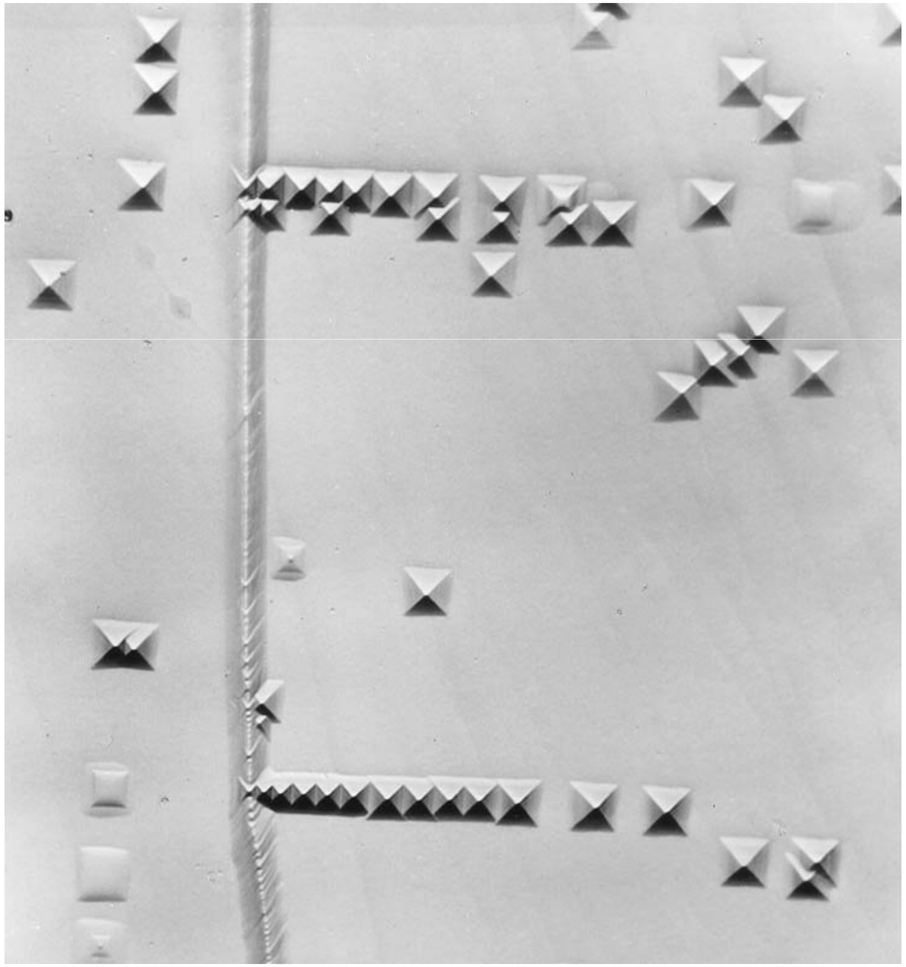
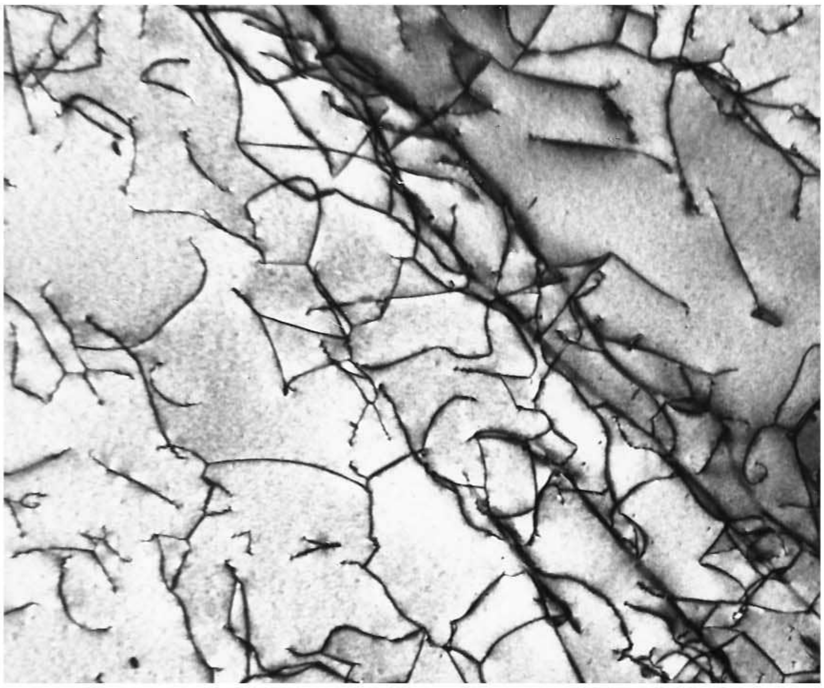
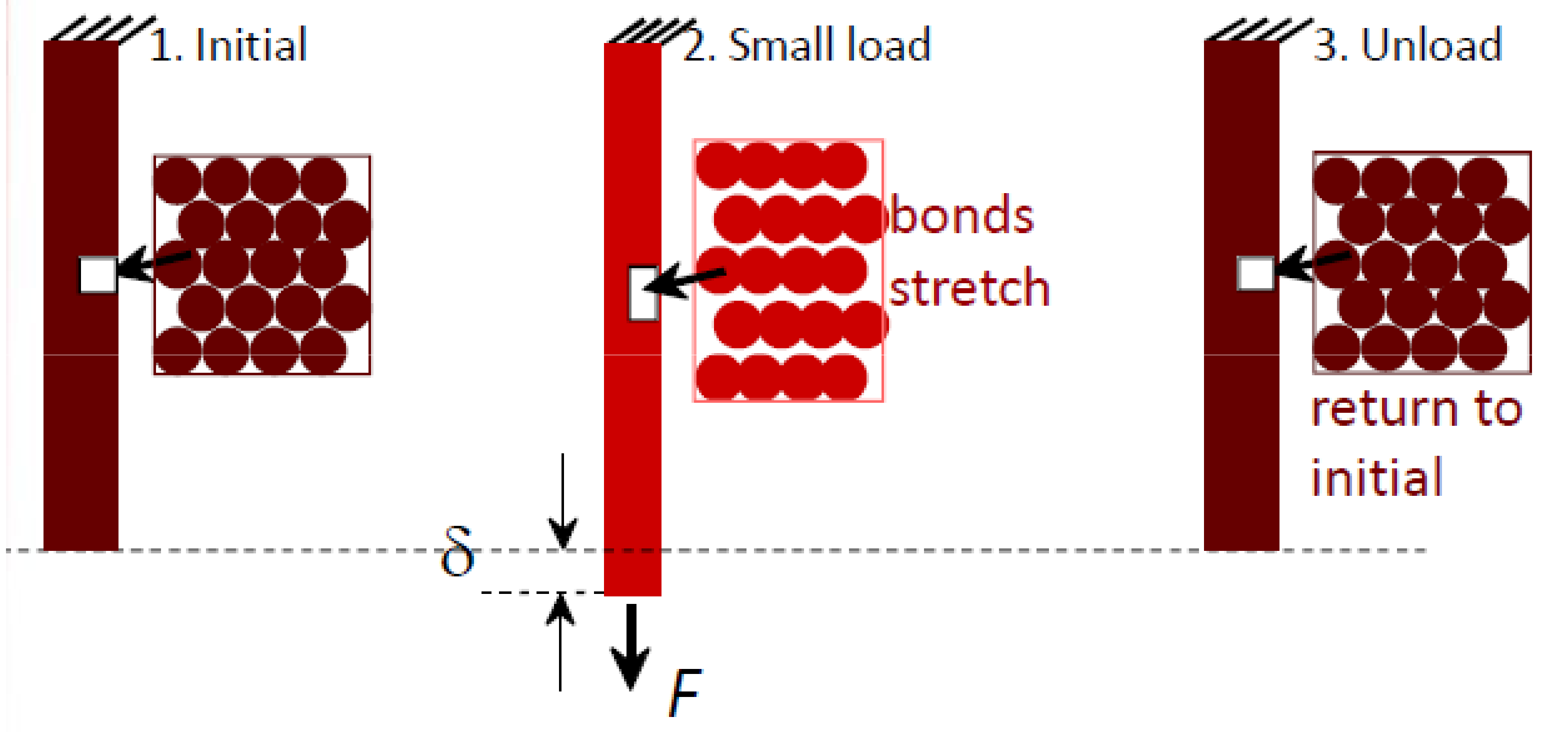
Capítulo 7 - Discordâncias e mecanismos de aumento de resistência

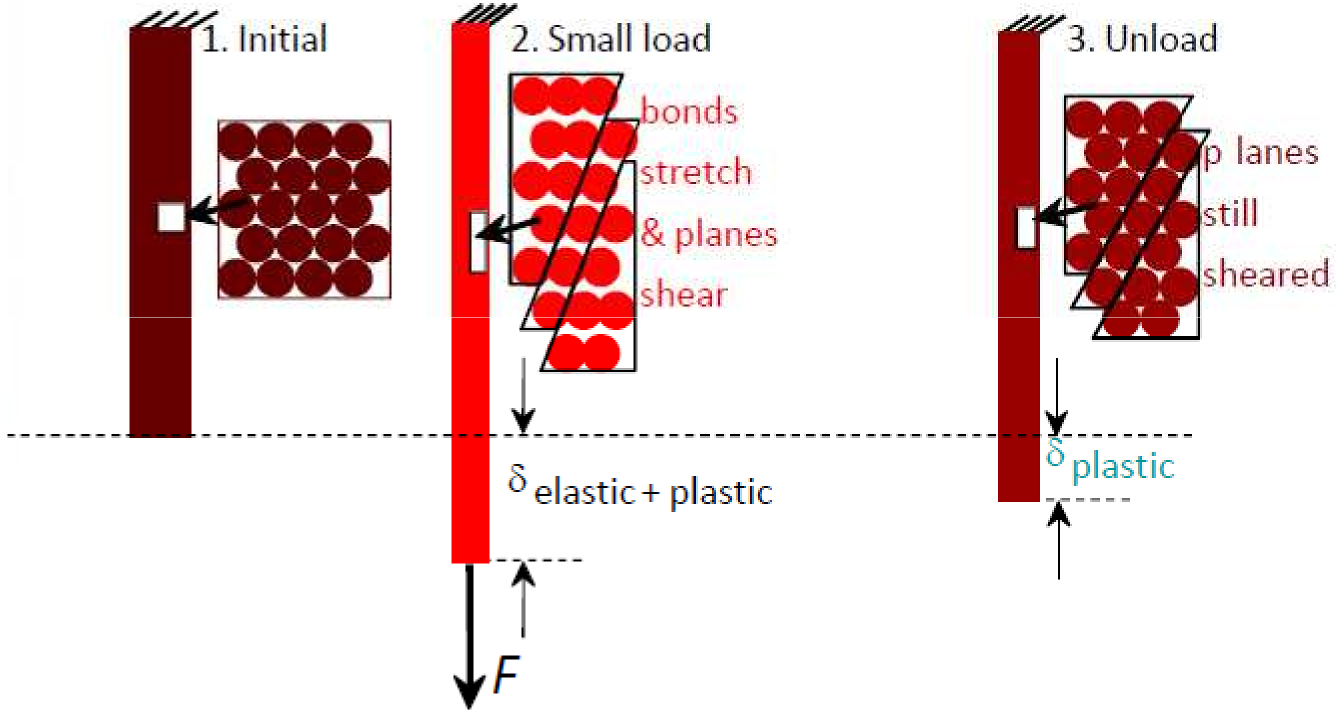




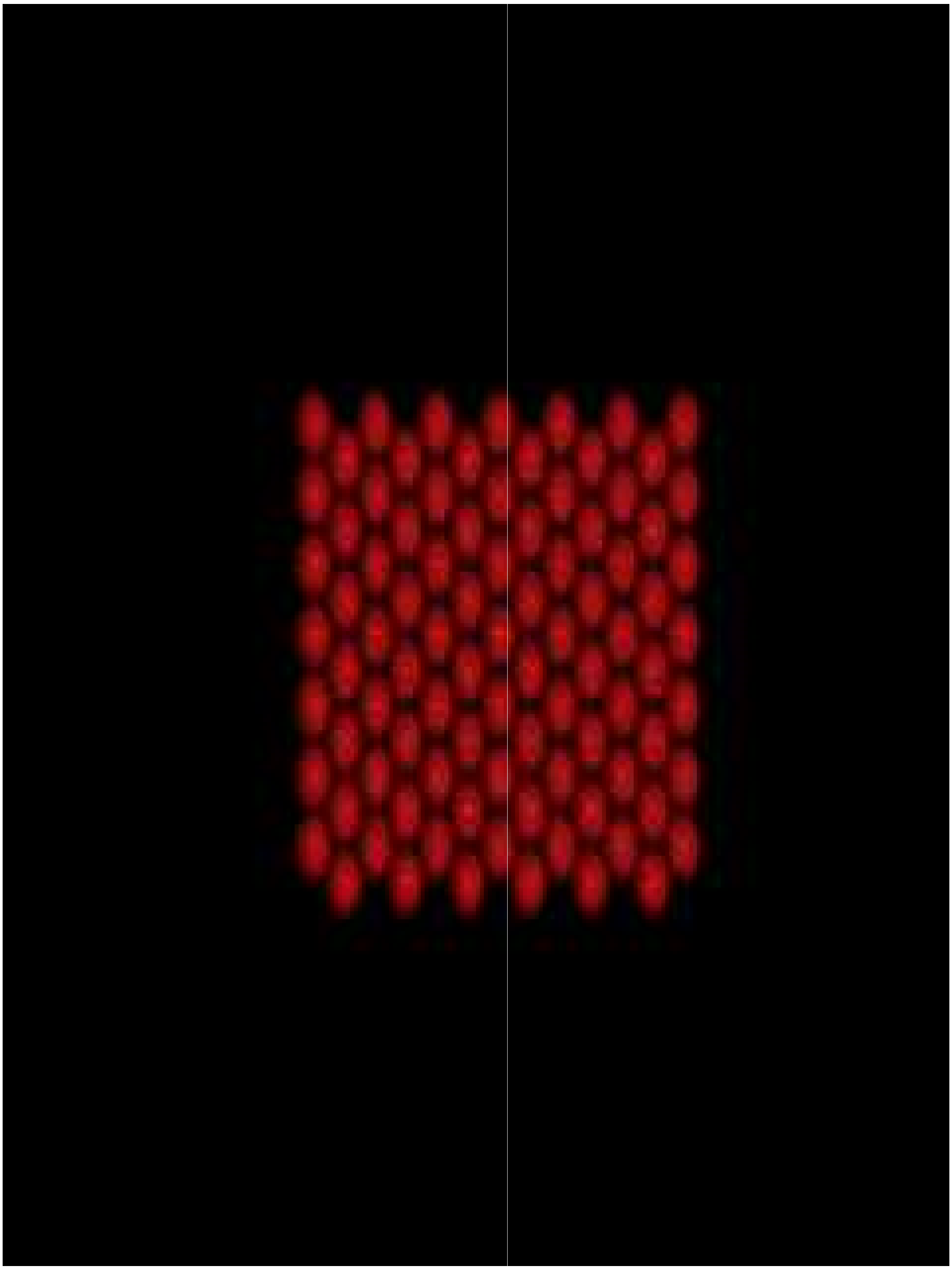
DEFORMAÇÃO ELÁSTICA



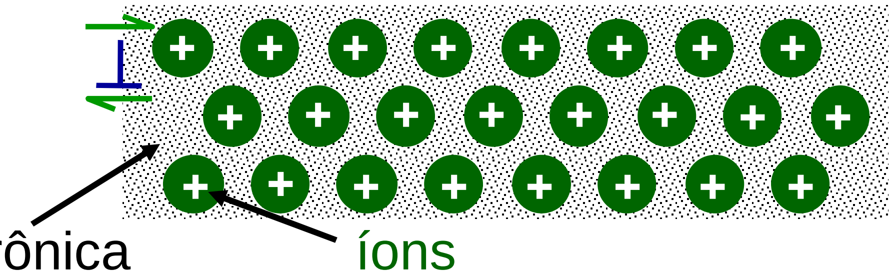
DEFORMAÇÃO PLÁSTICA



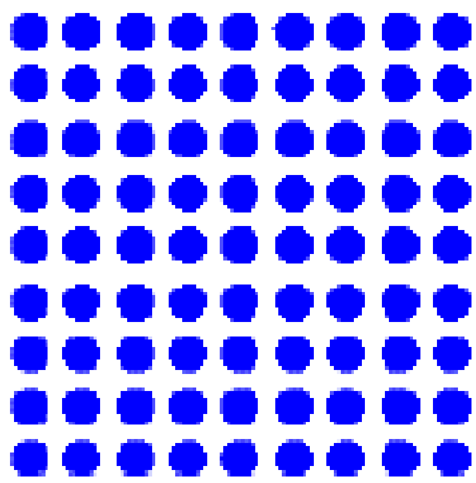
Fonte : Callister 7th edn. (2007)

