ME 531 April 15 2020

Monday Sameer is going to present crystal plasticity example.

(1) Latent Hardening (Theory)

(2) Geometric hardening, k_0, k, Eqn 3.12.14

(3) Stress Rate (Objective) $\frac{\text{WARP3D}}{\text{Jaummann}}$

Pierce Asaro Needleman

$$H_{\alpha\beta} = qH + (1-q)\, H\, \delta_{\alpha\beta}$$

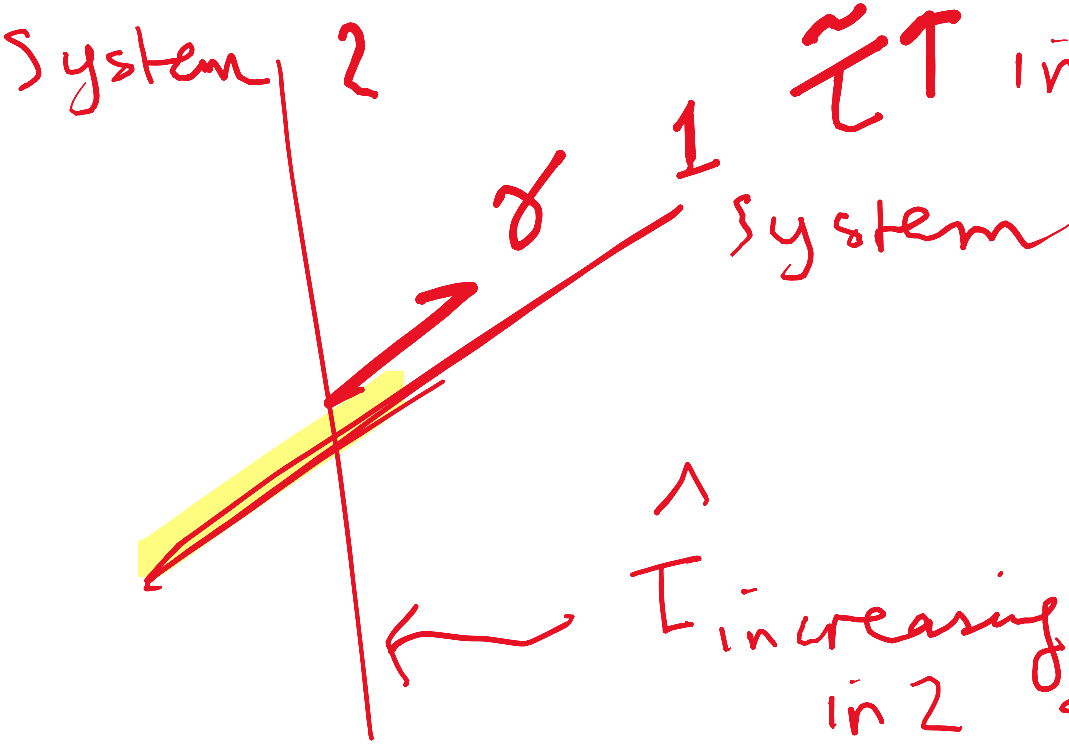
q = material constant

$$\dot{\tau}^{\alpha} = \sum_{\alpha=1}^{N} H_{\alpha\beta}\, \dot{\gamma}^{(\beta)}$$

$$H_{\alpha\beta} = \begin{bmatrix} \underline{H} & \underline{H} \\ \underline{H} & \underline{H} \end{bmatrix}$$

2 slip systems

$q = 1$



$\tilde{\tau} \uparrow$ increasing

$\hat{\tau}$ increasing (isotropic hardening) in 2 same amount as 1, H governs

$$H_{\alpha\beta} = q H + (1 - q) H \delta_{\alpha\beta}$$

q = const. (idealization)

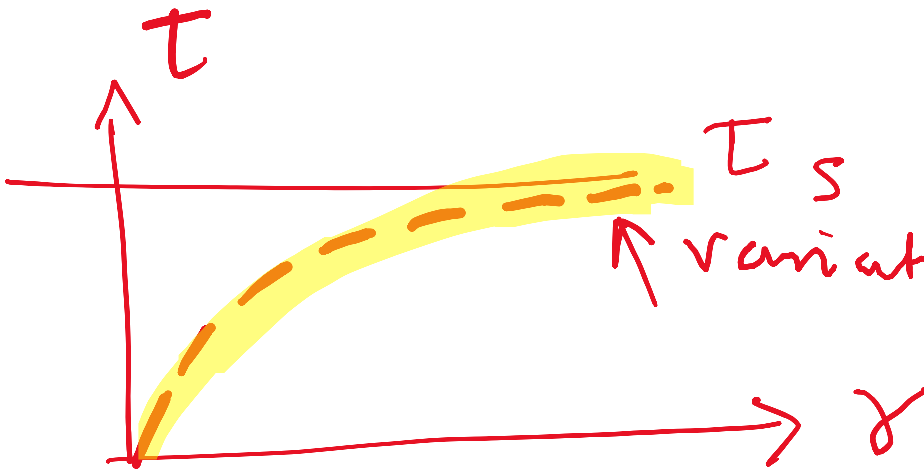
$$H(\gamma) = H_0 \operatorname{sech}^2\left(\frac{H_0 \gamma}{\tau_s - \tau_0}\right)$$

= PAN

= changes with γ

= (H_0, τ_0 current value of resolved shear

τ_s = saturation value)



$\dot{\tau} = H \dot{\gamma}$ single system

H can be determined from experiments on single crystals oriented ~~to~~ to activate a single slip system

$\Rightarrow$ upon integration

$$\tau(\gamma) = \tau_0 + (\tau_s - \tau_0) \tanh\left[\frac{H_0 \gamma}{\tau_s - \tau_0}\right]$$

WARP3D ⇒ MTS model for hardening

$$\tau \approx \tau_a + \tau_i + \tau_y$$

(single system) ($\dot{\varepsilon}$, T effects) mid term

Latent Hardening ?

