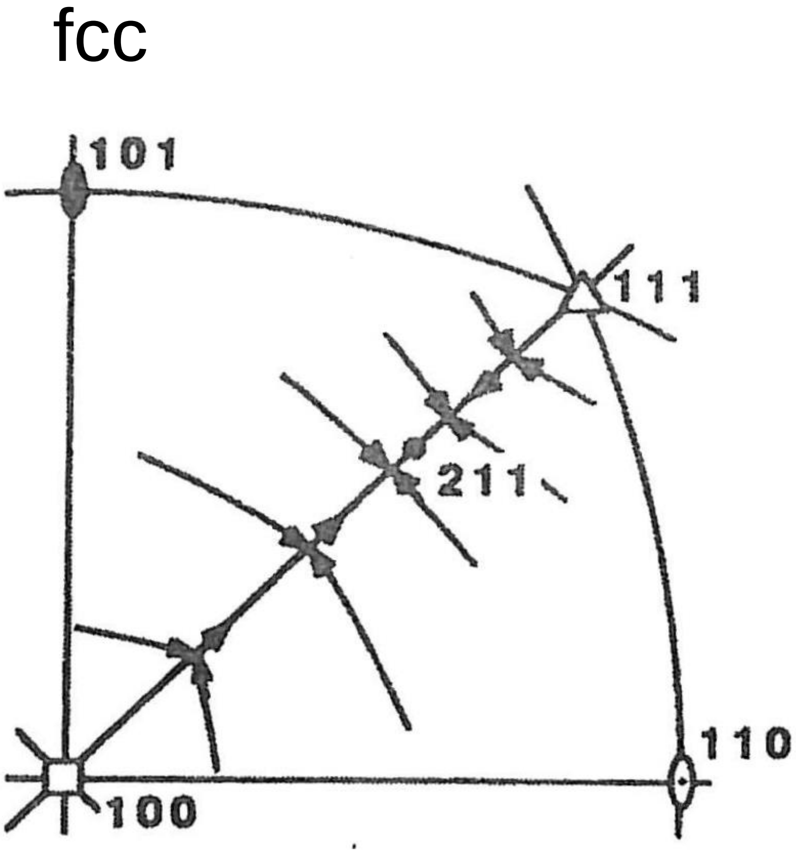
Lattice rotation during Tension

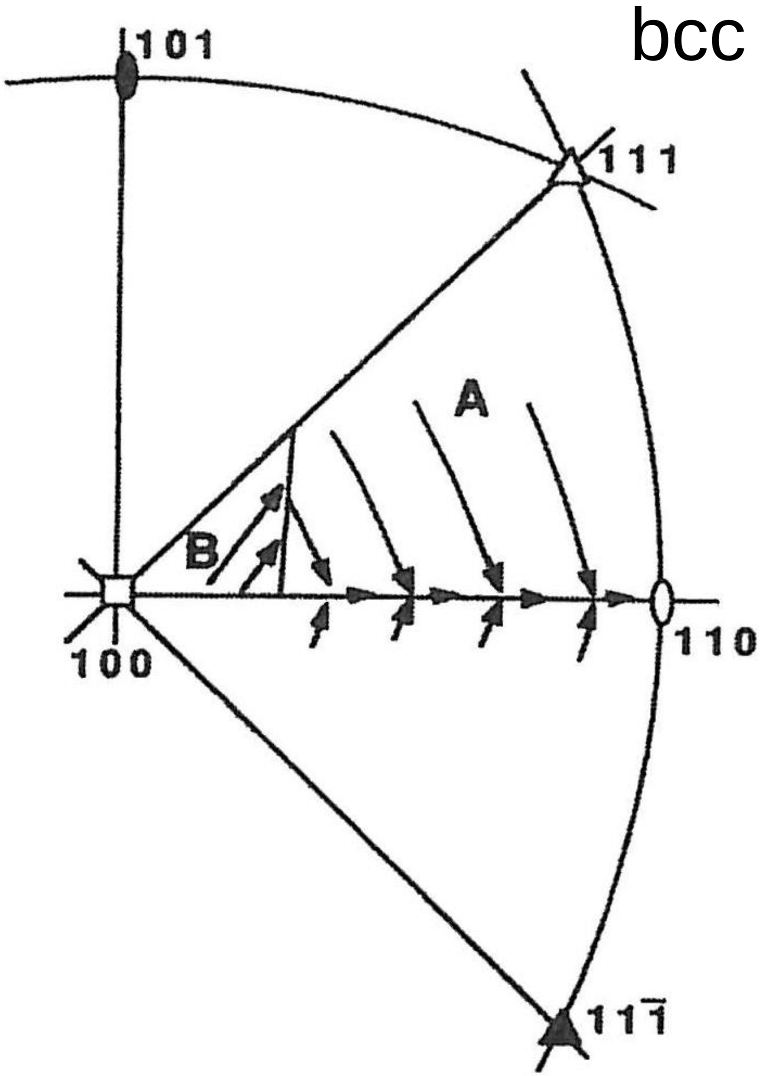


Representation of the tensile axis using orientation triangle