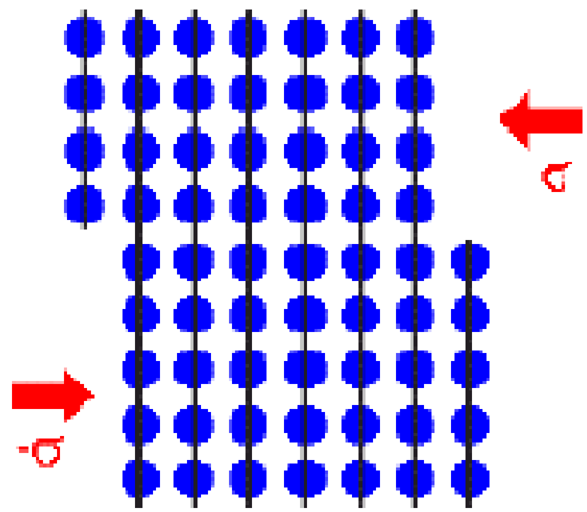


“Deformação plástica corresponde à mudança de um grande número de átomos em resposta a uma tensão aplicada”



Porque a deformação plástica ocorre com tensões bem menores do que às tensões previstas teoricamente?

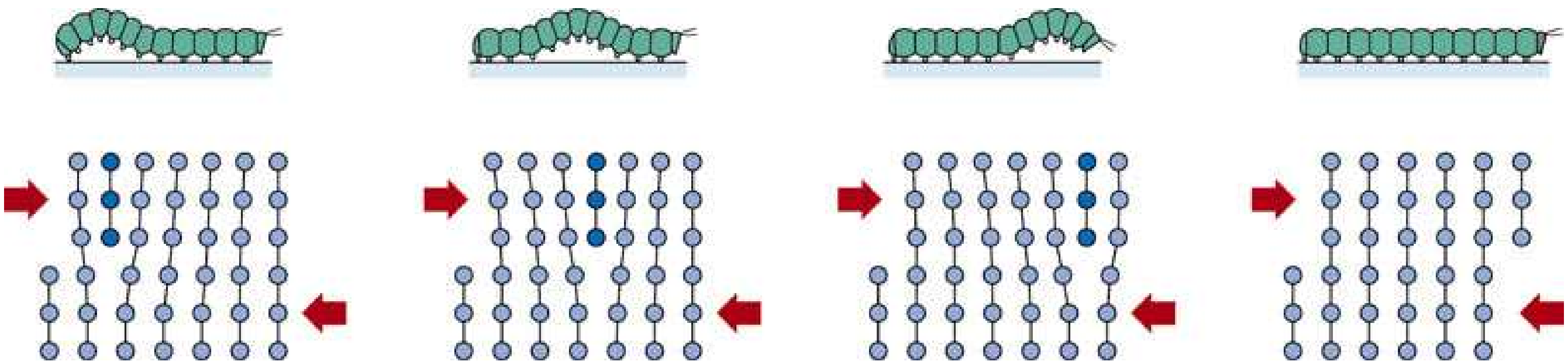




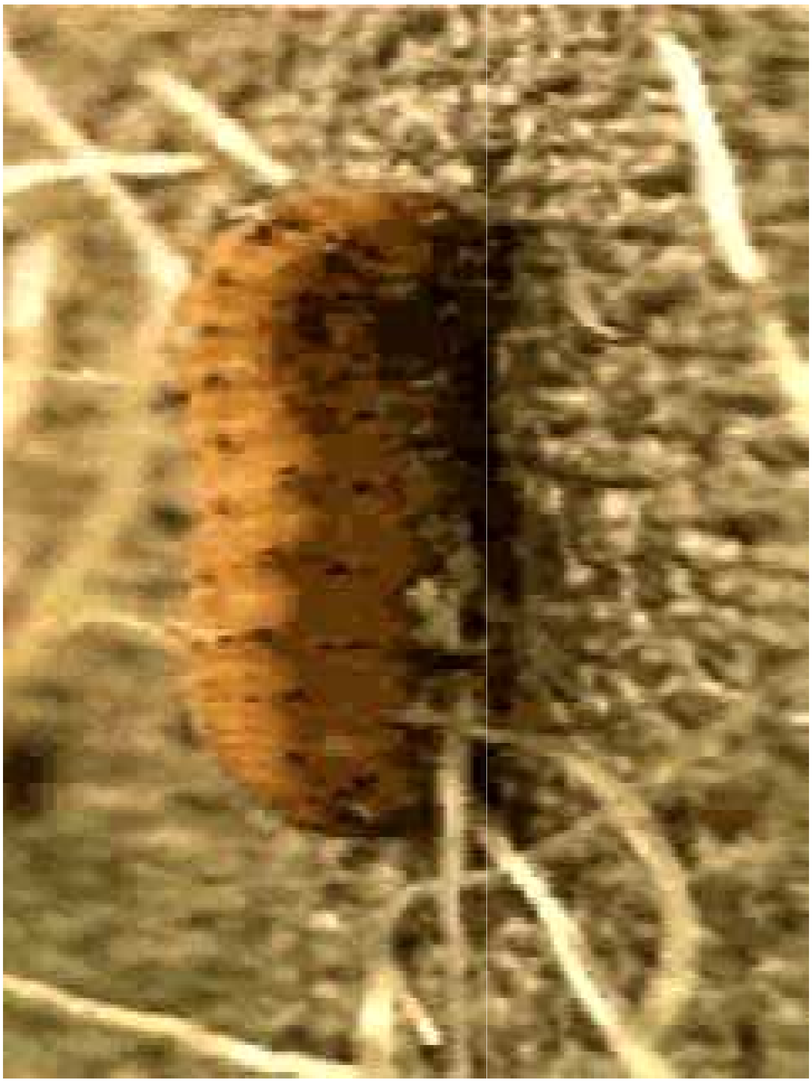
Resposta baseada na idéia proposta por Taylor, Orowan e Poliany em 1934:

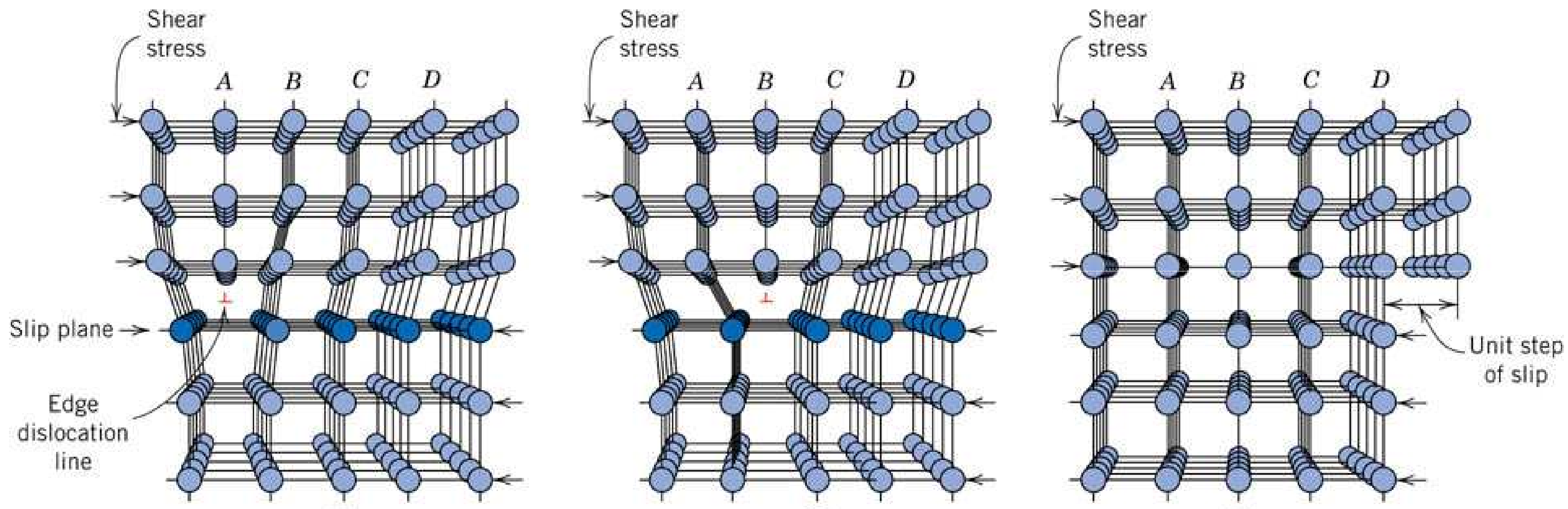
Deformação plástica corresponde a uma grande movimentação de discordâncias.

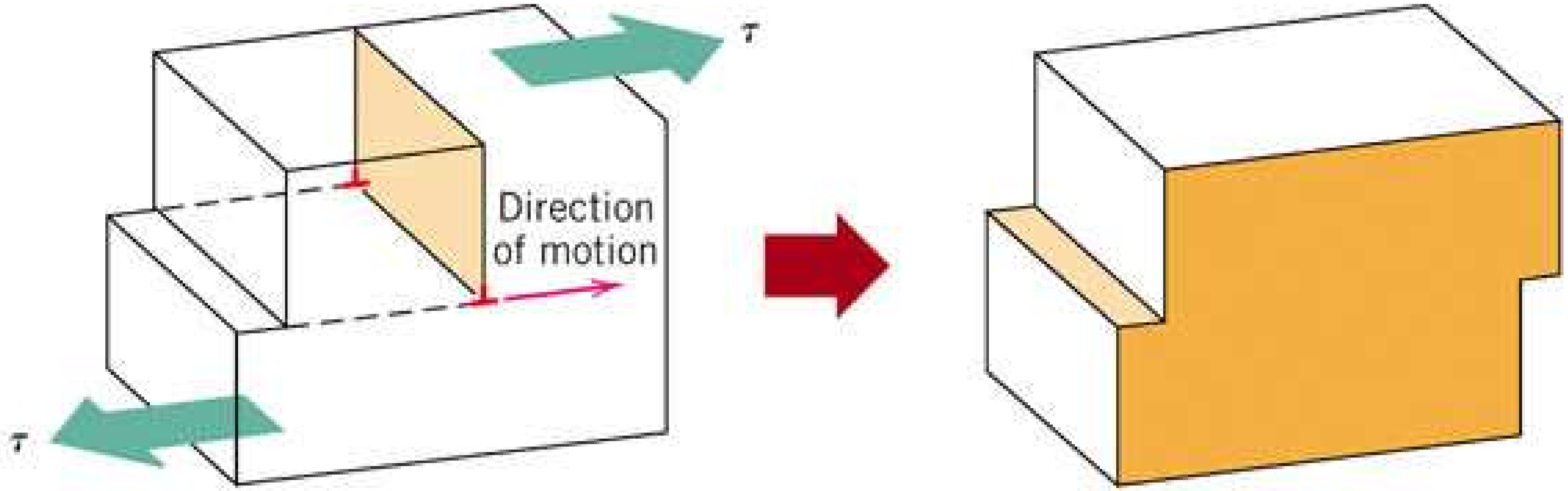
As discordâncias possibilitam a deformação plástica, pois a quebra das ligações atômicas ocorre de forma localizada exigindo assim menores tensões. Tal fenômeno é denominado DESLIZAMENTO (ou ESCORREGAMENTO).