LHR = Latent hardening ratio

$= L_{ji}$

latent system j , primary system, i

$$L_{ji} = \tau_j^{o} / \tau_i^{max}$$

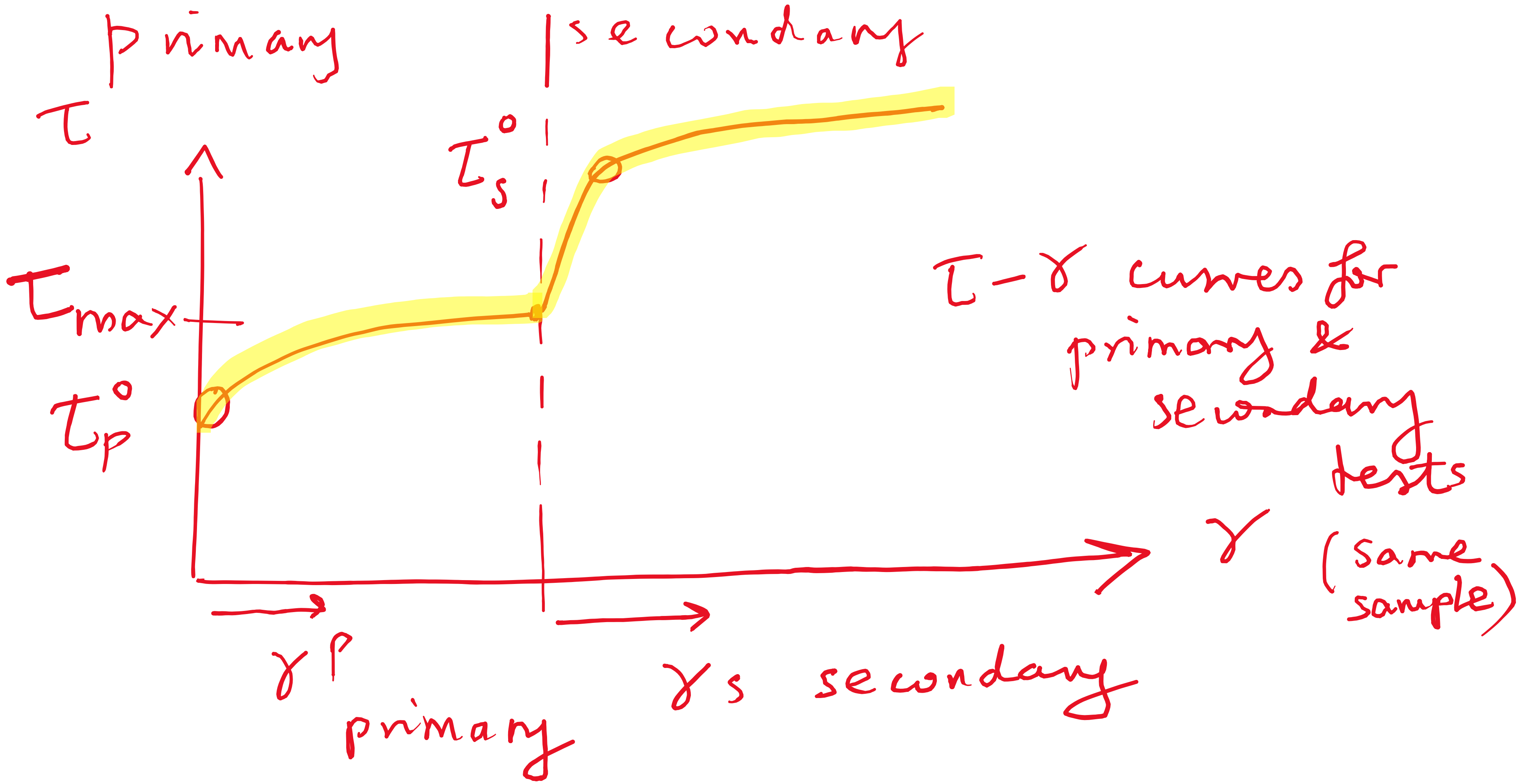
τ_j^{o} = yield stress of latent system

τ_i^{max} max stress reached in the primary system

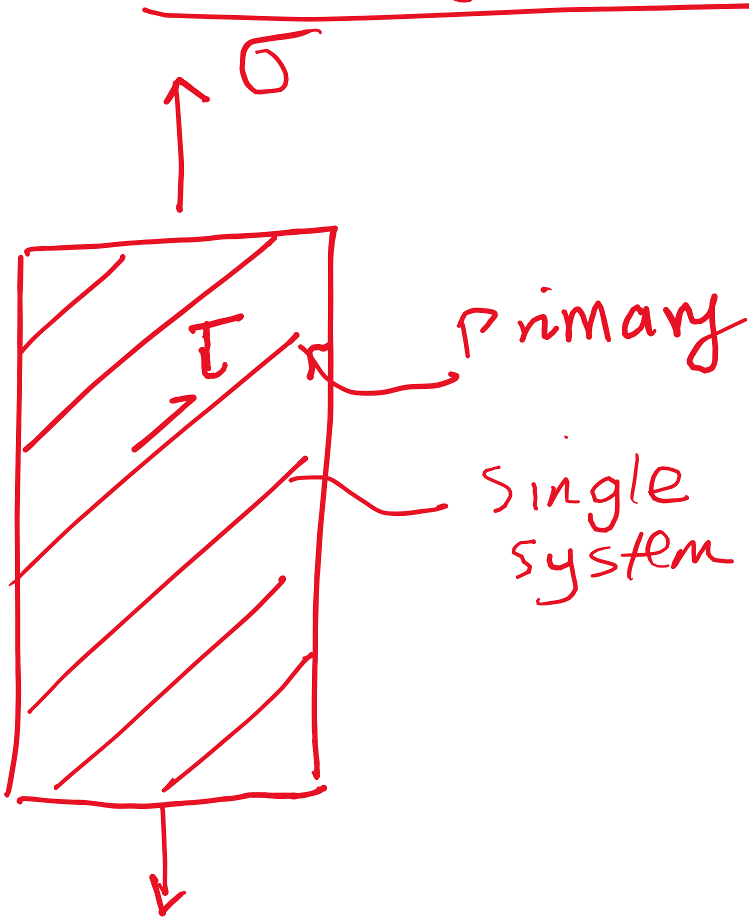
Primary deformation