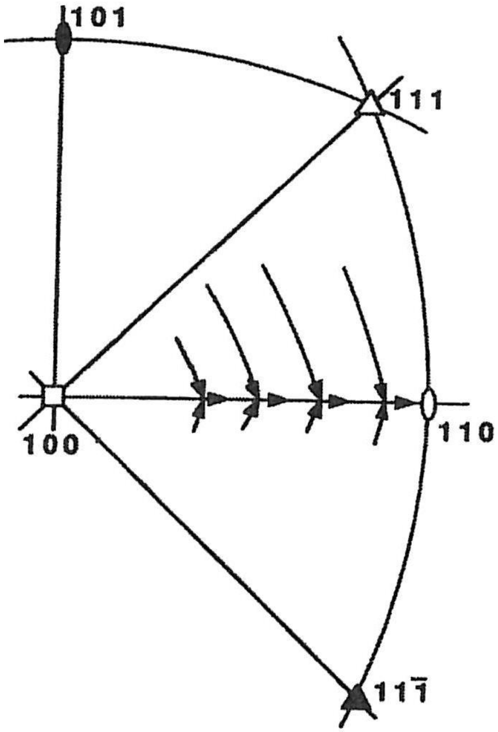


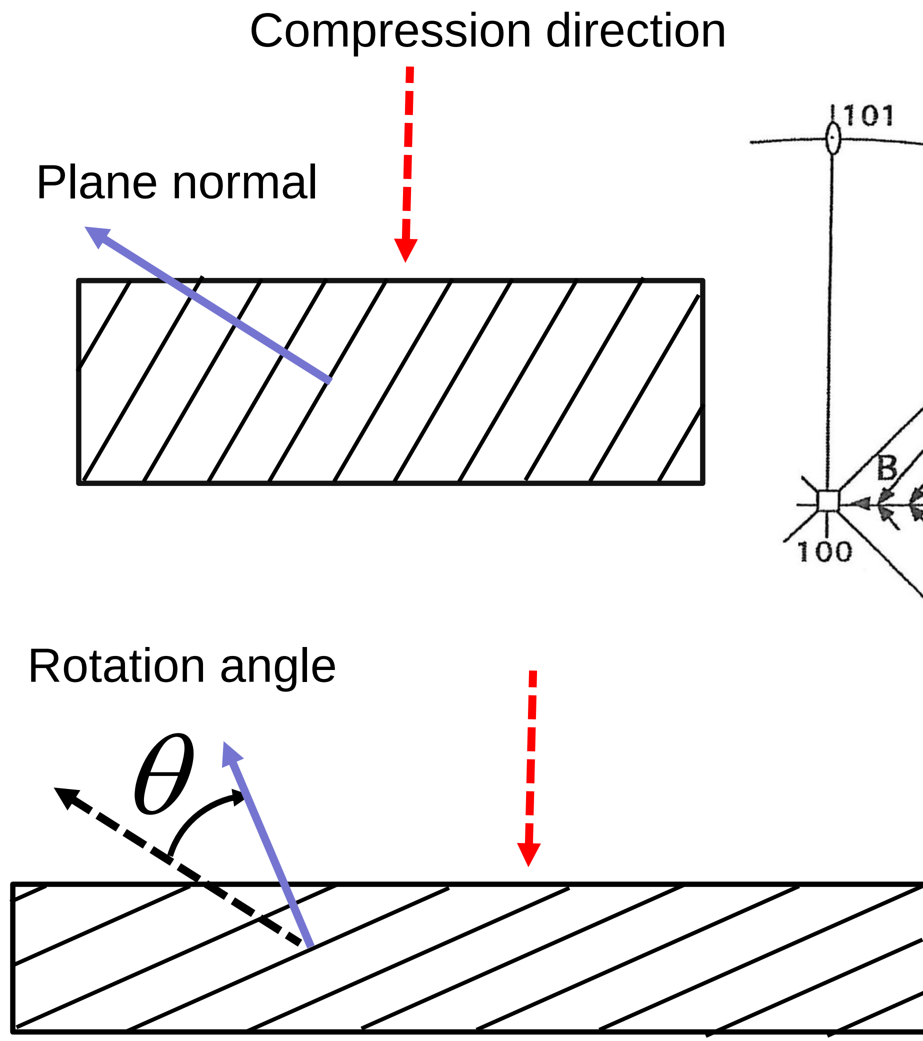
Representation of the tensile axis using orientation triangle