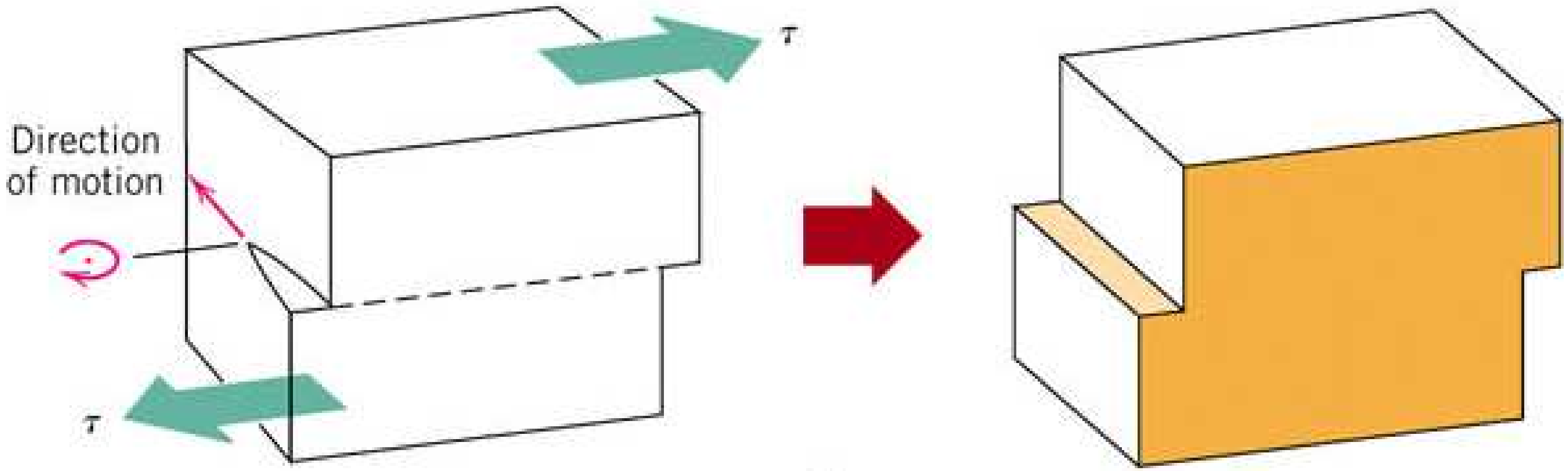
A movimentação das discordâncias ocorre em um plano preferencial: **O plano de deslizamento.**



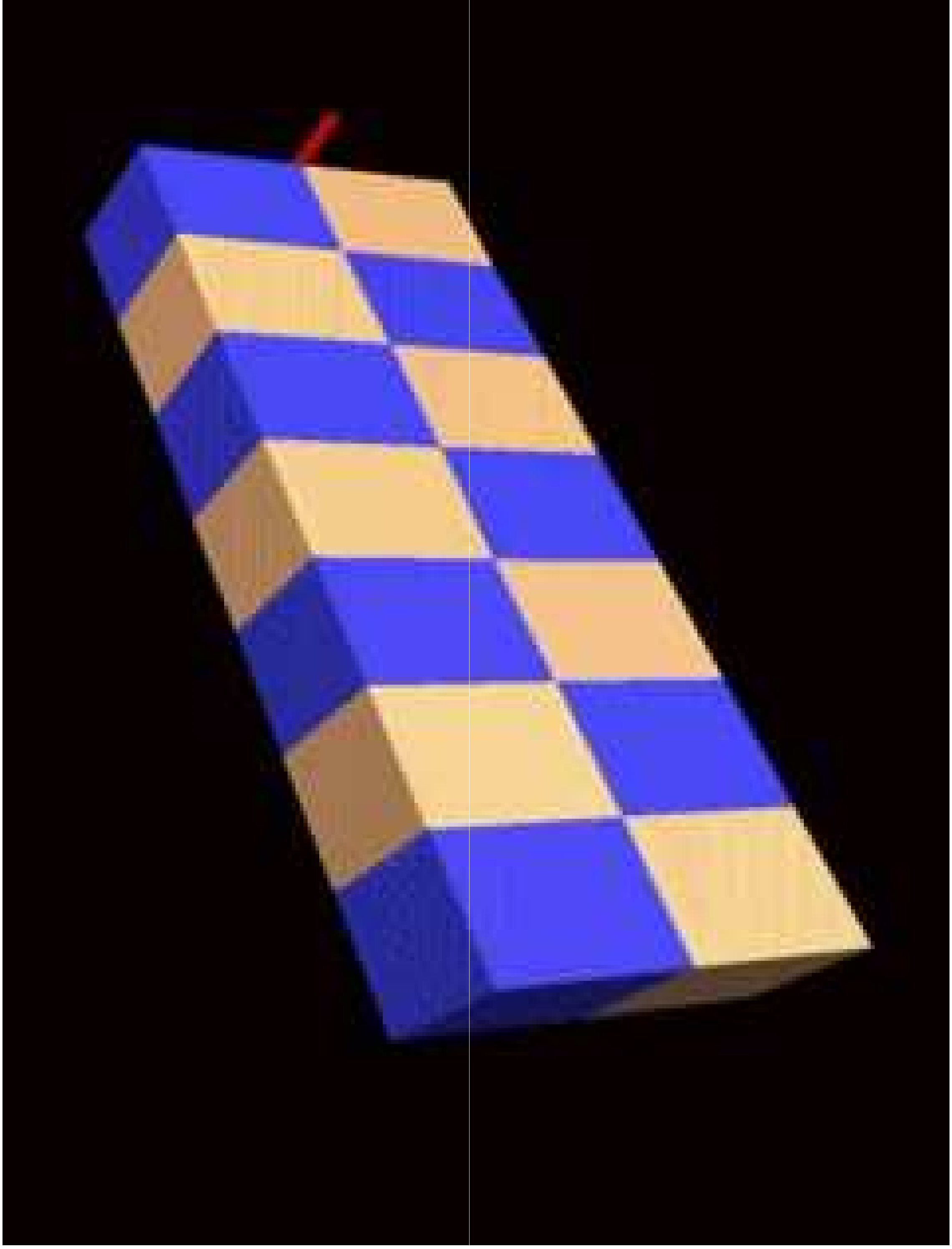

Shear stress
A
B
C
D
Slip plane
Edge dislocation line
Shear stress
A
B
C
D
Shear stress
A
B
C
D
Unit step of slip
(a) (b) (c)

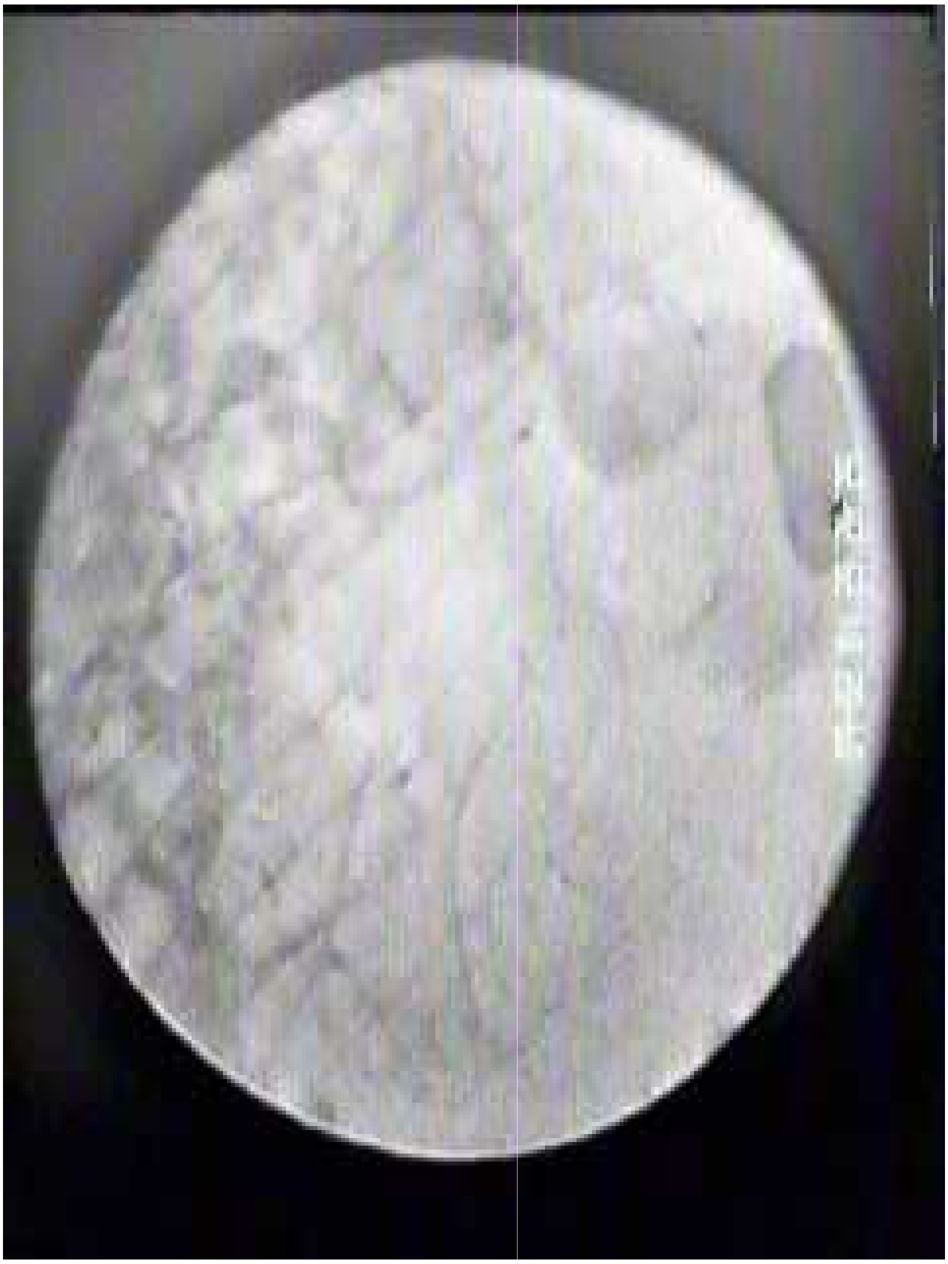


(a)

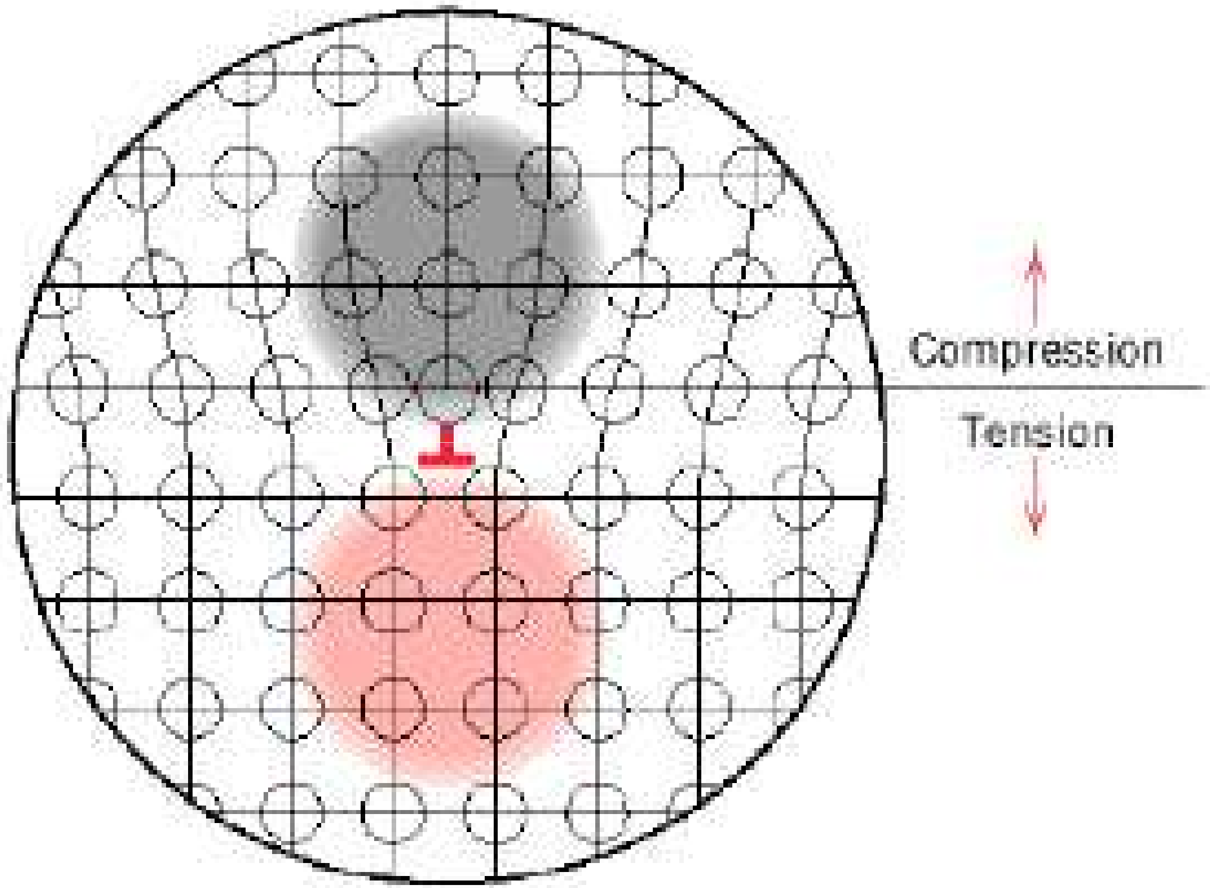


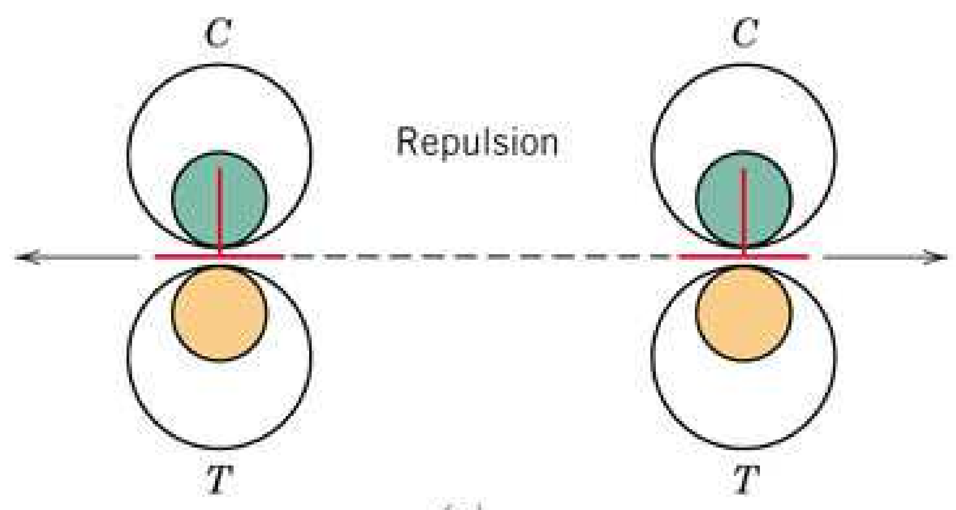
(b)



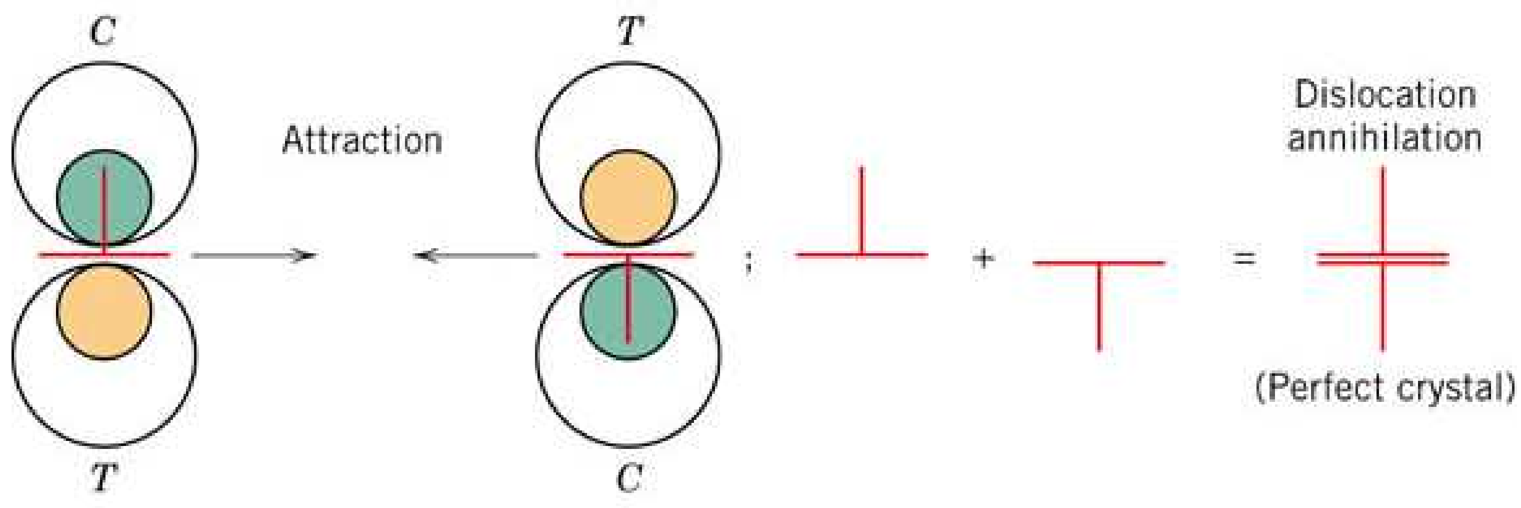


Campo de tensões ao redor de uma discordância




C
C
Repulsion
T
T

(a)


C
T
Attraction
T
C
Dislocation
annihilation
(Perfect crystal)

(b)

Da onde vem as discordâncias?