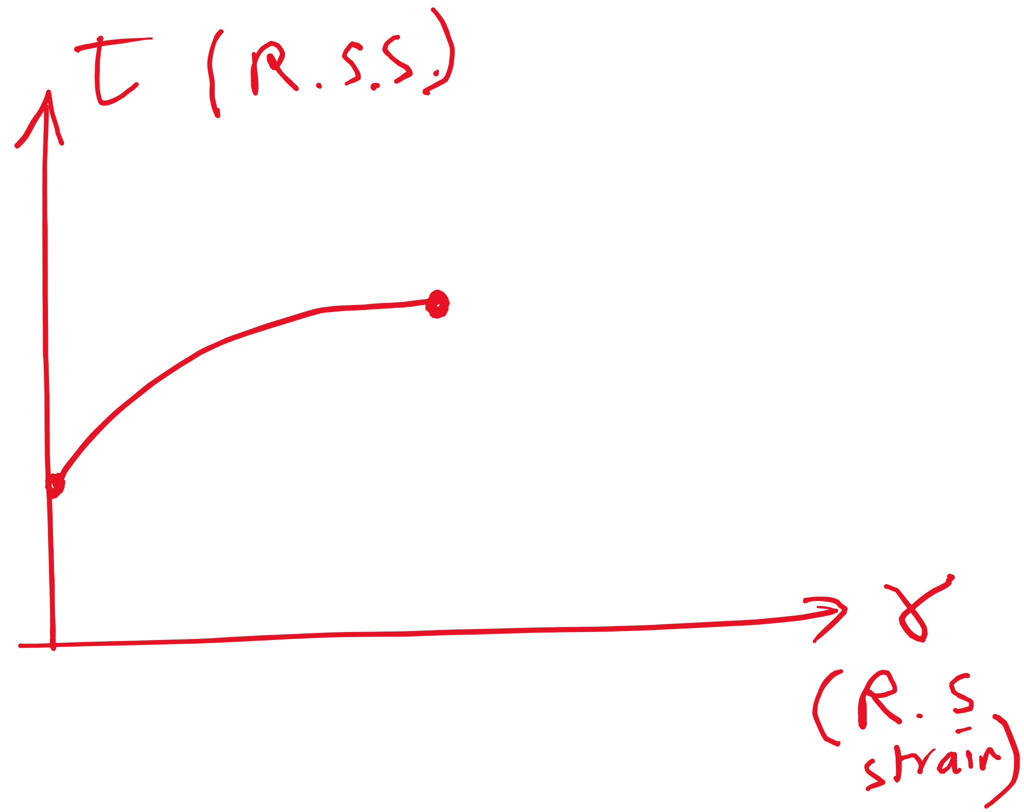
— easy glide - only one system is activated

Secondary test - latent system is active interacts with primary system.

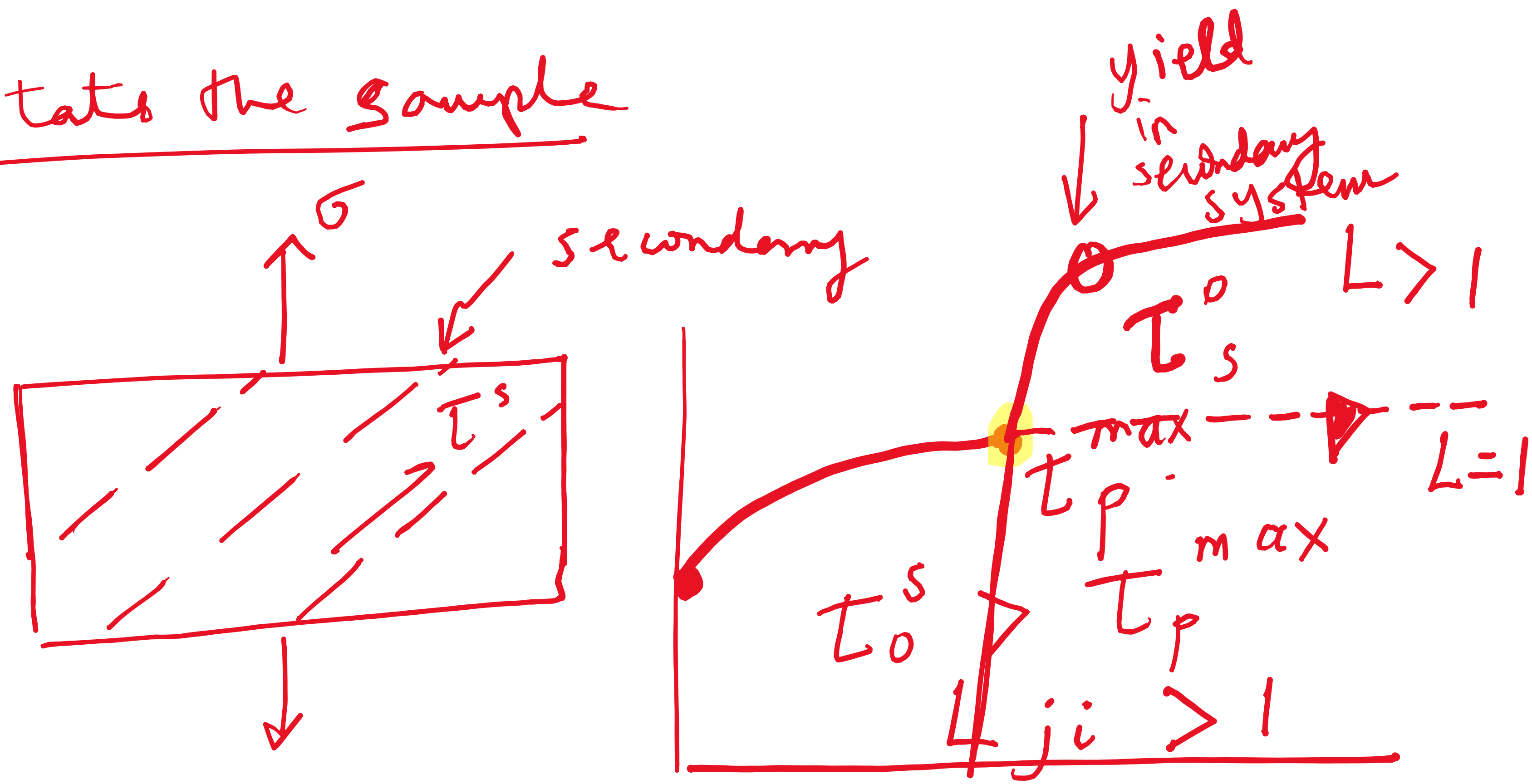

primary
secondary
τ
τ_s^o
τ_{max}
τ_p^o
τ - γ curves for primary & secondary tests
γ
(same sample)
γ^p
primary
γ_s secondary

