MEM2711

Materials Science

Hakan Yılmazer, KMA 205

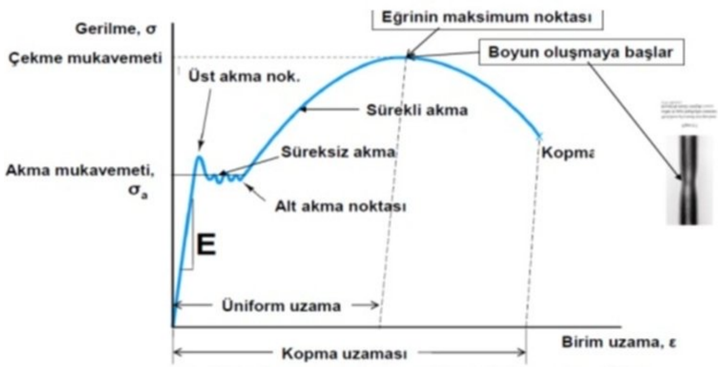
Lecture 8. Strengthening Mechanism

HATIRLATMA

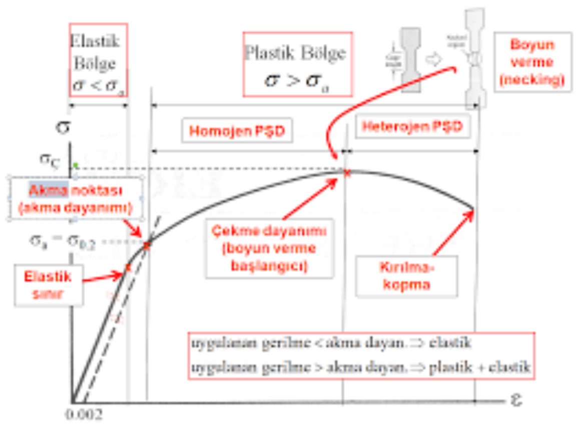
*Dislokasyonlar, hareketli olan ve kayma gerilmesi uygulandığında kafes boyunca hareket edebilen çizgisel kristal kafes hatalarıdır (kusurlarıdır).

*Malzeme özellikleri üzerinde son derece önemli etkileri vardır. Özellikle mekanik dayanım üzerinde, çünkü malzemelerin akması ve plastik olarak deforme olmasını sağlayan mekanizmadır.

*Dislokasyonların hareketini zorlaştırarak metallerin dayanımı artırılabilir.



Düşük karbonlu çelik için gerilme-birim uzama eğrisi



Neredeyse bütün mukavemet (dayanım) artırıcı yöntemlerdeki esas aşağıdaki kurala dayanır:

DİSLOKASYON HAREKETLERİNİ SINIRLAMAK VEYA ENGELLEMEK MALZEMENİN DAHA YÜKSEK SERTLİĞE ULAŞMASINI VE DAHA YÜKSEK DAYANIMLI OLMASINI SAĞLAR

ÇOK SAYIDA YÖNTEMLE BU SAĞLANABİLİR

1. Solid Solution Strengthening
2. Grain Size Reduction Strengthening
3. Work hardening (straining) Strengthening
4. Precipitation Strengthening
5. Dispersion Strengthening

Mechanism of Strengthening in Metals

- The ability of a metal to plastically deform depends on the ability of dislocations to move.
- Hardness and strength are related to the ease with which plastic deformation can be made to occur
  - To enhance mechanical strength ➔ reduce dislocation mobility ➔ greater mechanical forces required to initiate plastic deformation.
- Strengthening mechanism for single phase metal
  - By grain size reduction
  - Solid-solution alloying
  - Strain-hardening

4 Strategies for Strengthening
1. Solid Solution Strengthening Mechanism

Metalik malzemelerde katı çözelti oluşturmanın en önemli etkisi katı çözelti sertleşmesidir.

Katı çözeltinin mukavemet artırıcı etkisi, dislokasyon hareketlerine direncin artırılması sayesinde oluşur.

Cu-Zn (Pirinç) alaşımının saf Cu'dan ve Fe-C alaşımı olan çeliğin saf demirden daha mukavemetli olması katı çözelti sertleşmesi sayesinde olur.