A quantidade de discordâncias em um material é expressa na forma de uma propriedade:

A Densidade de Discordâncias (DD) dada em mm/mm3 ou /mm2

Ex: 10^5 /mm2

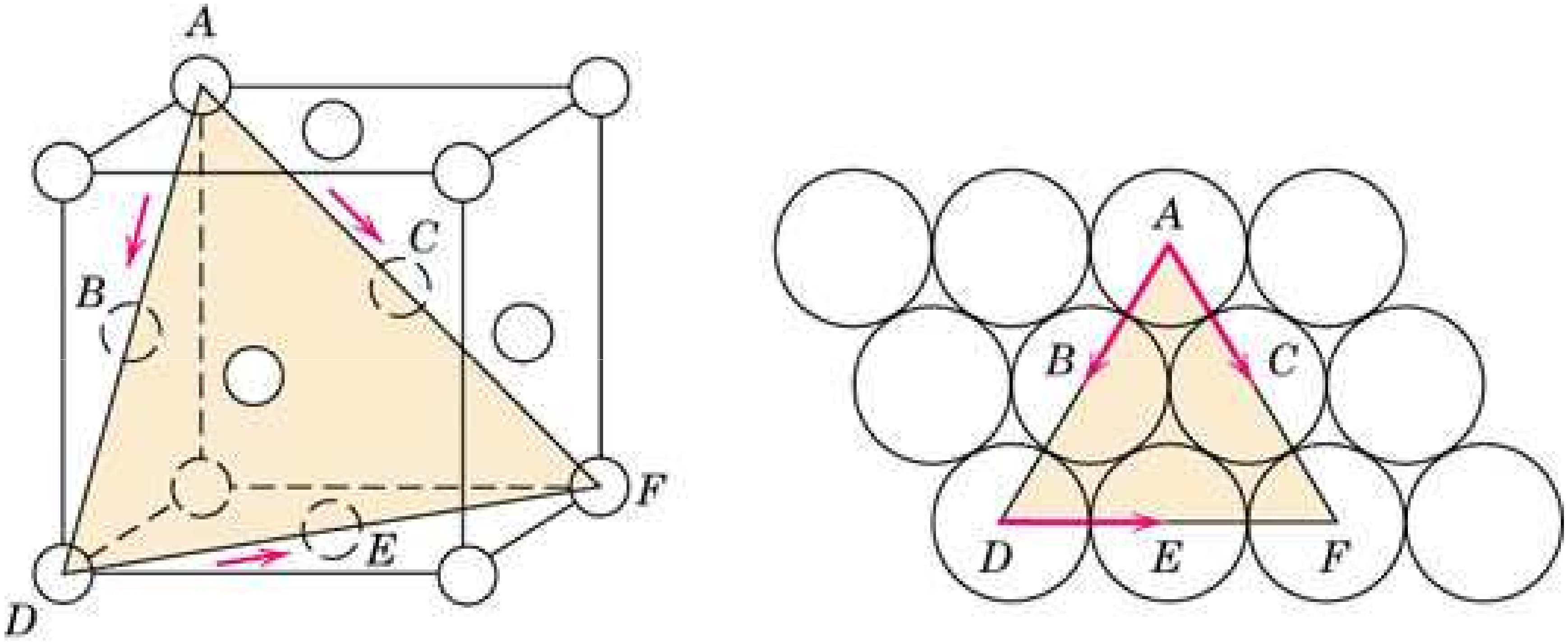
As discordâncias são provenientes de tensões internas (mecânicas ou térmicas) do material geradas no processamento destes.

O número de discordâncias cresce de forma elevada por meio de deformações plásticas.

Ex: material fundido DD 10^5 /mm2

material laminado a frio (encruado) DD 10^{12} /mm2

Sistemas de Escorregamento



(a) (b)

Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

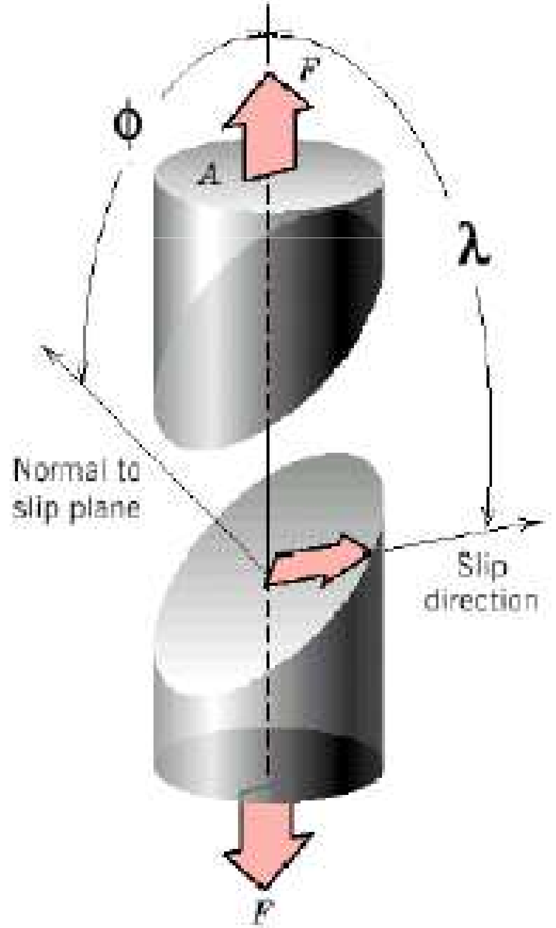
Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11\rangle$	12
α-Fe, W	$\{211\}$	$\langle \bar{1}11\rangle$	12
α-Fe, K	$\{321\}$	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

ESCORREGAMENTO EM MONOCRISTAIS

As discordâncias se movem em resposta às tensões de cisalhamento aplicadas sobre as mesmas.

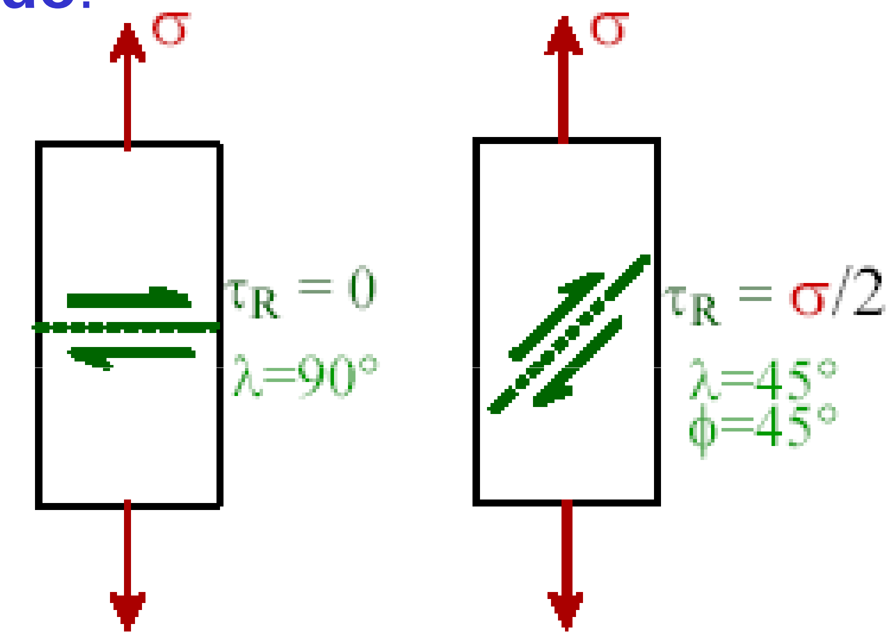
Tensão de Cisalhamento Projetada τ_R

$$\boxed{\tau_R = \sigma \cos\phi \cos\lambda}$$



Maior valor de cosΦcosλ corresponde ao ângulo de 45 graus = 0,5 logo σy = 2τCRSS

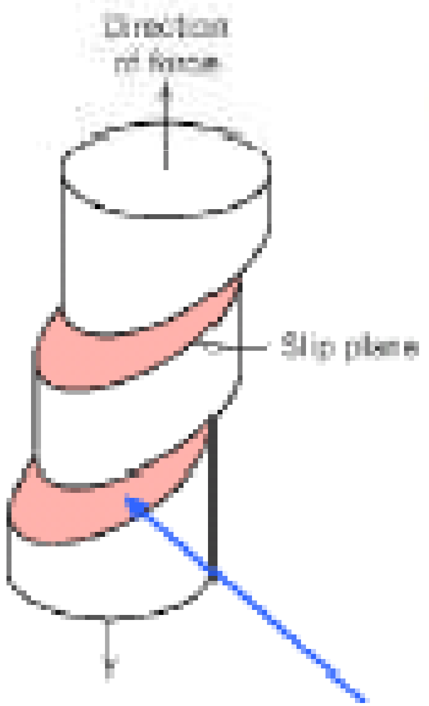
Quando:

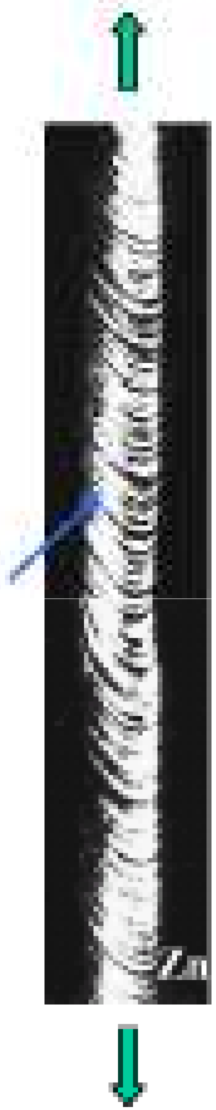


Tensão de Cisalhamento Projetada Crítica τ_{CRSS} – A menor tensão de cisalhamento requerida para iniciar o deslizamento.

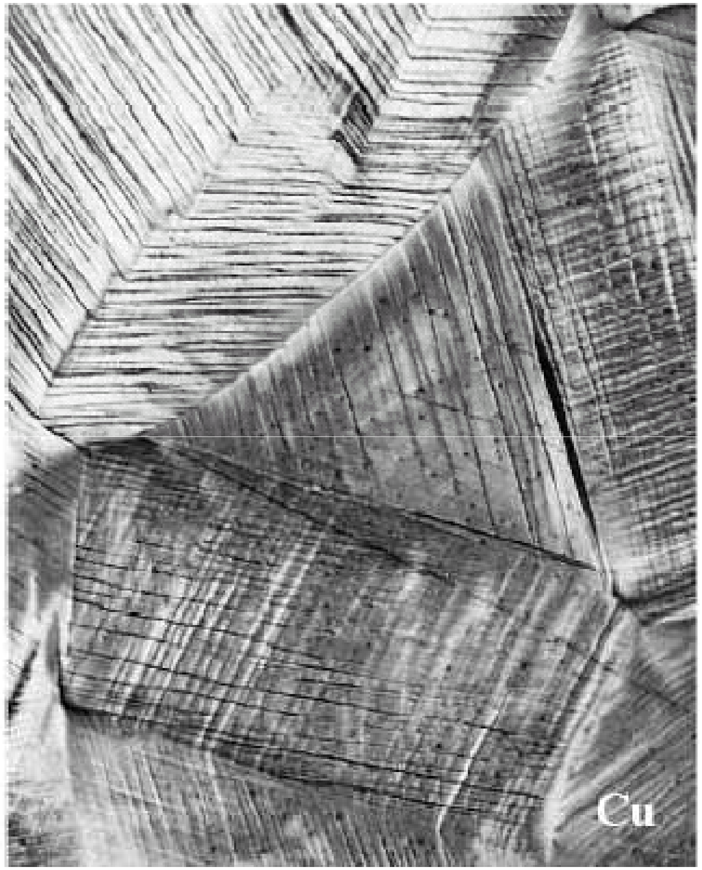
$$\boxed{\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}}$$

$$\boxed{\sigma_y = \frac{\tau_{CRSS}}{(\cos\phi \cos\lambda)_{MAX}}}$$


Direction
of force
Slip plane


Zn

DEFORMAÇÃO PLÁSTICA EM MATERIAIS POLICRISTALINOS



Antes

Depois

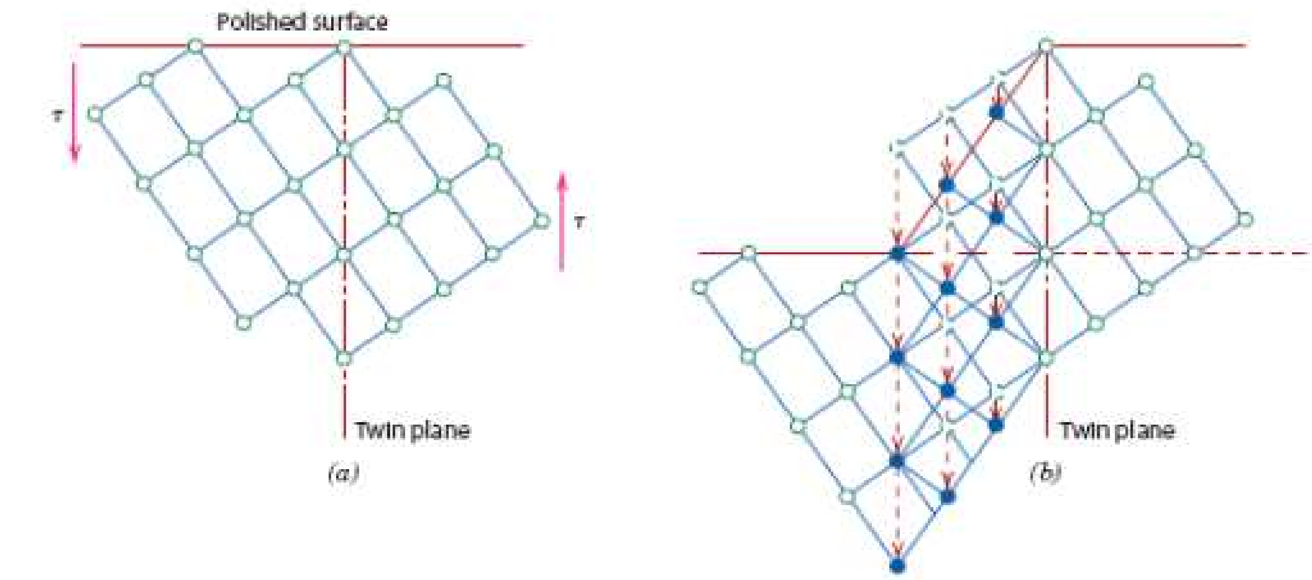


Figure 7.12 Schematic diagram showing how twinning results from an applied shear stress τ. In (*b*), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions, respectively. (From G. E. Dieter, *Mechanical Metallurgy*, 3rd edition. Copyright © 1986 by McGraw-Hill Book Company, New York. Reproduced with permission of McGraw-Hill Book Company.)