Primary test





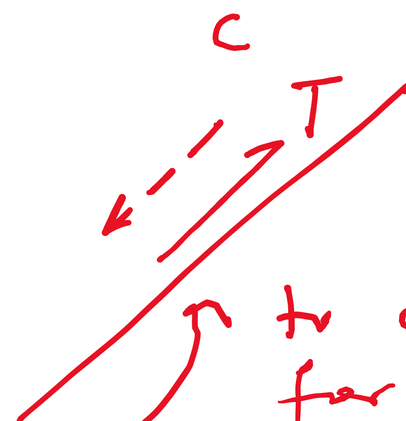
Rotate the sample



Latent hardening (cross hardening)

In real life

$H_{\alpha\beta}$ 12 x 12 matrix



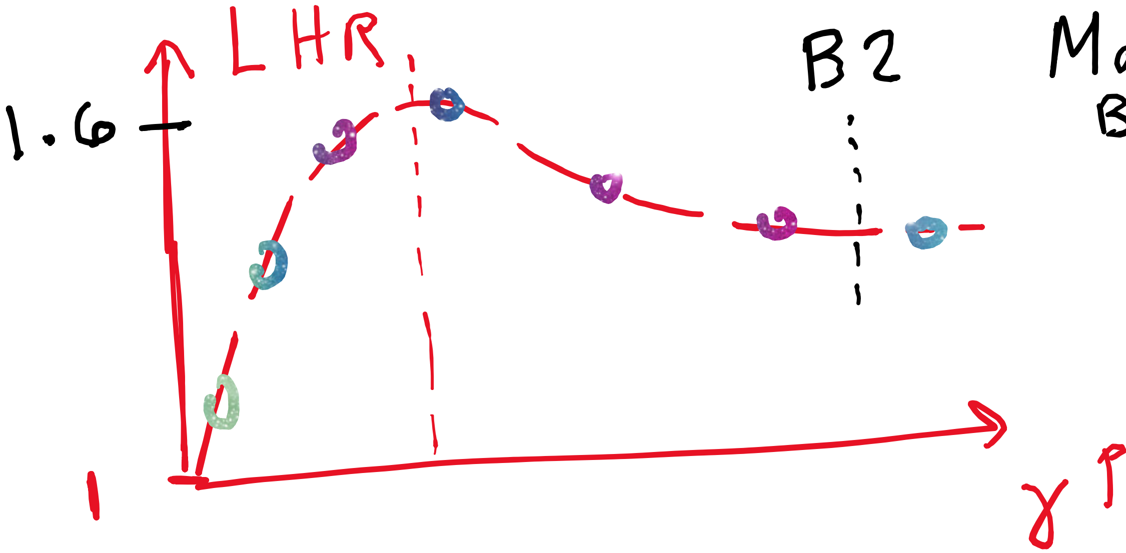
in fact

$H_{\alpha\beta}$ 24 x 24 matrix — to account for Tension, Compression

(symmetries)

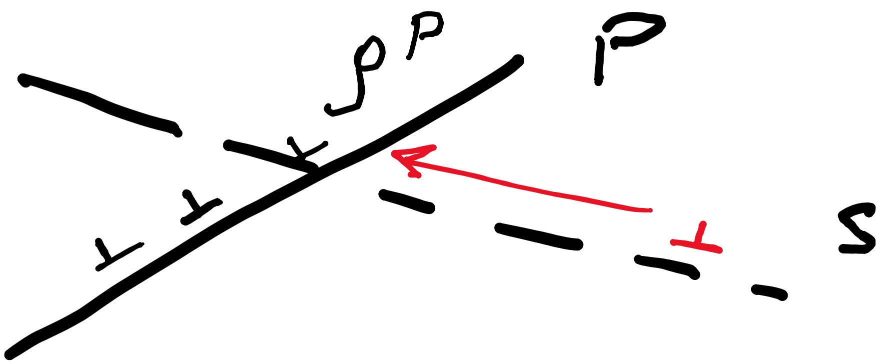
FCC — results are available

For BCC, HCP it is more complicated



Marcel Berveiller,
Francois Zaoui,
⋮

FCC] some results.
BCC
HCP] totally not understood



A to D

A $(\bar{1}11)$

B (111)