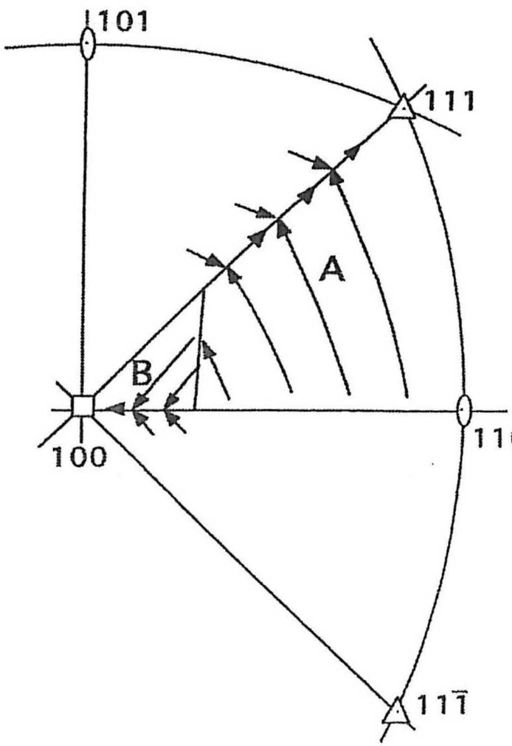


Lattice rotation in Tension for fcc and bcc metals fcc





bcc



Normal direction rotates
to the compression axis

Lattice rotation in Compression for fcc and bcc metals

Table 8.2. Comparison of theoretical end orientations with preferred orientations

Crystal structure and slip systems	Single crystals: end orientations		Polycrystals: preferred orientation	
	Tension	Compression	Tension	Compression
fcc $\{111\}\langle 110\rangle$	$\langle 112\rangle$	$\langle 110\rangle$	$\langle 100\rangle$ & $\langle 111\rangle$	$\langle 110\rangle$
bcc $\langle 111\rangle$-pencil glide	$\langle 110\rangle$	$\langle 100\rangle$ & $\langle 111\rangle$	$\langle 110\rangle$	$\langle 100\rangle$ & $\langle 111\rangle$
hcp $(0001)\langle 11\bar{2}0\rangle$	$\langle 11\bar{2}0\rangle$	[0001]	$\langle 11\bar{2}0\rangle$	[0001]
hcp $\{1\bar{1}00)\langle 11\bar{2}0\rangle$ and $\{110\bar{1})\langle 11\bar{2}0\rangle$	$\langle 10\bar{1}0\rangle$	[0001]	$\langle 10\bar{1}0\rangle$	[0001]

Summary of stable orientations during deformation

$$\varepsilon_{xx} = m_{xx1}\gamma_1 + m_{xx2}\gamma_2 + m_{xx3}\gamma_3 + \ldots\ldots\ldots + m_{xxj}\gamma_j$$

$$\varepsilon_{yy} = m_{yy1}\gamma_1 + m_{yy2}\gamma_2 + m_{yy3}\gamma_3 + \ldots\ldots\ldots + m_{yyj}\gamma_j$$

$$\varepsilon_{zz} = m_{zz1}\gamma_1 + m_{zz2}\gamma_2 + m_{zz3}\gamma_3 + \ldots\ldots\ldots + m_{zzj}\gamma_j$$

$$\gamma_{xy} = m_{xy1}\gamma_1 + m_{xy2}\gamma_2 + m_{xy3}\gamma_3 + \ldots\ldots\ldots + m_{xyj}\gamma_j$$

$$\gamma_{yz} = m_{yz1}\gamma_1 + m_{yz2}\gamma_2 + m_{yz3}\gamma_3 + \ldots\ldots\ldots + m_{yzj}\gamma_j$$

$$\gamma_{zx} = m_{zx1}\gamma_1 + m_{zx2}\gamma_2 + m_{zx3}\gamma_3 + \ldots\ldots\ldots + m_{zxj}\gamma_j$$