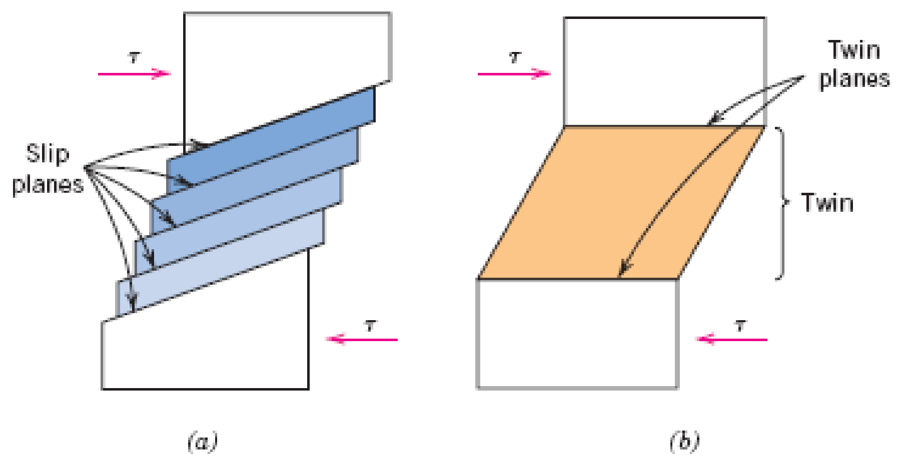


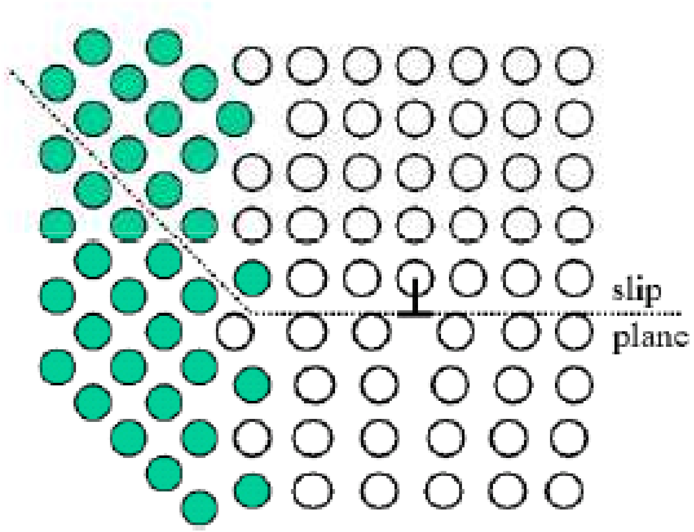
Figure 7.13 For a single crystal subjected to a shear stress τ, (*a*) deformation by slip; (*b*) deformation by twinning.

MECANISMOS DE AUMENTO DE RESISTÊNCIA EM METAIS.

- **Redução do tamanho do Grão**

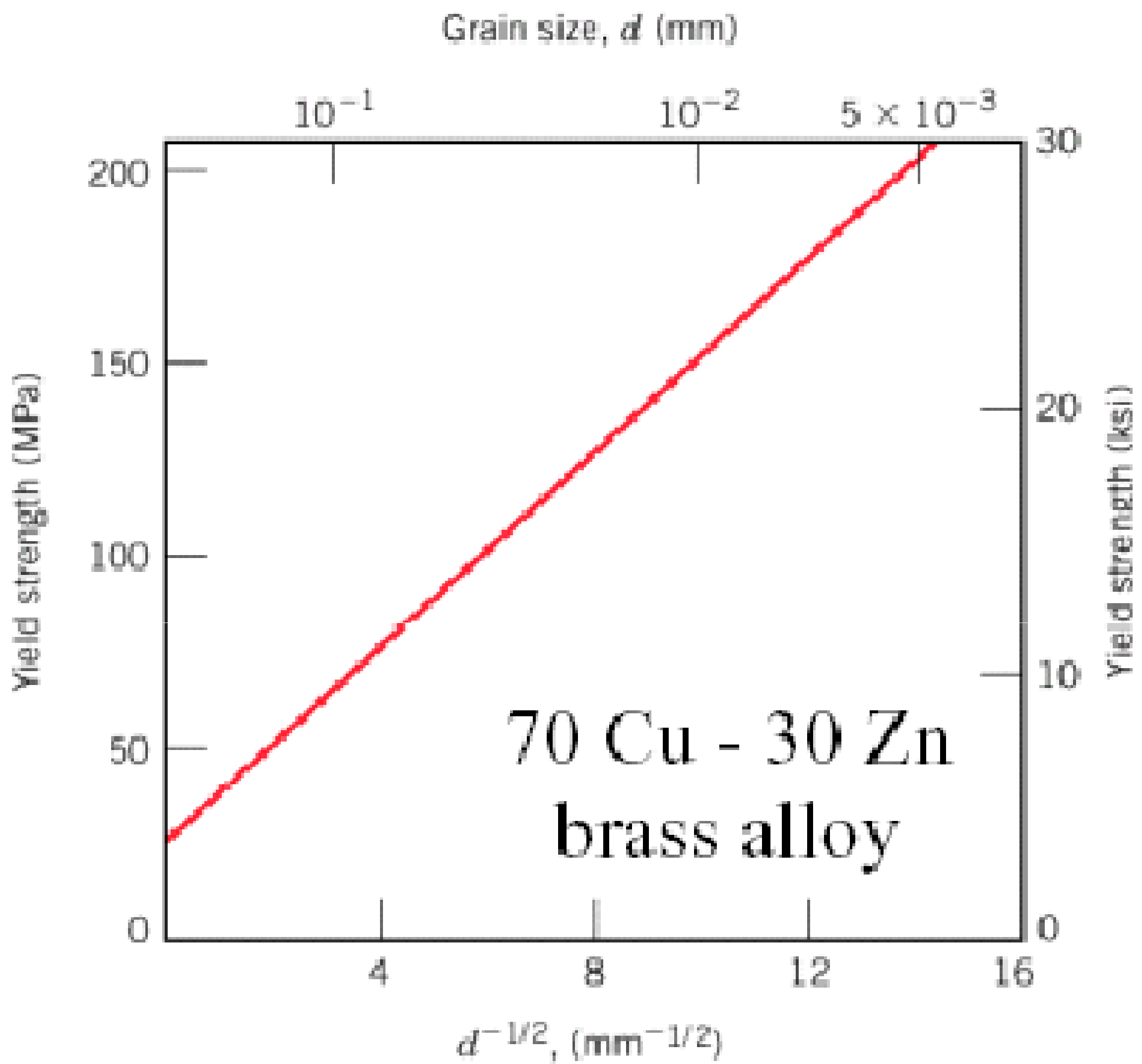
- **Solução sólida**

- **Encruamento**

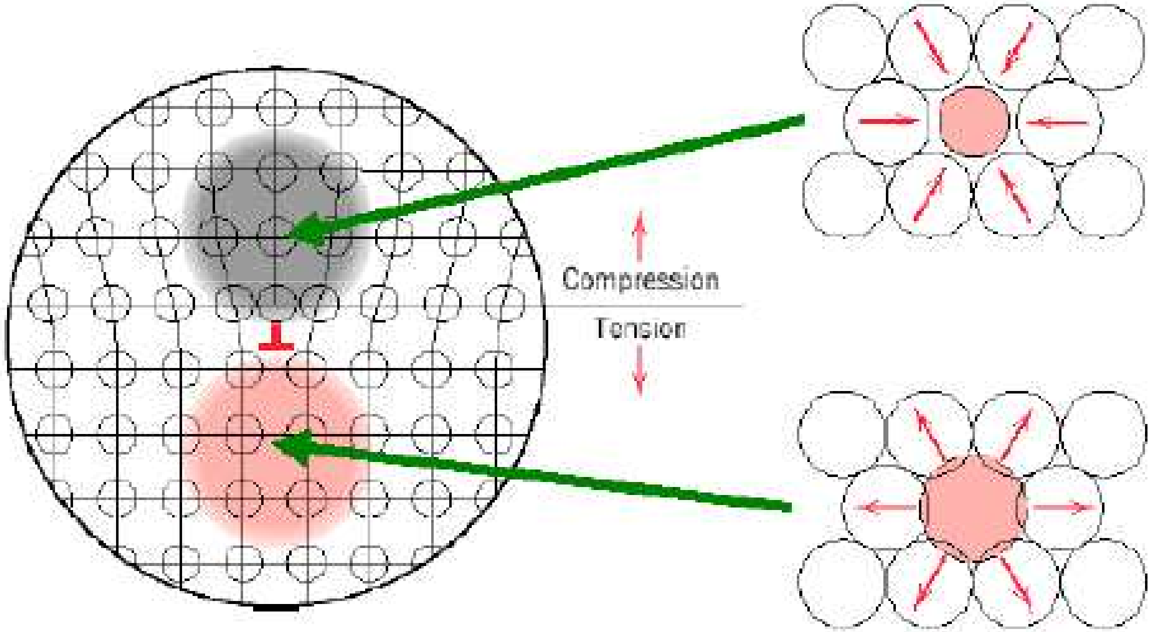


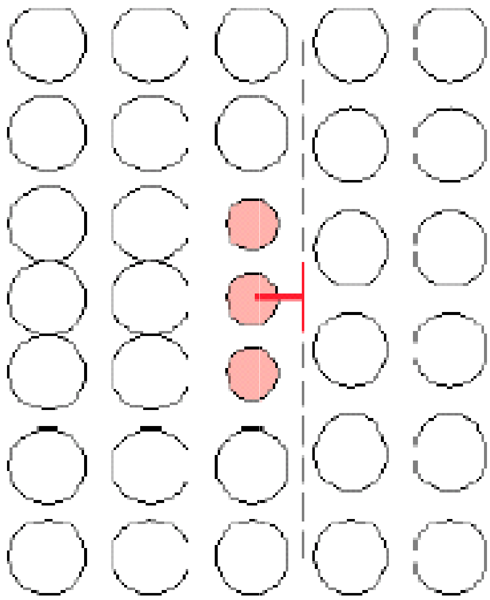
$$\sigma_y = \sigma_0 + k_y / \sqrt{d}$$

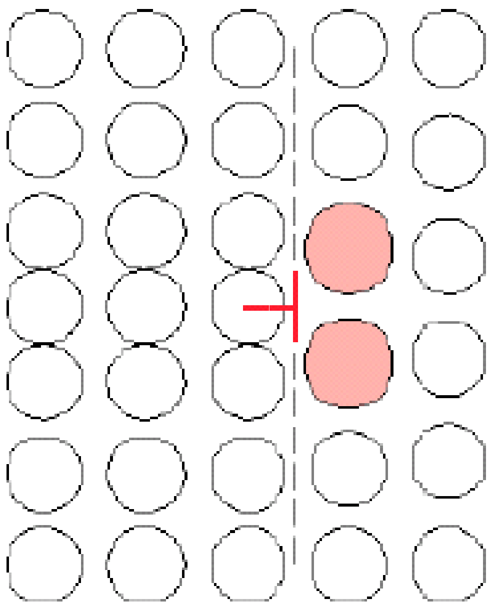
eq Hall Petch

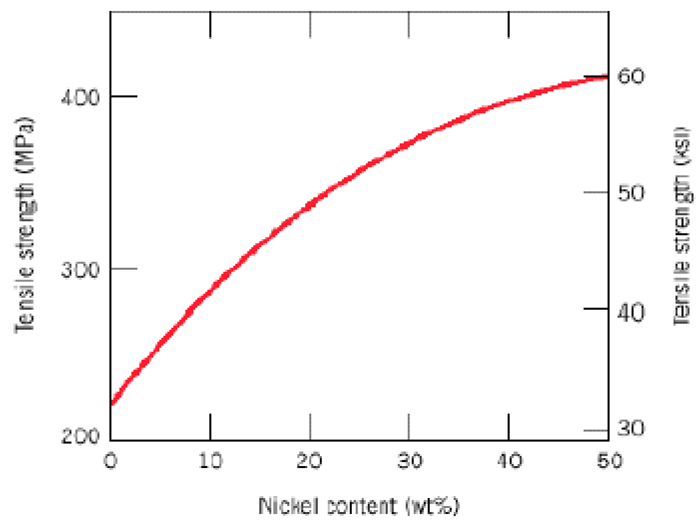

Grain size, d (mm)
10^−1
10^−2
5 × 10^−3
Yield strength (MPa)
200
150
100
50
0
Yield strength (ksi)
30
20
10
0
4
8
12
16
d^−1/2, (mm^−1/2)
70 Cu - 30 Zn
brass alloy

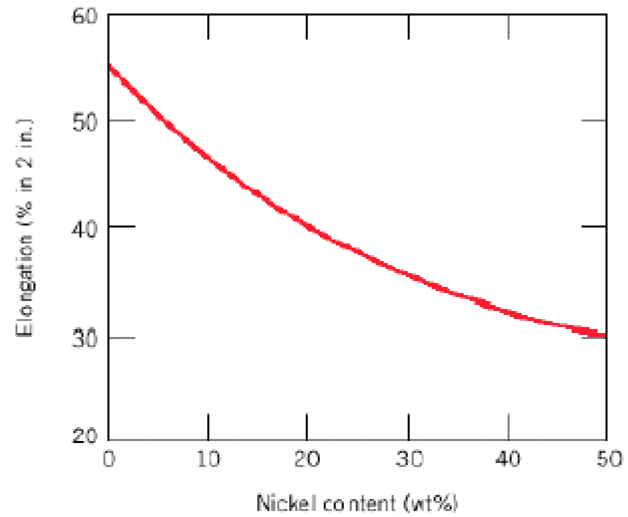
Aumento da resistência por Solução Sólida