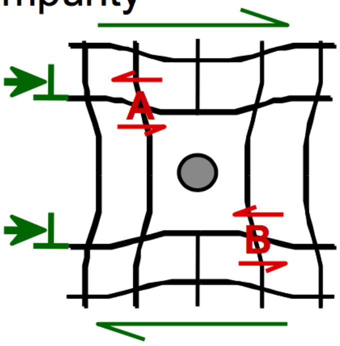
HATIRLATMA:
KATI ÇÖZELTİ (ERGİYİK): Malzemeler yapılarının içerisinde, belli oranlarda farklı atomları çözebilirler. Bu durum "katı çözeltiler" olarak adlandırılır. Bir çözelti çözen ve çözünen olmak üzere iki bileşenden oluşur.

ÇÖZÜNÜRLÜK: Yabancı bir atomun farklı bir elementin kristal yapısına yeralan veya arayer atomu olarak yerleşmesidir. Çözünürlükte meydana gelen yapıdaki elementler kendi özelliklerini kaybeder ve oluşan çözelti tek bir yapı gibi davranır.
A)Sınırlı Çözünürlük
B)Sınırsız Çözünürlük (Kuralları var: boyut faktörü, kristal yapı, valans elektron sayısı, elektronegatiflik)

4 Strategies for Strengthening
1. Solid Solution Strengthening Mechanism

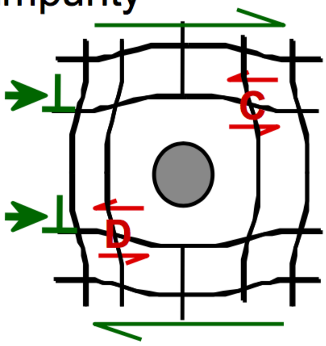
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

- Smaller substitutional impurity



Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

4 Strategies for Strengthening

1. Solid Solution Strengthening Mechanism

KATI ÇÖZELTİ (Solid Solution):
Malzemeler yapılarının içerisinde, belli oranlarda farklı atomları çözebilirler. Bu durum "katı çözeltiler" olarak adlandırılır. Bir çözelti çözen ve çözünen olmak üzere iki bileşenden oluşur.

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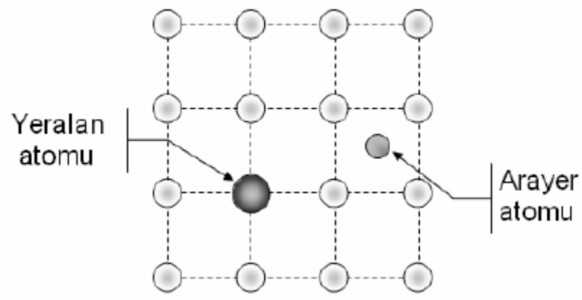
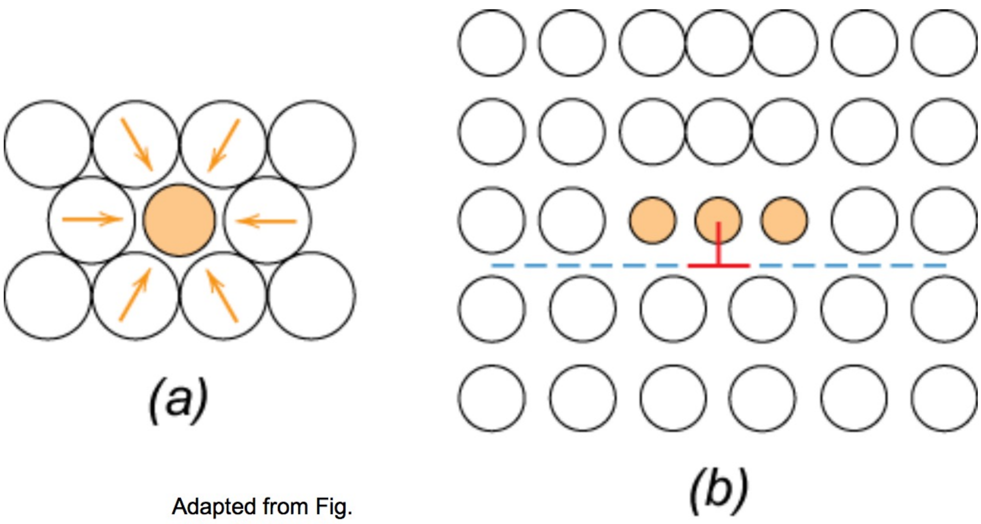