C $(\bar{1}\bar{1}1)$

D $(1\bar{1}1)$

numbers 1 to 6

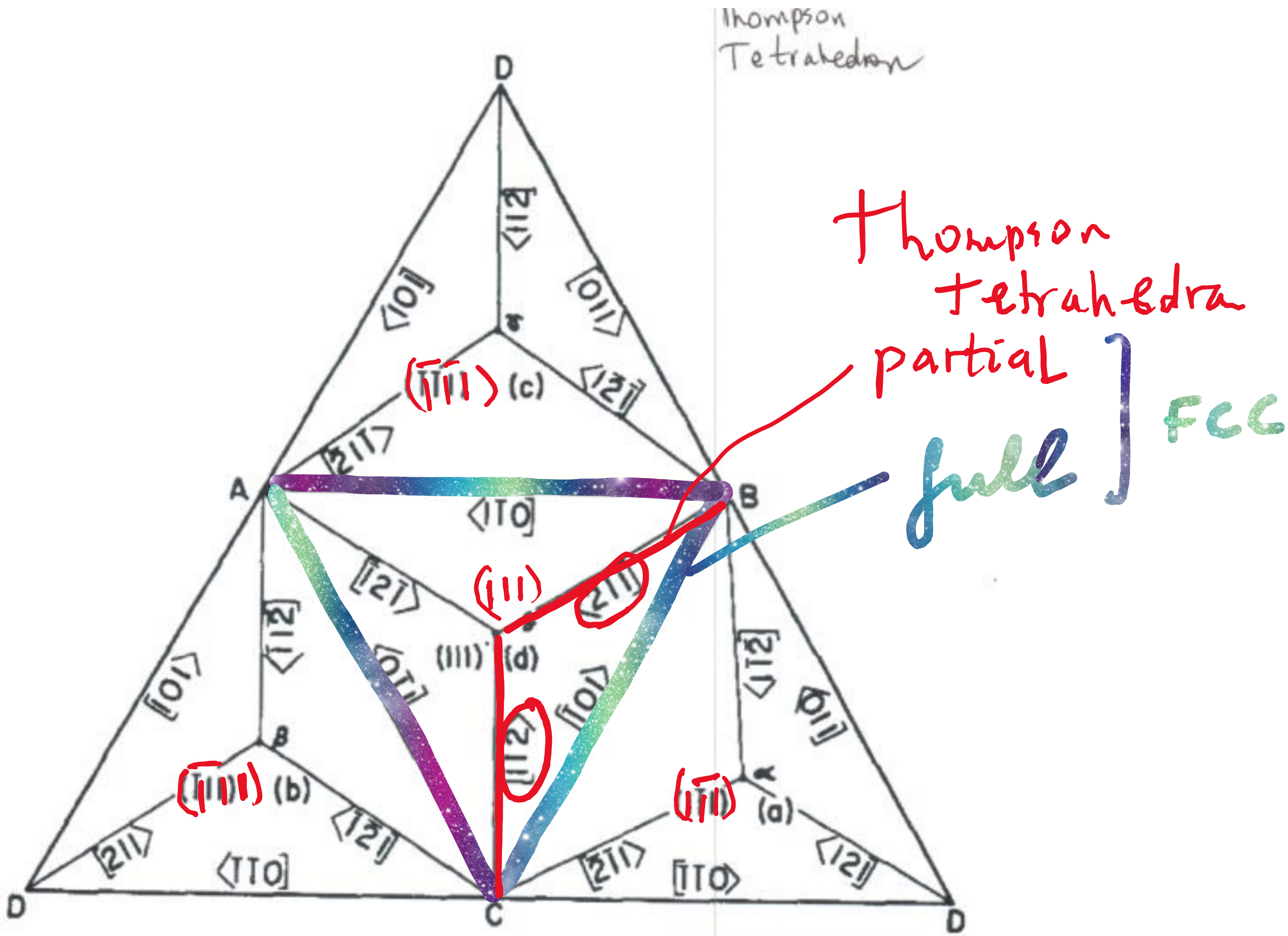
$\pm[011]$ $\pm[101]$ $\pm[1\bar{1}0]$

$\pm[0\bar{1}1]$ $\pm[\bar{1}01]$ $\pm[110]$

are slip directions

Stereographic projection has 24 standard triangles each representing one slip system.

1) Thompson Tetrahedra
2) Stereographic projection


Thompson
Tetrahedron
Thompson
tetrahedra
partial
full
FCC
D
A
B
C
(a)
(b)
(c)
(d)
(111)