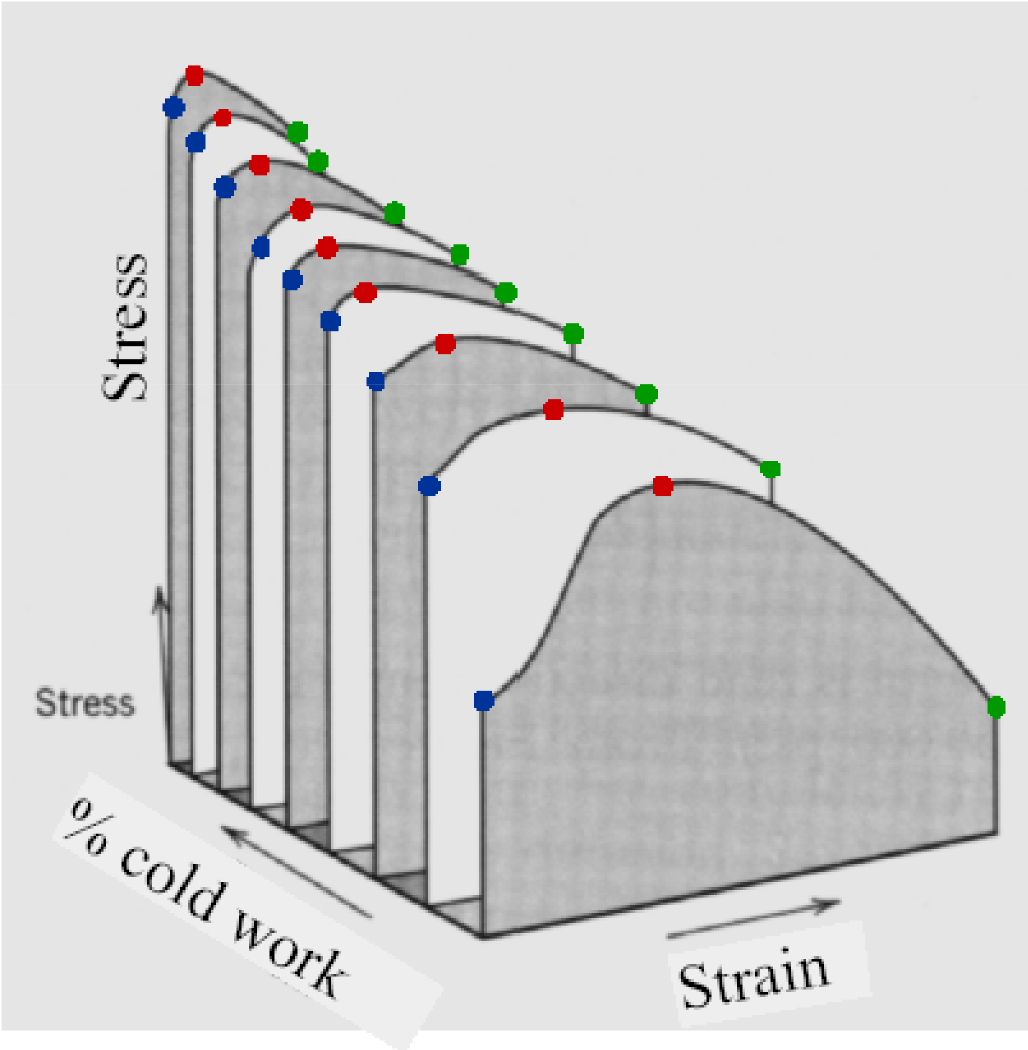


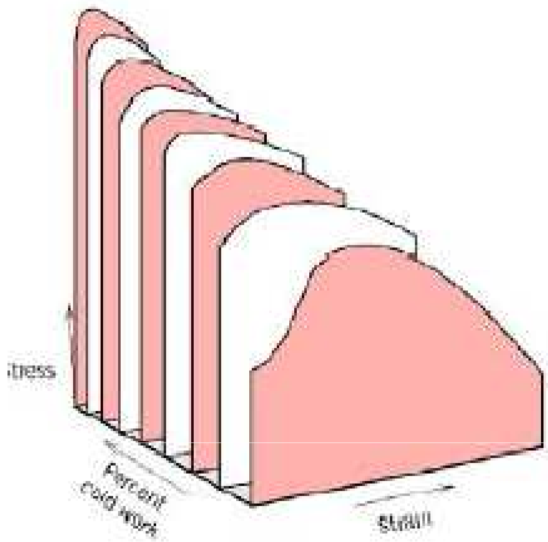


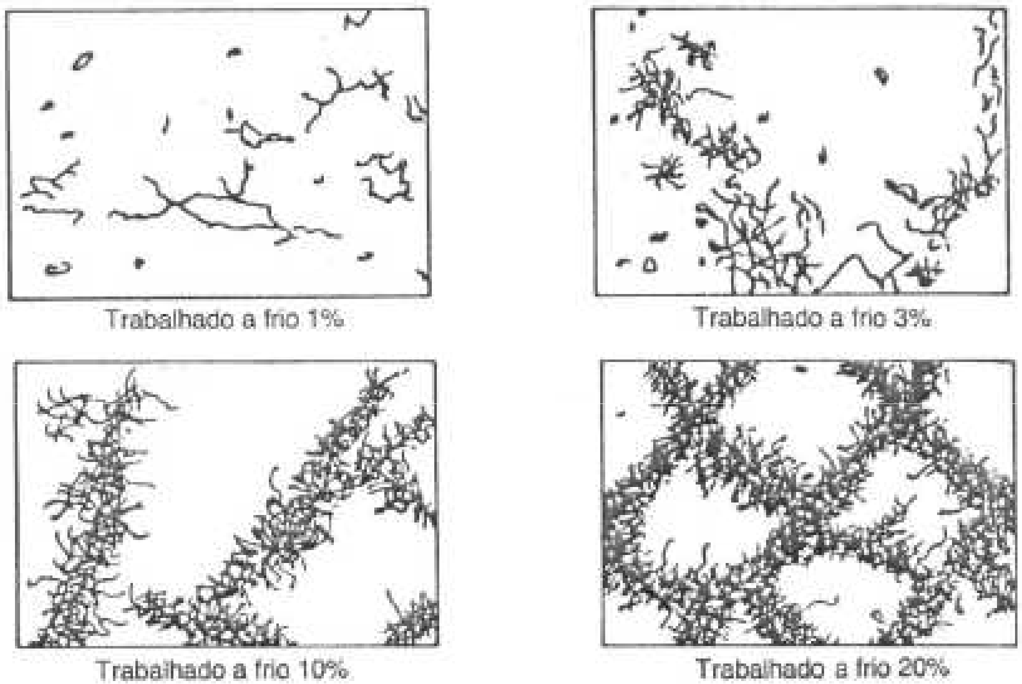

Tensile strength (MPa)
Tensile strength (ksi)
Nickel content (wt%)
400
300
200
60
50
40
30
0
10
20
30
40
50


Elongation (% in 2 in.)
Nickel content (wt%)
60
50
40
30
20
0
10
20
30
40
50

Aumento da resistência pelo aumento da Densidade de Discordâncias – Deformação a frio, trabalho a frio ou encruamento.



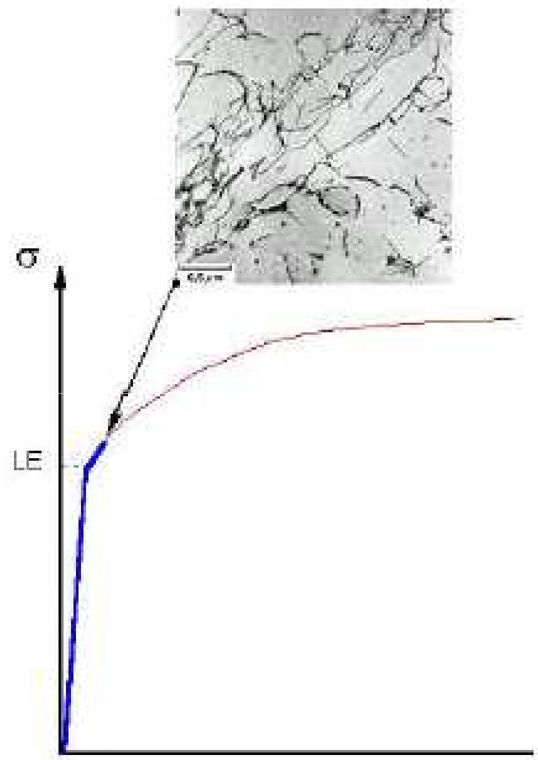


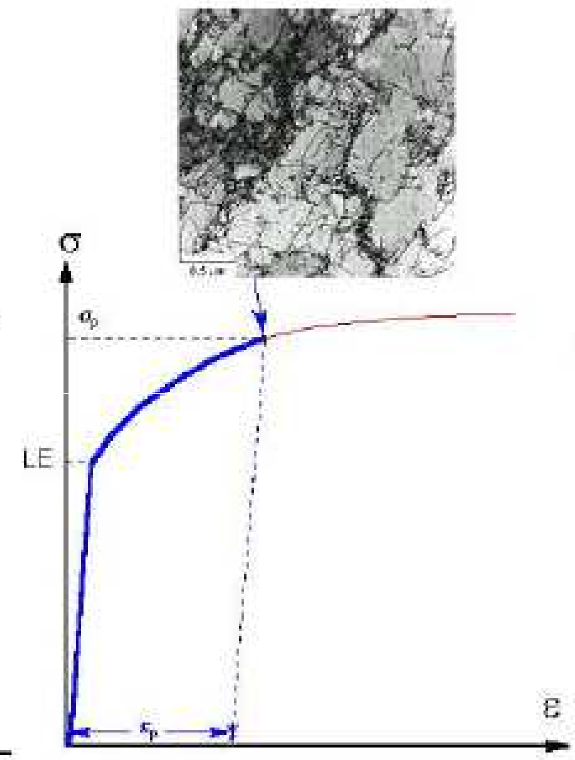


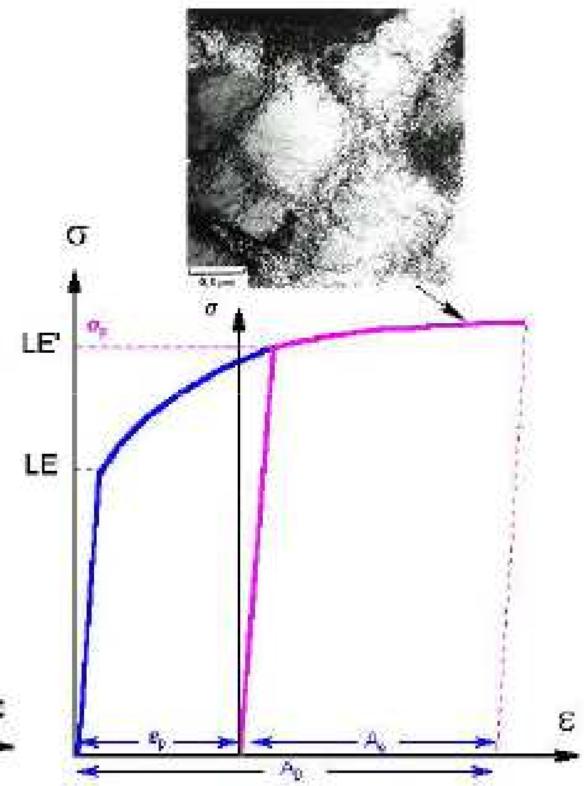
Aumento da densidade de discordâncias com a porcentagem de trabalho a frio