Strengthening by Alloying

- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation ∴ increase strength



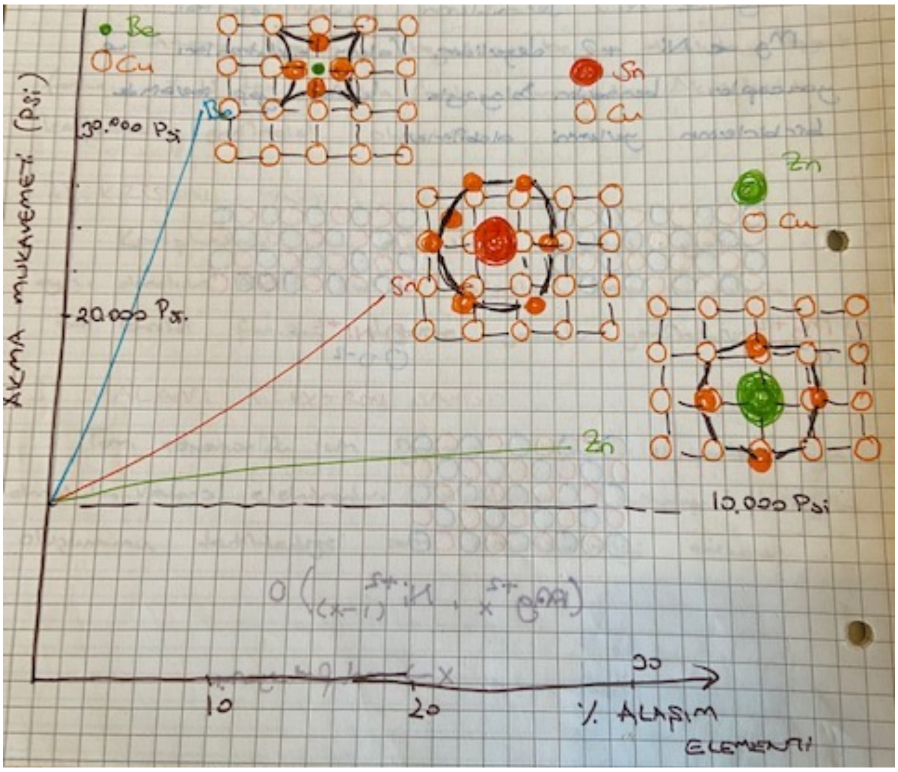
Adapted from Fig. 7.17, *Callister 7e.*

1. Katı Çözelti (Ergiyik) Sertleşmesi

Cu-Be

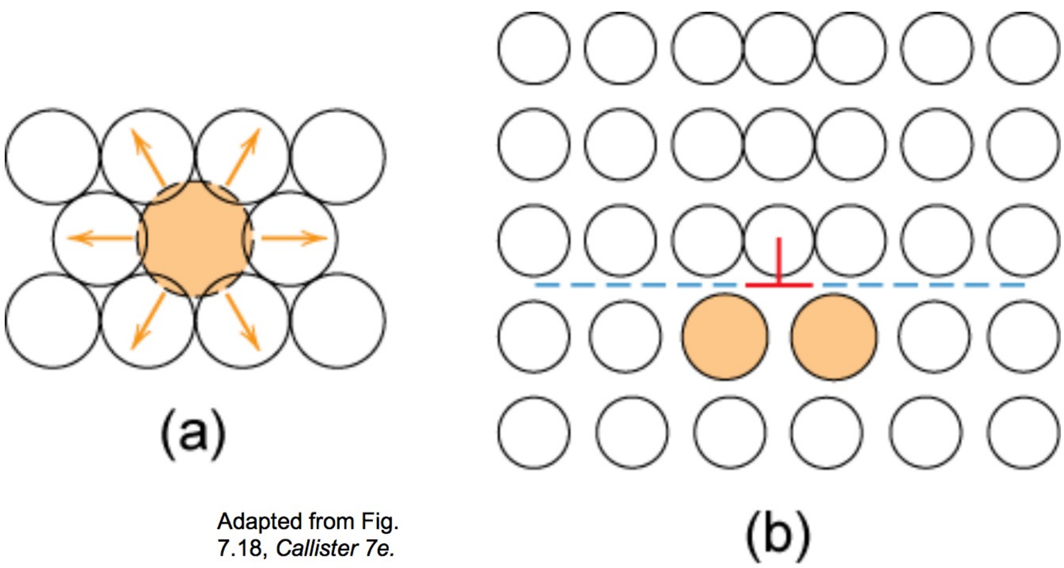
Cu-Sn

Cu-Zn



Strengthening by alloying

- large impurities concentrate at dislocations on low density side

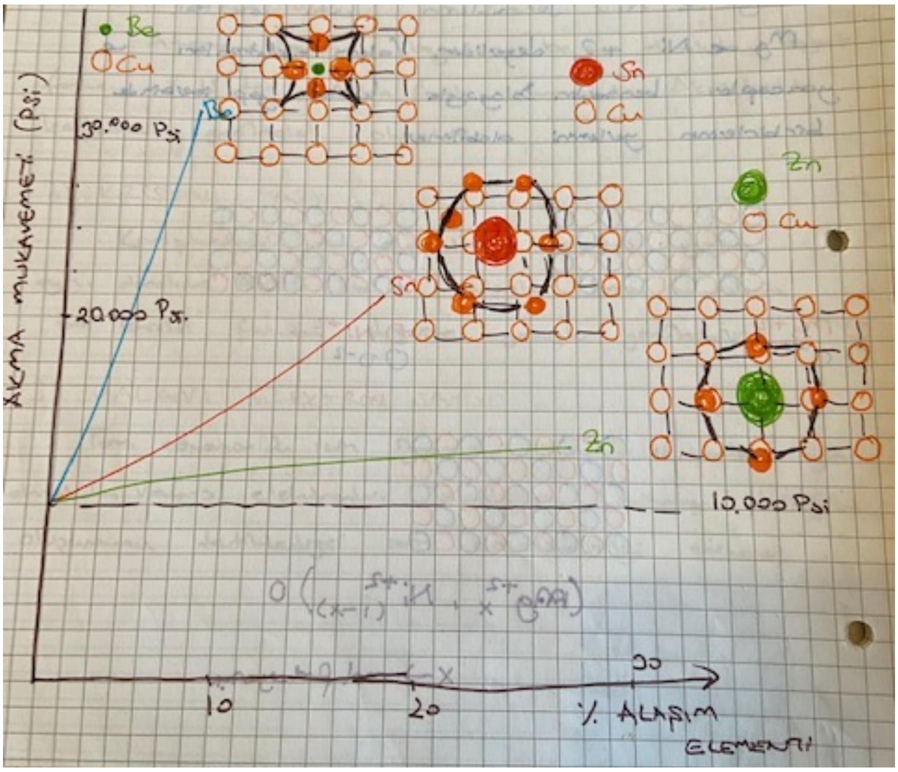


Adapted from Fig. 7.18, *Callister 7e.*

Cu-Be

Cu-Sn

Cu-Zn



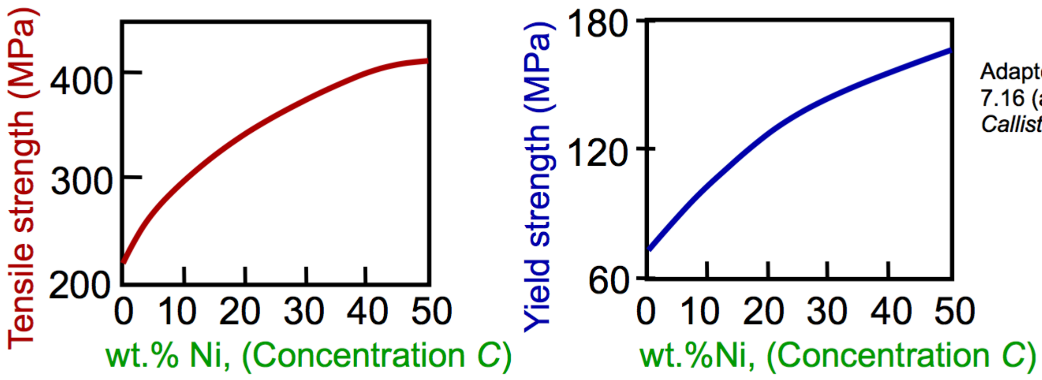
- Alloys are stronger than pure metals
  - Impurity atoms impose lattice strain on surrounding host atoms
  - Lattice strain field interaction between dislocation and impurity atoms result
    - ➔ dislocation movement is restricted

- An impurity atom that is smaller than a host atom ➔ substitution results tensile strains on the surrounding crystal lattice (Fig 7.17a)

- Larger substitutional atom imposes compressive strains in its vacinity (Fig 7.18a)

Ex: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.