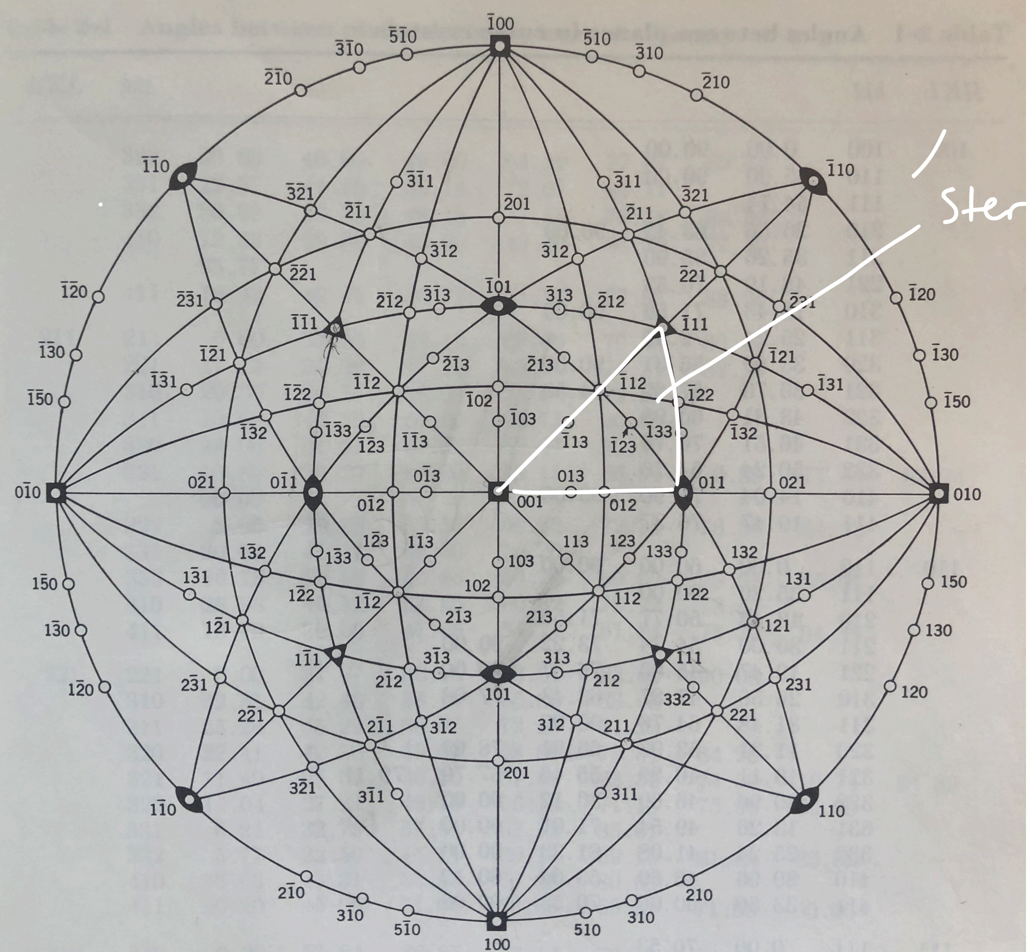
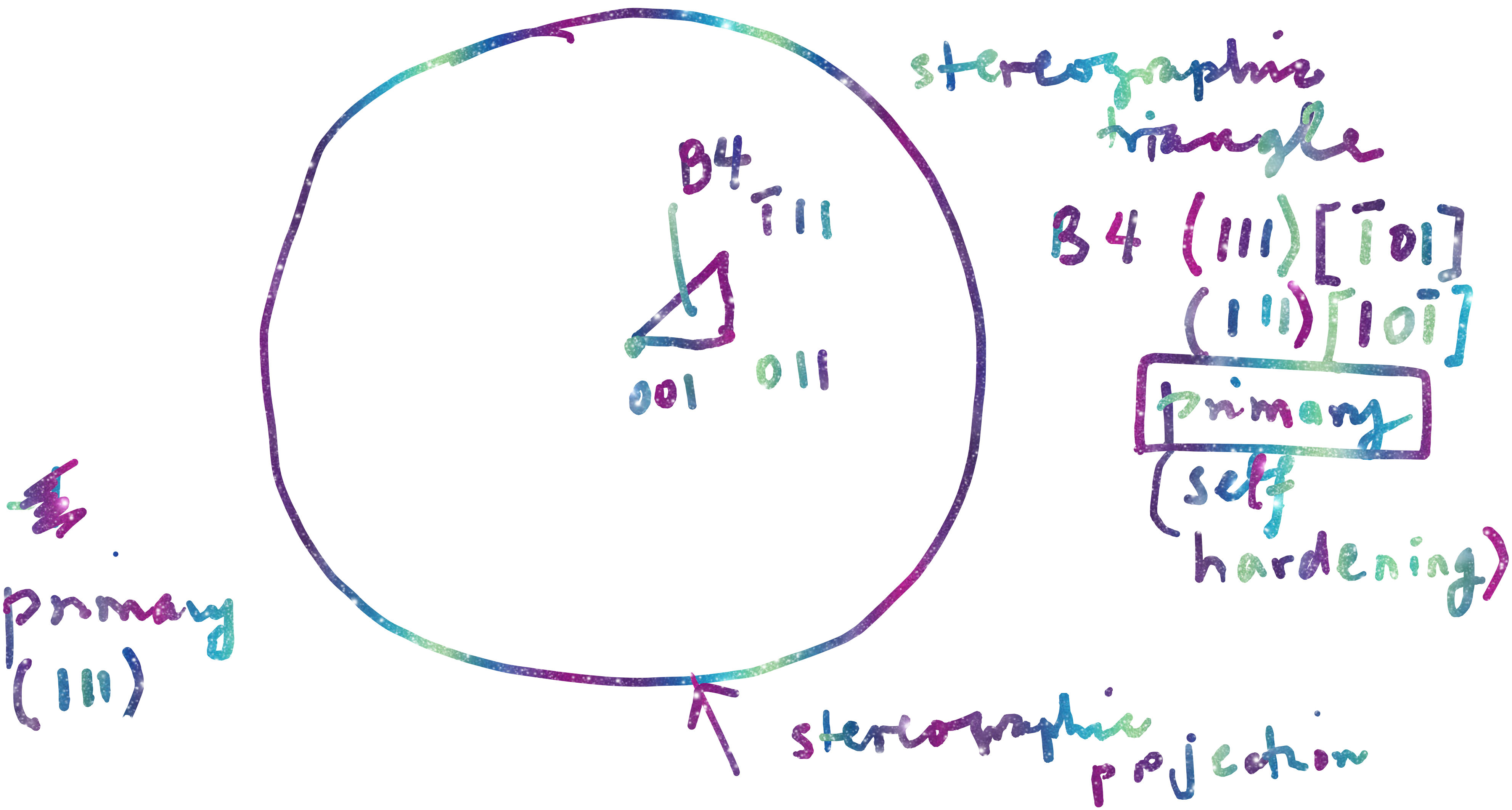
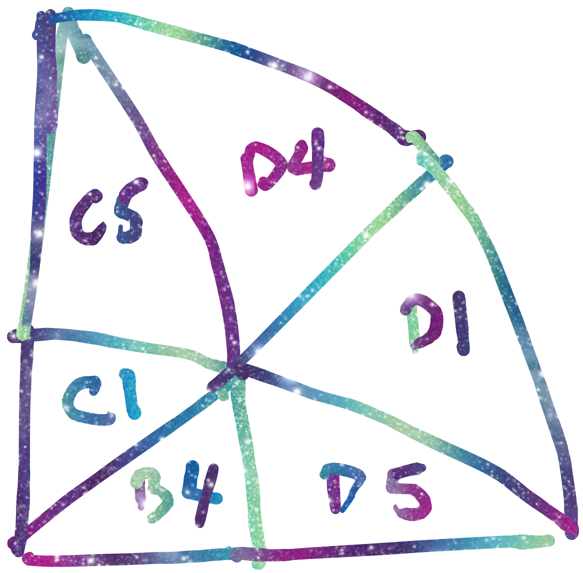