DEFORMAÇÃO A FRIO

AUMENTO DE RESISTÊNCIA MECÂNICA DO METAL VIA ENCRUAMENTO RESULTANTE DA MULTIPLICAÇÃO DAS DISCORDÂNCIAS



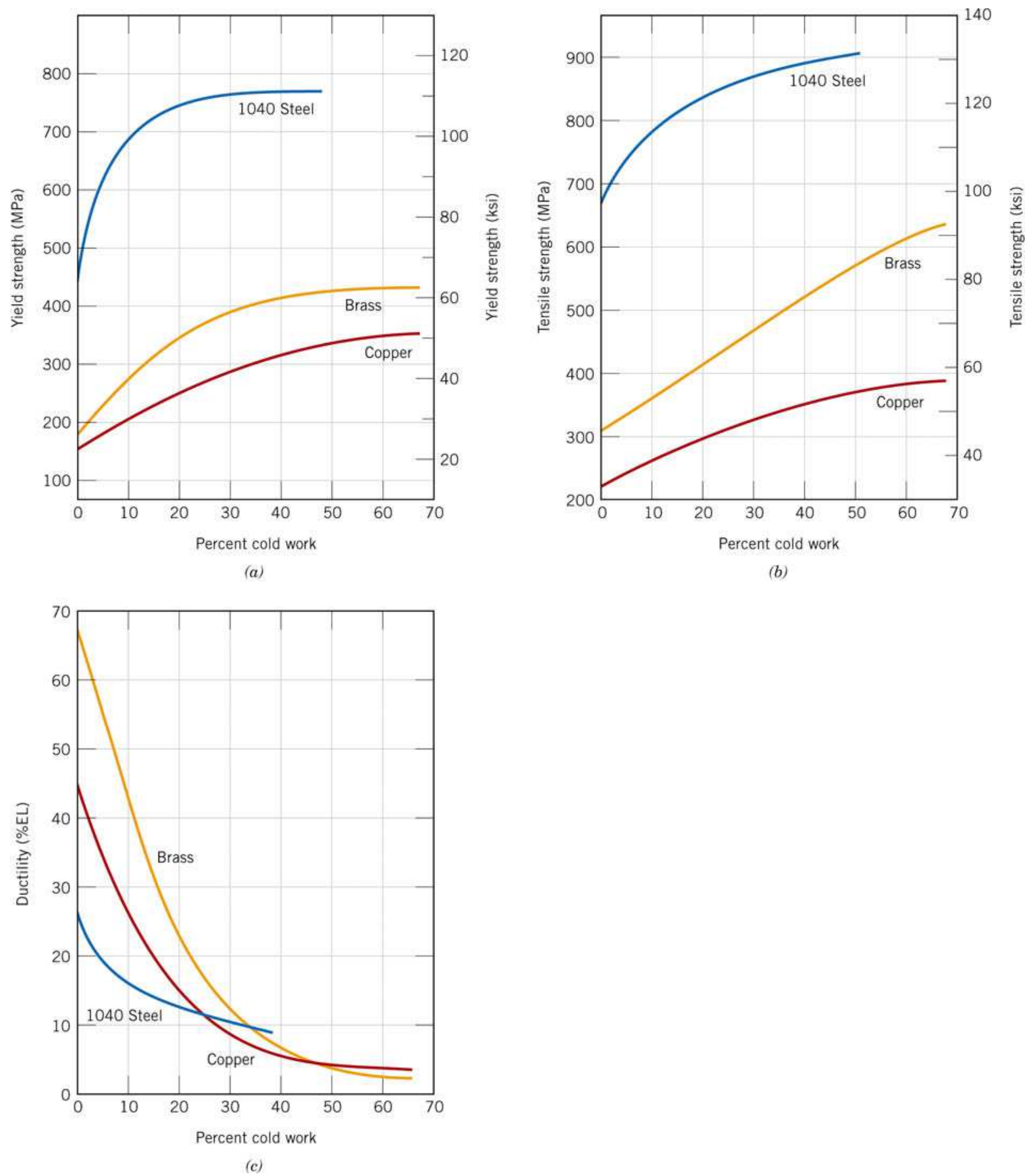




DENSIDADE DE DISCORDÂNCIAS

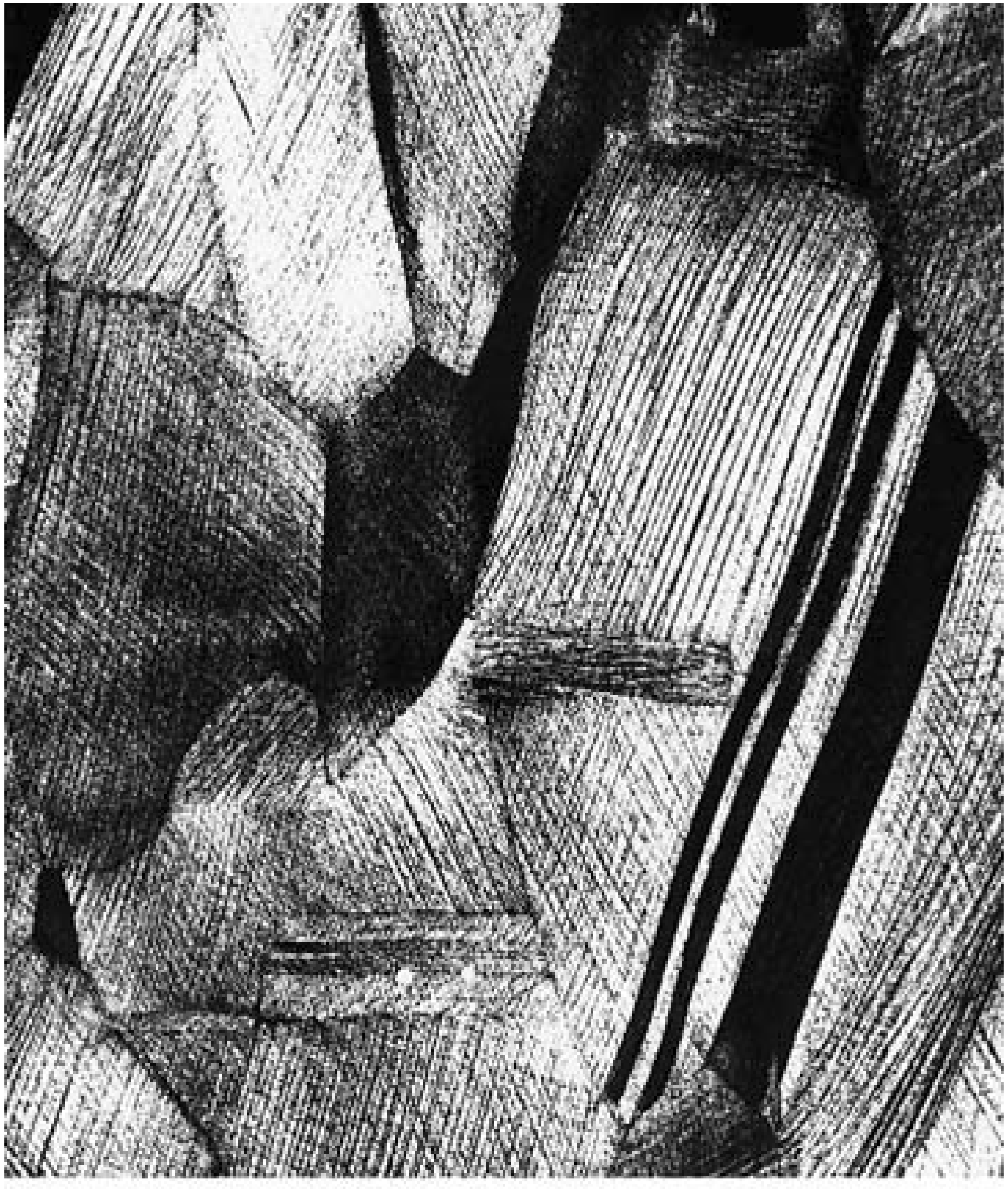
Metal recozido: $10^{7\text{-}8}$ cm/cm^3

Metal Encruado: $10^{11\text{-}12}$ cm/cm^3

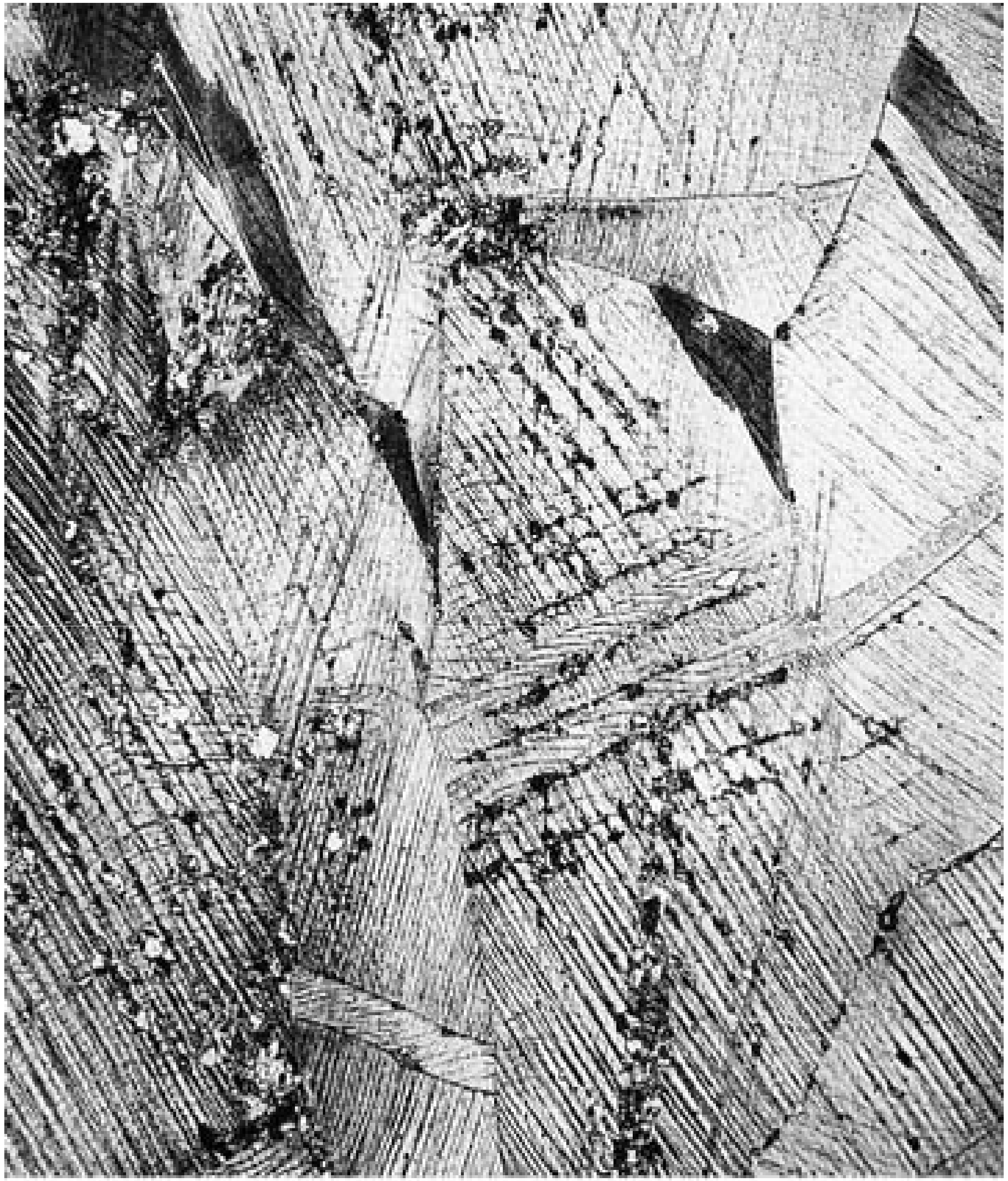

Yield strength (MPa)
Yield strength (ksi)
1040 Steel
Brass
Copper
Percent cold work
Tensile strength (MPa)
Tensile strength (ksi)
Ductility (%EL)

(a) (b) (c)

RECUPERAÇÃO, RECRISTALIZAÇÃO E CRESCIMENTO DE GRÃO



(a)

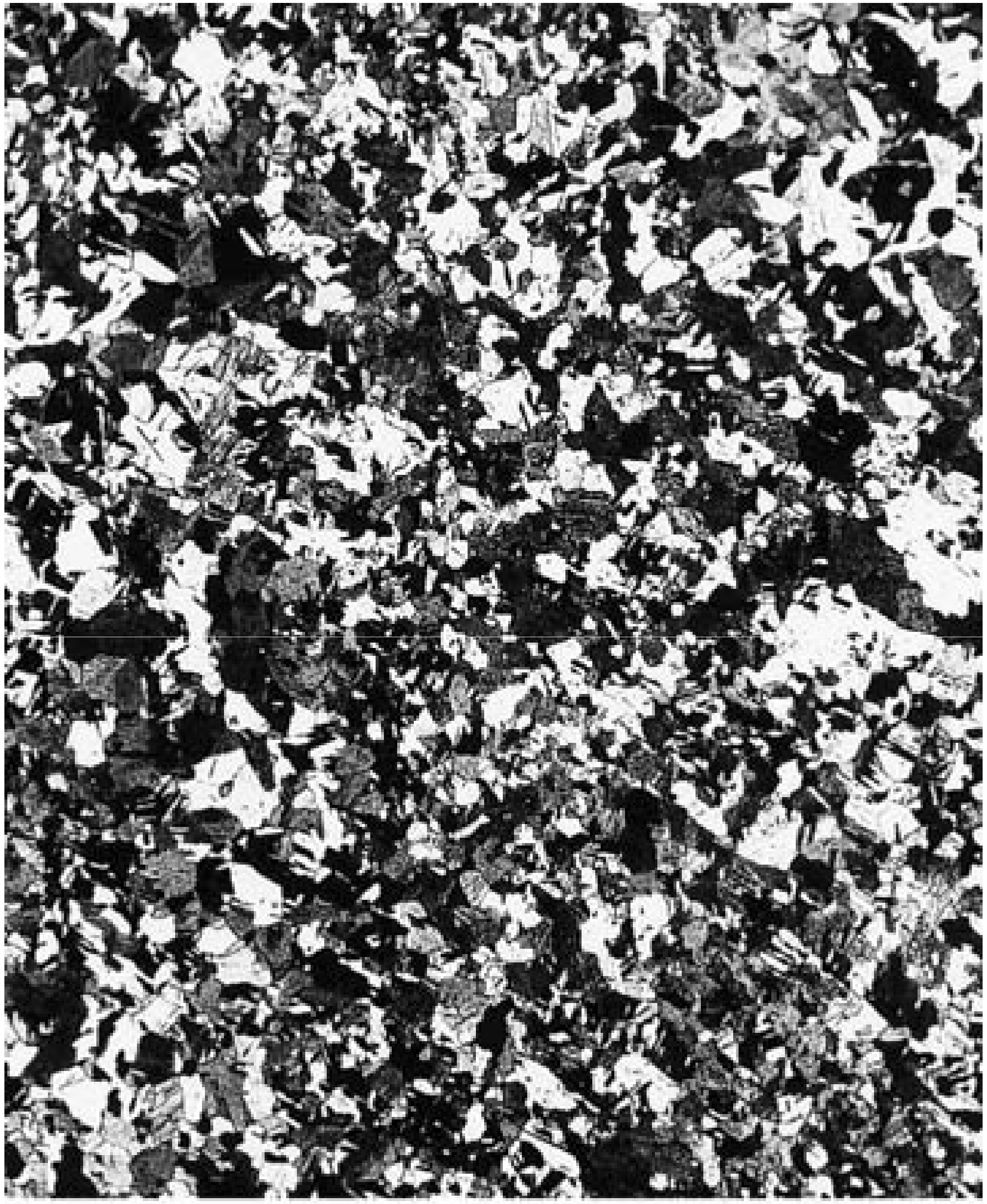


(b)

Após 3 s,
580 C

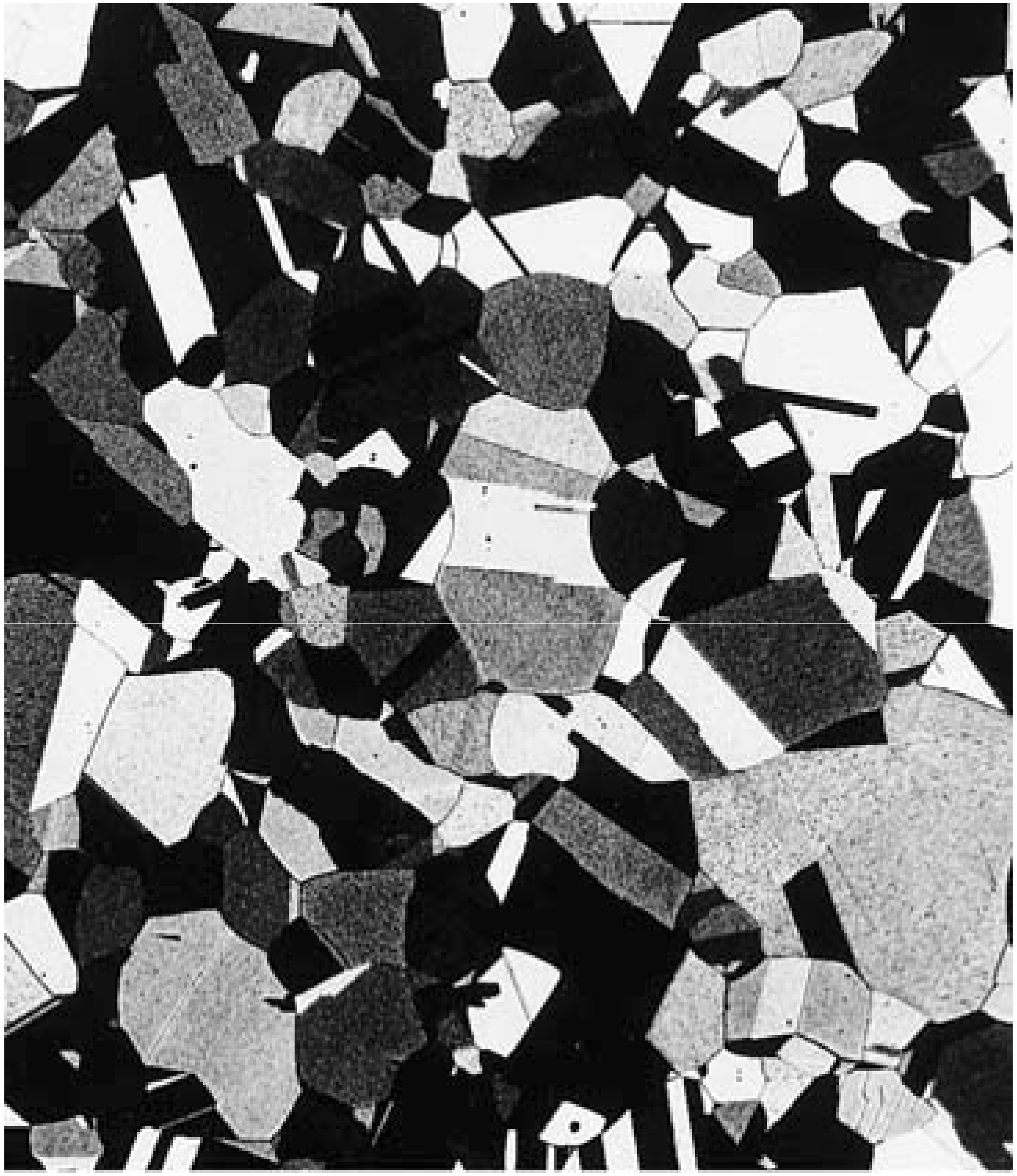
(c)