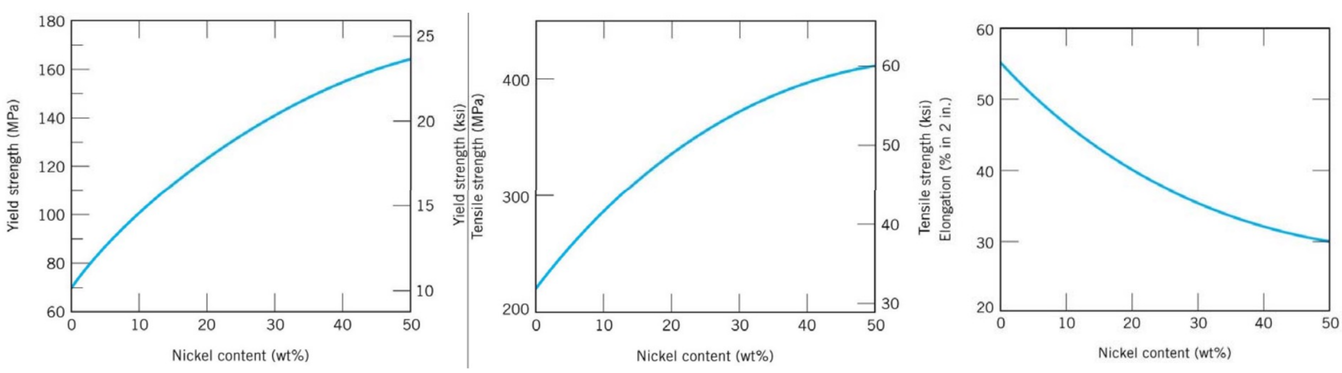


Adapted from Fig. 7.16 (a) and (b), *Callister 7e.*

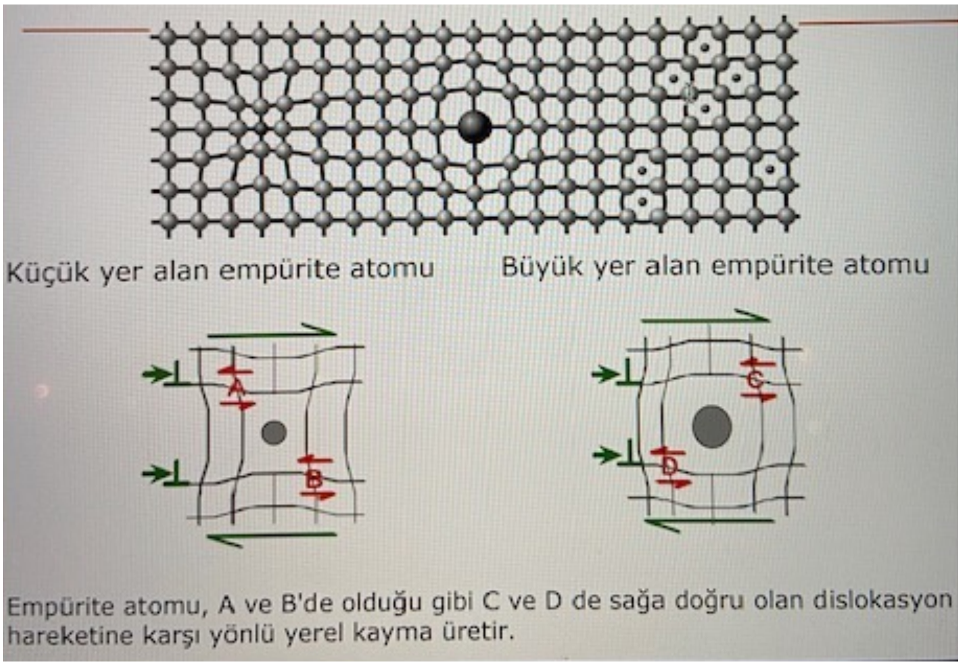
- Empirical relation: $\sigma_y \sim C^{1/2}$

- Alloying increases σ_y and *TS*.