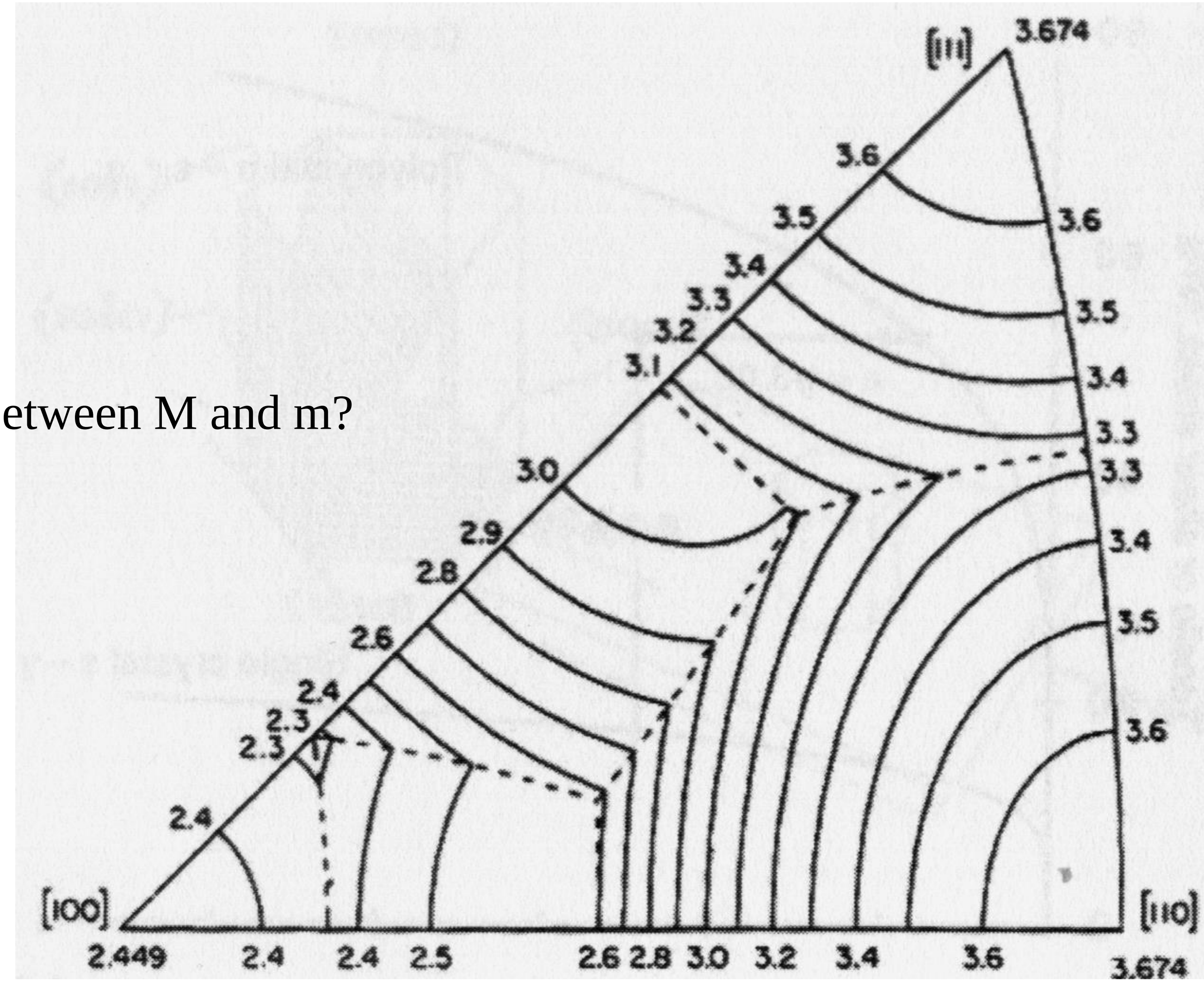
Only five independent equations?

$$\sigma_x d\varepsilon_x = \tau d\gamma$$

$$M = \frac{d\gamma}{d\varepsilon_x} = \frac{\sigma_x}{\tau}$$

M: Taylor factor

What is the difference between M and m?