Fig. 2-9 Standard (001) stereographic projection of poles and zone circles for

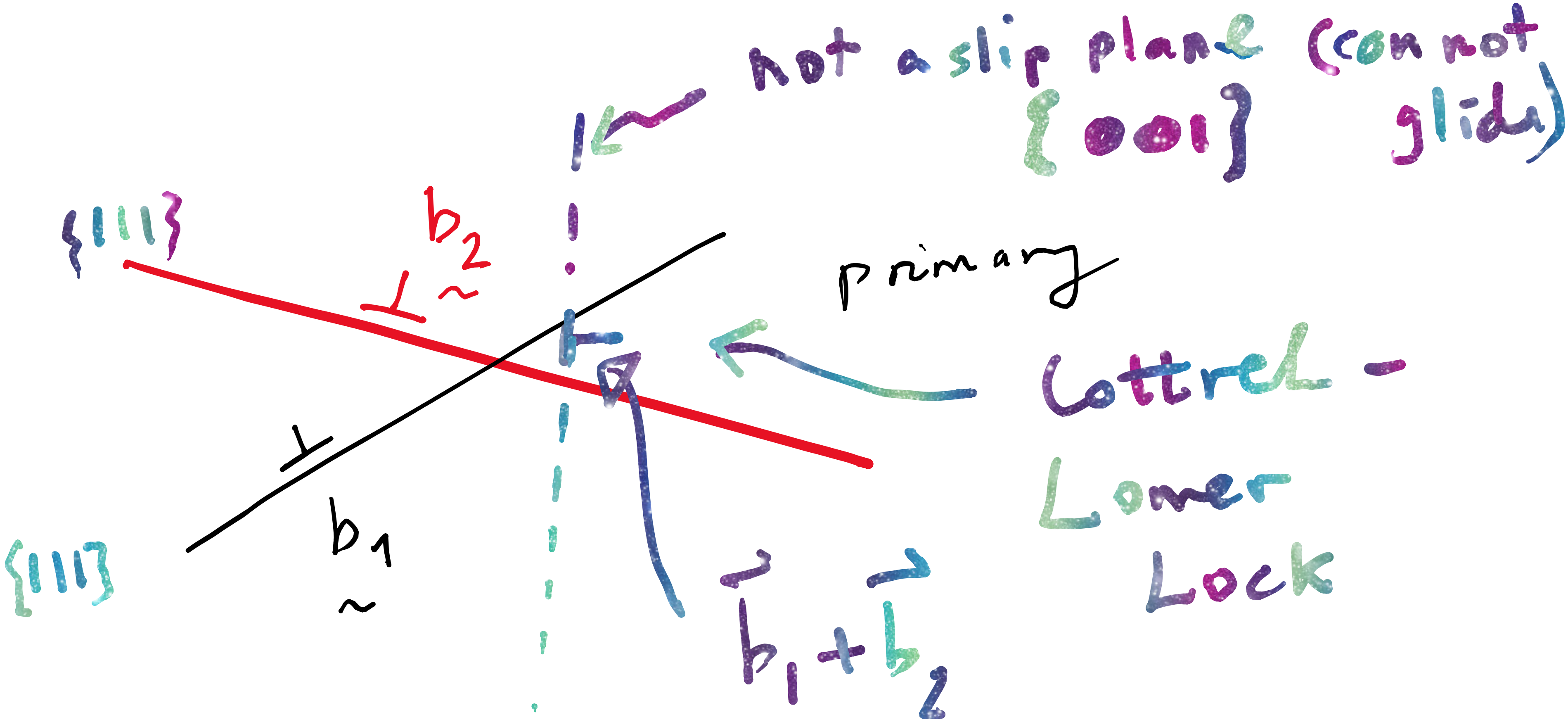


B4
$\bar{1}11$
001
011
stereographic triangle
B4 $(111)[\bar{1}01]$
$(111)[10\bar{1}]$
primary
(self hardening)
primary
(111)
stereographic projection



Dislocations in the primary system can interact with conjugate or critical systems to create Lomer Cottrell dislocations
If the resulting dislocation has slip planes that lies on neither one

of the intersecting planes.



L – C sessile lock formation

(B4 primary)

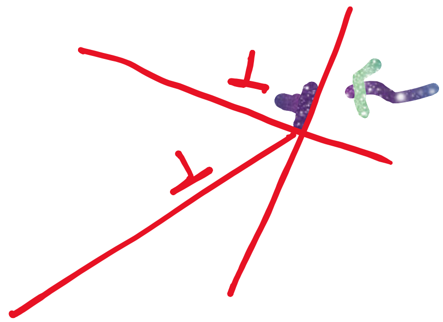
		Angle Between two planes	resultant b	resultant SP (slip plane)
1) A6	($\bar{1}$11)[110]	70.5°	[011]	(100)
A6	($\bar{1}$11)[$\bar{1}$10]	70.5		
C1	($\bar{1}\bar{1}$1)[0$\bar{1}\bar{1}$]	109.5	[$\bar{1}\bar{1}$0]	(001)
C1	($\bar{1}\bar{1}$1)[011]	109.5	[$\bar{1}$12]	(110)

1] **Lomer Lottrell Lock** (strongest)

2) **Hirth Lock**

A3

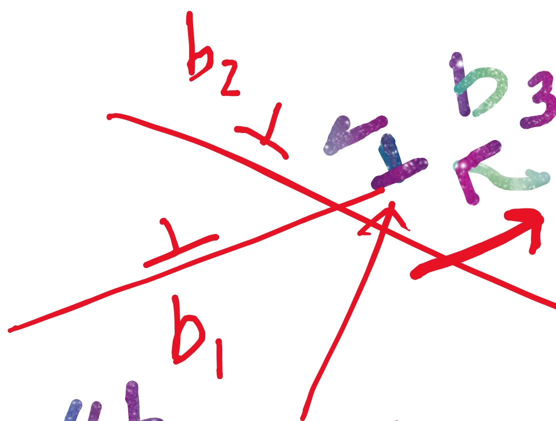
C3



← acts as a barrier

resultant dislocation on a slip plane (third dislocation)

3) Glissile ~~Attractive~~ Junction



← sign is such attractive (Force needed to separate from the junction)

$b_3 \parallel b_1$

(resultant ~~dislocation~~ dislocation on either slip plane)

B4 primary + $\frac{\text{A2, C5, D1, D6}}{\text{secondary}}$ ⇒ glissile attractive junct.

(4) Crosslip in system D4

(5) Coplanar system B2 & B5

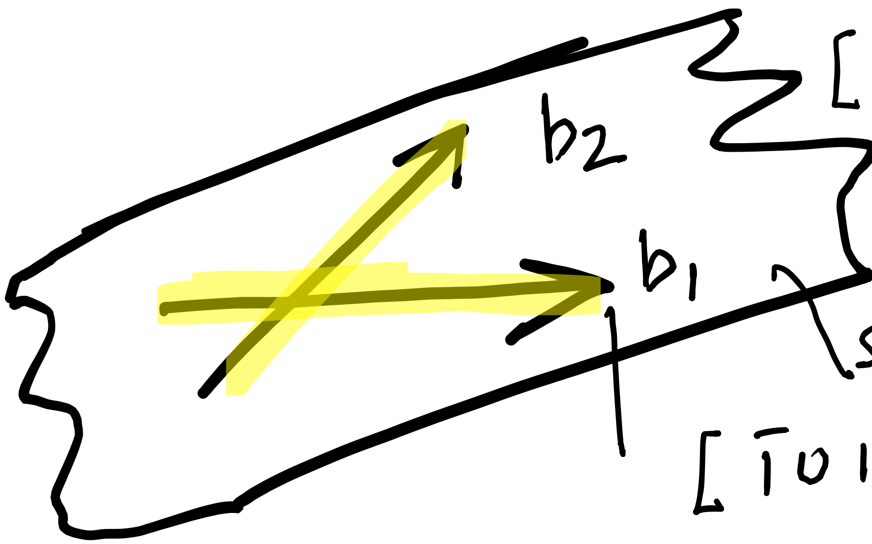
(6) Self hardening in system B4

(6) Self Hardening

B4 (111) $[\bar{1}01]$ 0

(111) $[10\bar{1}]$ 180

(5)