Ex: Solid Solution Strengthening in Copper



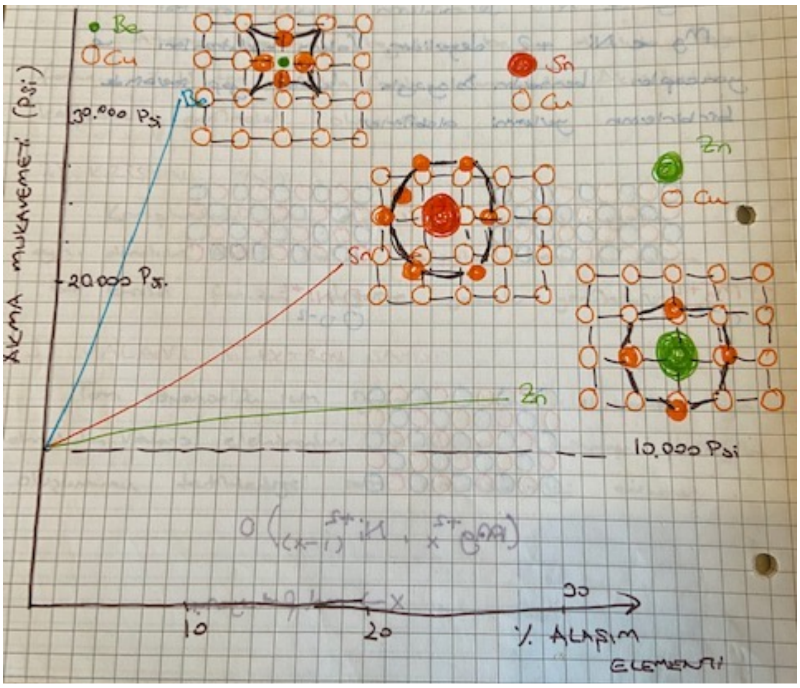
1. Katı Çözelti (Ergiyik) Sertleşmesi



1. Katı Çözelti (Ergiyik) Sertleşmesi

KATI ÇÖZELTİ SERTLEŞMESİNİN ne kadar etkin olacağı iki faktöre bağlıdır;

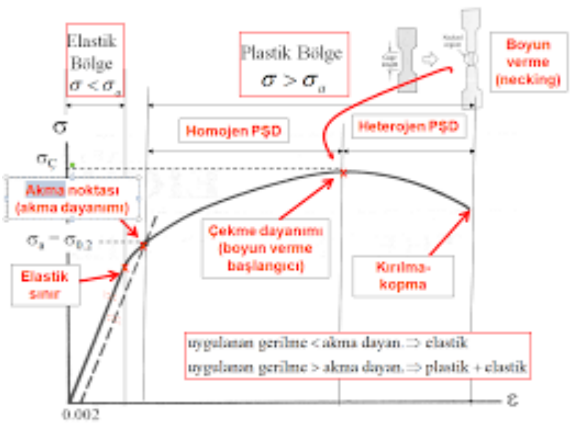
1. Ev sahibi ve misafir (yabancı) atomlar arasındaki yarıçap farkı ne kadar fazla ise (yeralan atom için) oluşan mukavemet artışı o kadar büyüktür.
2. Alaşım elemntinin miktarı arttıkça oluşan mukavemet artışı o kadar fazla olur.



1. Katı Çözelti (Ergiyik) Sertleşmesinin SONUÇLARI

Katı çözelti sertleşmesi ile MALZEME ÖZELLİKLERİ DEĞİŞİR;

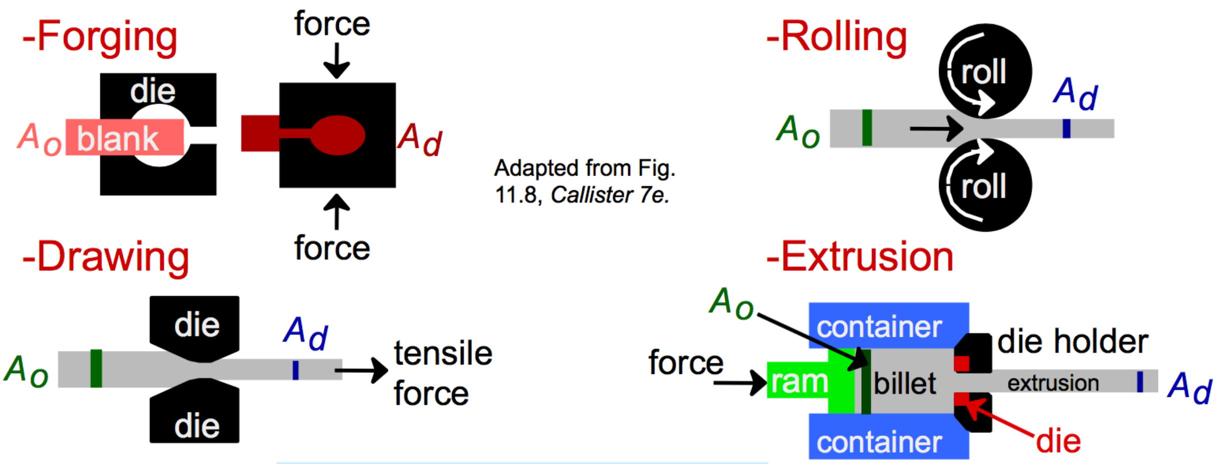
1. Malzemenin akma dayanımı, maksimum çekme mukavemeti ve sertliği artar, alaşım yapmanın temel felsefesi budur.
2. Malzemenin sünekliği düşer (sadece çok özel durumlarda (Cu-Zn alaşımı, hem mukavemet hem de süneklik artar)
3. Malzemenin elektrik iletkenliği saf malzemeye göre düşüktür
4. Malzemenin sürünme mukavemeti veya yüksek sıcaklıktaki mukavemeti önemli derecede azalmaz.