Após 4 s, 580 C



(d)

Após 8 s, 580C



(e)

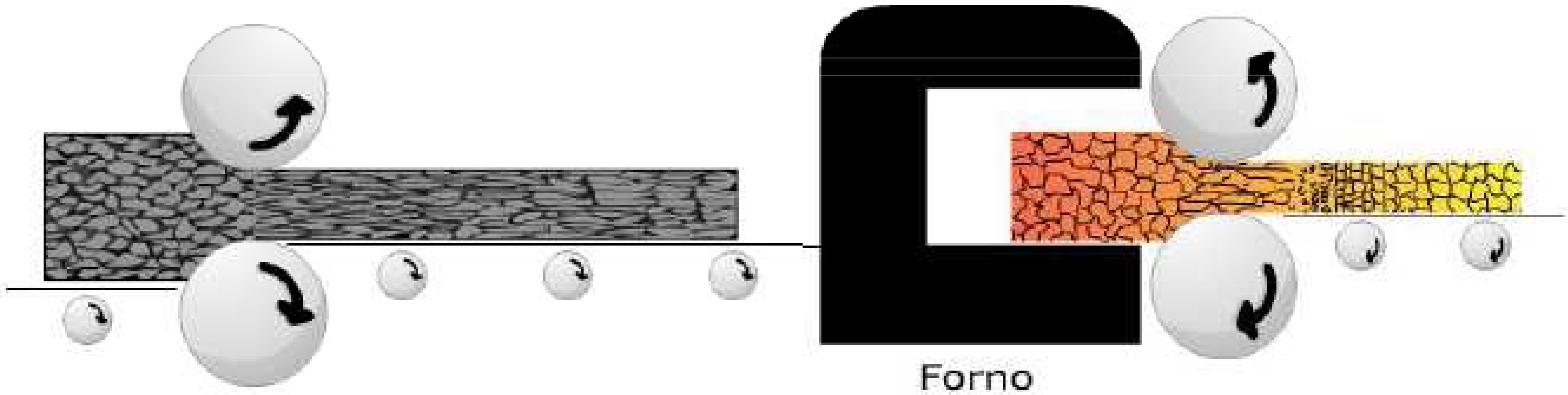
Após 15 min, 580C

(f)

Após 10 min, 700C

TRABALHO A FRIO X TRABALHO A QUENTE

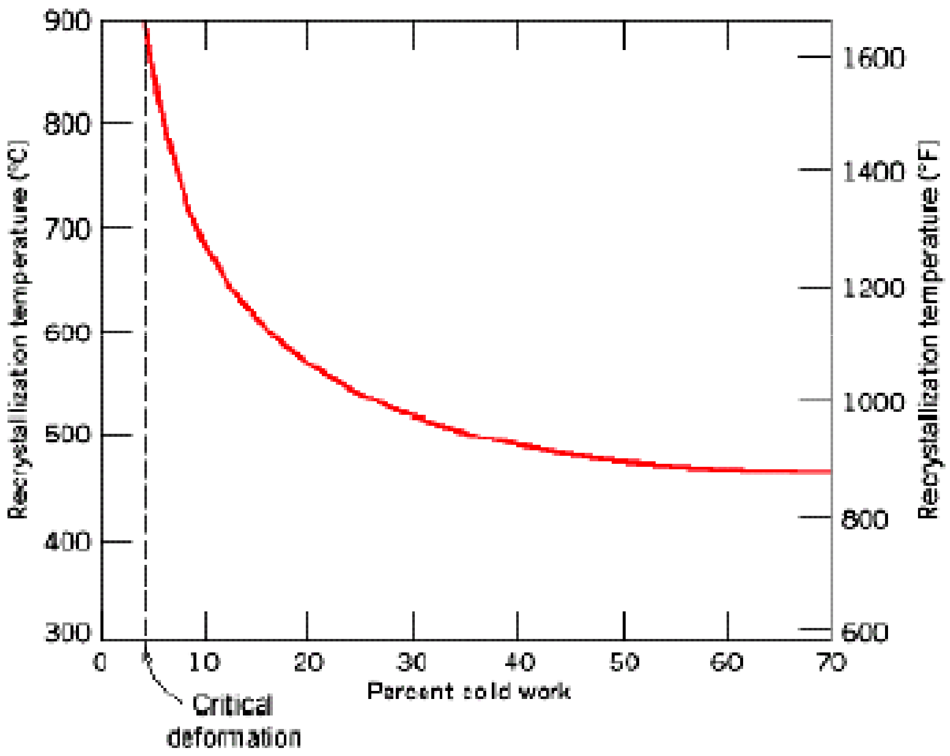
Trabalho a quente: o processo de conformação do metal, ou a deformação plástica, ocorre acima da temperatura de recristalização, visando alívio dos esforços de deformação e a recristalização dinâmica do material processado.



a frio

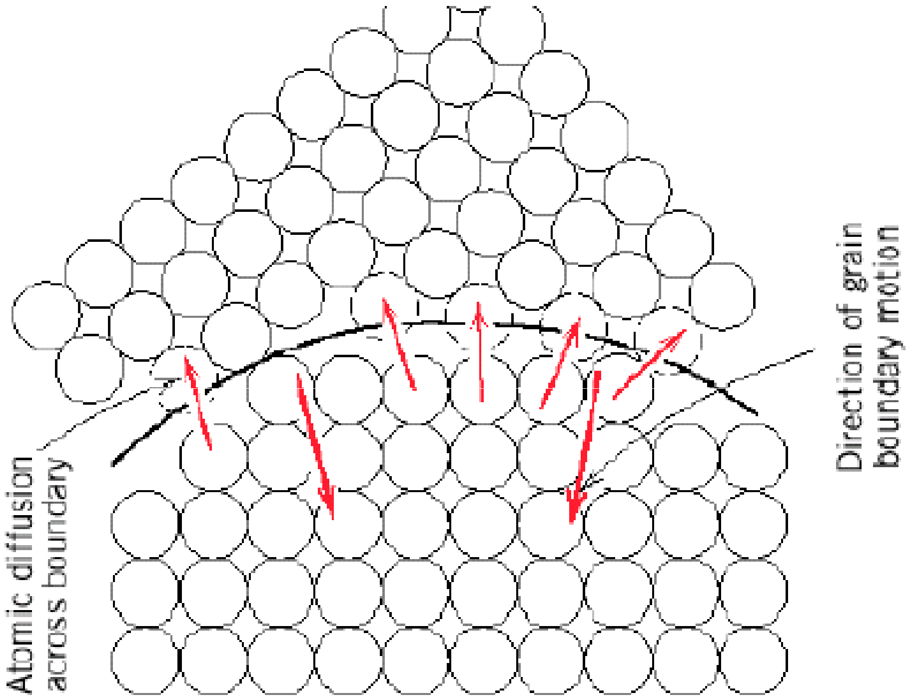
a quente

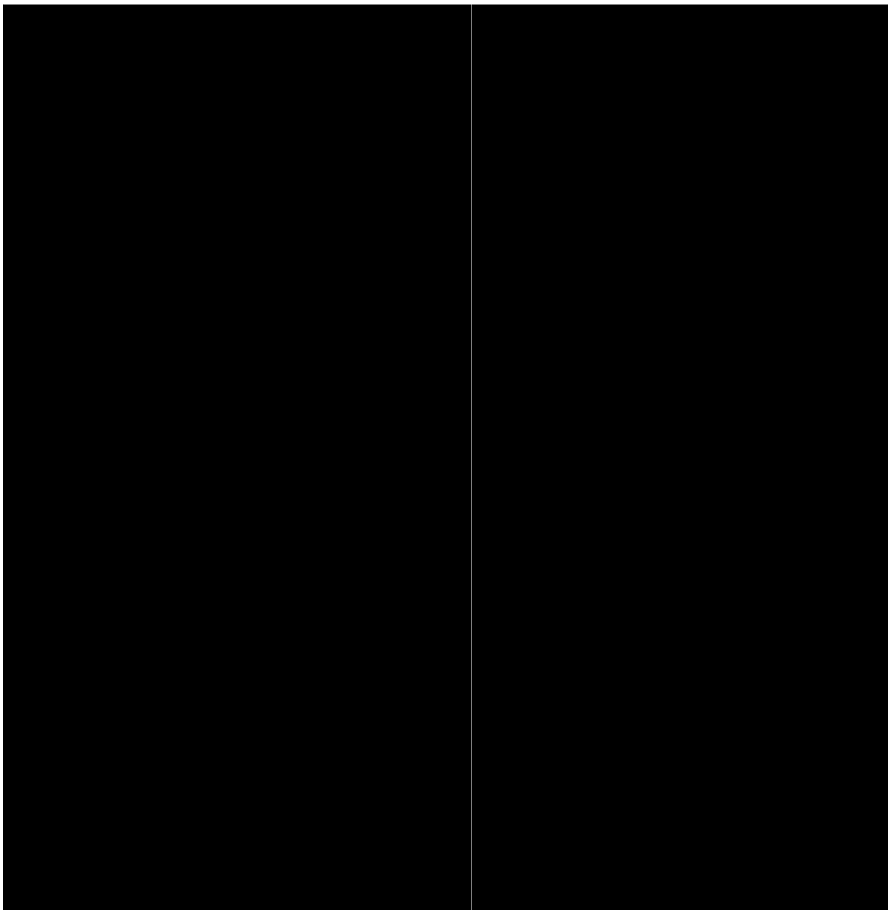
RECRISTALIZAÇÃO

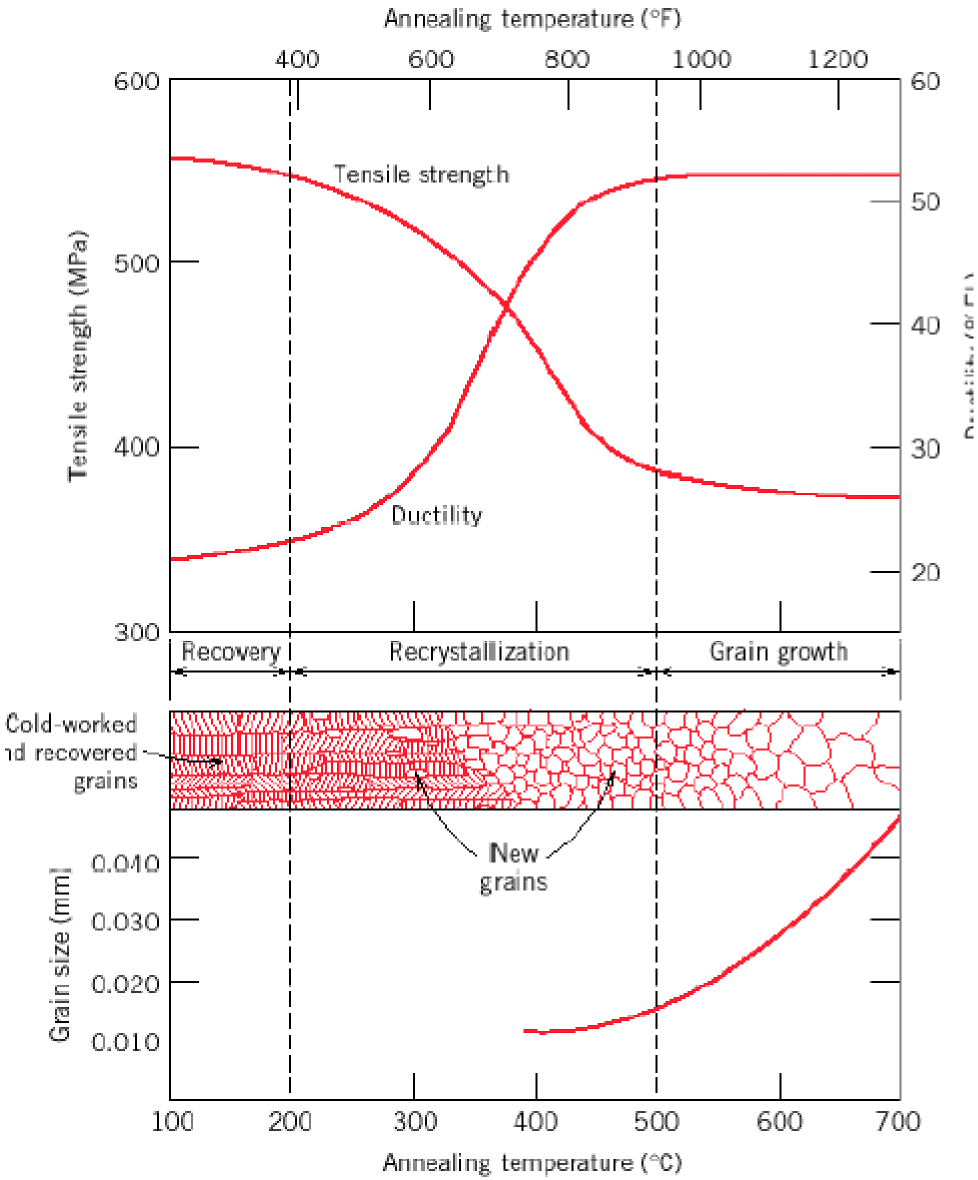


	Recrystallization Temperature		*Melting Temperature*	
Metal	***°C***	***°F***	***°C***	***°F***
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

CRESCIMENTO DE GRÃO







Annealing temperature (°F)
400
600
800
1000
1200
600
500
400
300
Tensile strength (MPa)
60
50
40
30
20
Tensile strength
Ductility
Recovery
Recrystallization
Grain growth
Cold-worked
nd recovered
grains
New
grains
0.040
0.030
0.020
0.010
Grain size (mm)
100
200
300
400
500
600
700
Annealing temperature (°C)