$[01\bar{1}]$ or $[1\bar{1}0]$ coplanar

specific (111) plane

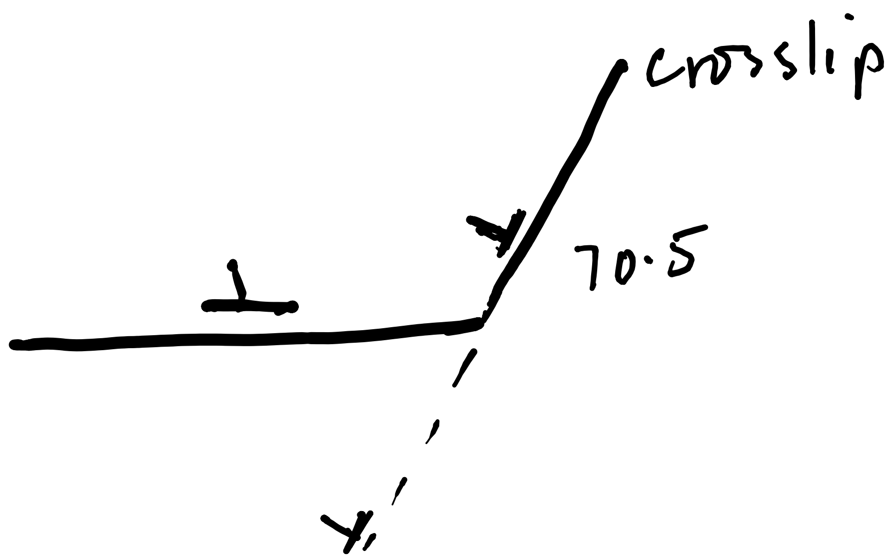
$[\bar{1}01]$

B2 B5

(4) Crossslip

D4 (1$\bar{1}$1) [$\bar{1}$01] 70.5

D4 (1$\bar{1}$1) [10$\bar{1}$] 70.5



Further Analysis:

$$\tau_j = \sum h_{ji} \gamma_i$$

Primary system active step I

$$\tau_1 = h_{11} \gamma_1$$

$$\tau_2 = h_{21} \gamma_1$$

only γ_1 active

τ_1 primary (p) τ_2 is secondary (s)

Step II (γ_2 active only)

$$\tau_2 = h_{22}\gamma_2 + h_{21}\gamma_1^{max}$$

γ_2 ↑ active

$h_{21}\gamma_1^{max}$: from step I loading

$$\tau_1 = h_{11}\gamma_1^{max} + h_{12}\gamma_2$$

$h_{11}\gamma_1^{max}$: initial strength from step I

$h_{12}\gamma_2$: latent hardening

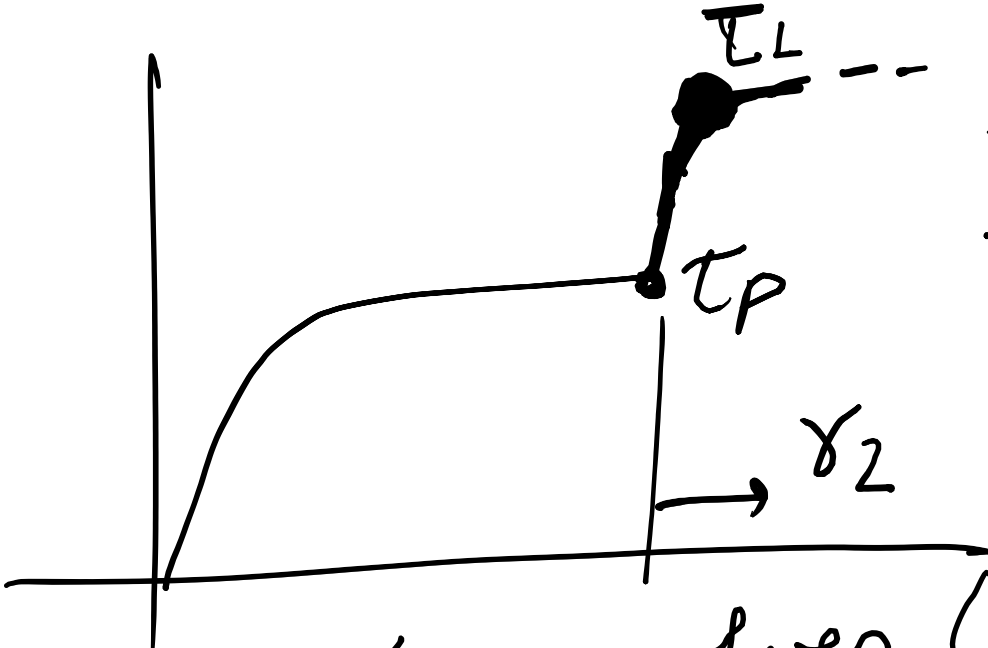
During step II loading,

$$L_{ij} = \frac{\tau_L}{\tau_p} = \frac{h_{22}\gamma_2 + h_{21}\gamma_1^{max}}{h_{11}\gamma_1^{max} + h_{12}\gamma_2}$$

When $\gamma_2 = 0$ at beginning Step II

one can evaluate the

h_{21}/h_{11} ratio.



$$\frac{\tau_L}{\tau_p} = \text{Known for } \gamma_2 = 0$$

As γ_2 evolves (if h_{12} is assumed same as h_{21}) one can use this equation to solve for h_{22}.

In fact LHR increases first reaches a peak. Exp. results imply that h_{22} may not be const. it decreases with applied strain.

$$h_{\alpha\beta} = q\,h + (1-q)^2\,\delta_{\alpha\beta}\,h$$

$h_{22} \gg h_{11}$?

$1 \le q \le 1.4$ Asaro $q = 1.4$

Jaweer, WARP 3D CP option Monday

1) ✓ Latent hard. ✓

2) <u>geom.</u> $k_0 = 0$

3) stress rates ($\overset{\diamond}{\sigma} =$)

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