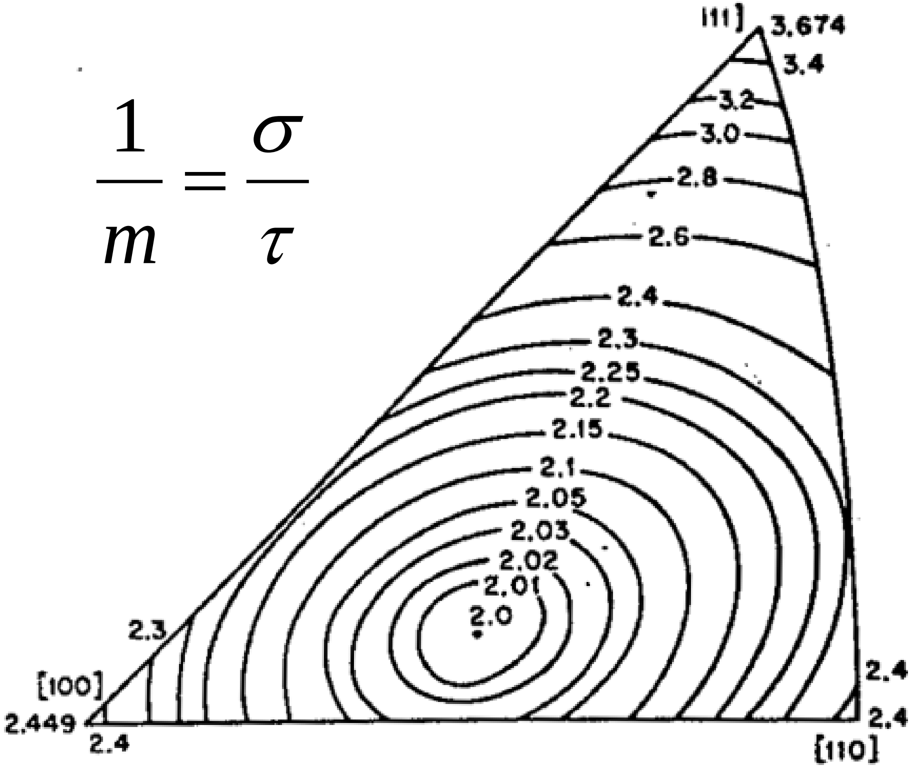


Taylor factor M for axisymmetric flow from Chin

The selected slip system and thus texture evolution can be predicted by the geometry of shear with respect to the external stress by Schmid's law, applied by Sachs for **single slip**. For **multiple slip** which is able to fulfill the strain compatibility of grains, the Taylor theory predicts the necessary slip systems.

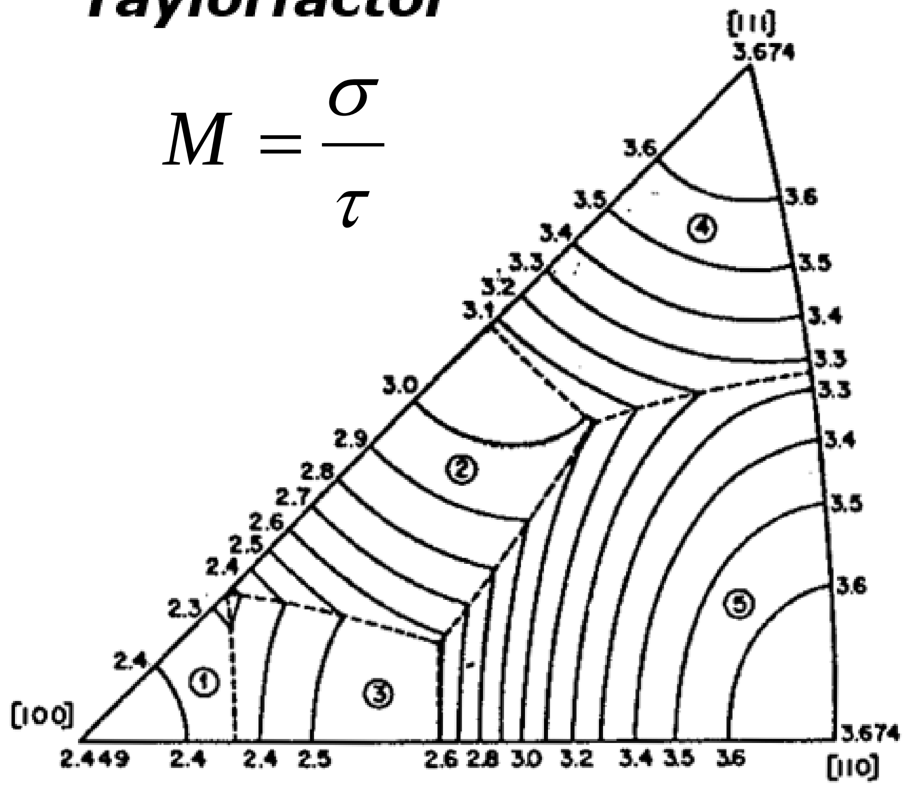
Schmidfactor

$$\frac{1}{m} = \frac{\sigma}{\tau}$$



Taylorfactor

$$M = \frac{\sigma}{\tau}$$



Schmid factor 1/m and Taylor factor M

1. D.E. Laughlin and K. Hono, “Physical Metallurgy”, fifth edition, Elsevier, Amsterdam, Netherlands, 2014.

References