4 Strategies for Strengthening

2.Cold Working Strengthening (Strain Hardening) Mechanism

- Room temperature deformation.
- Common forming operations change the cross sectional area:

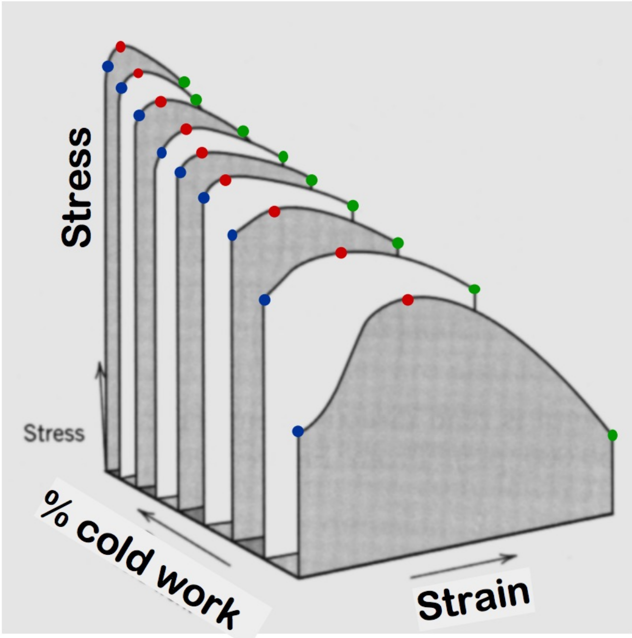


Adapted from Fig. 11.8, *Callister 7e.*

$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Impact of Cold Work

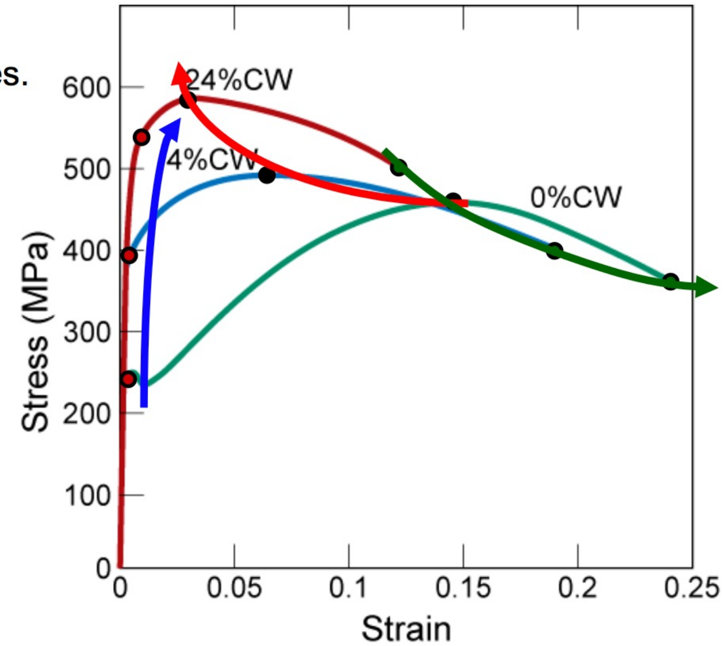
- Yield strength (σ_y) increases
- Tensile strength (TS) increases
- Ductility (%EL;%RA) decreases



Impact of Cold Work

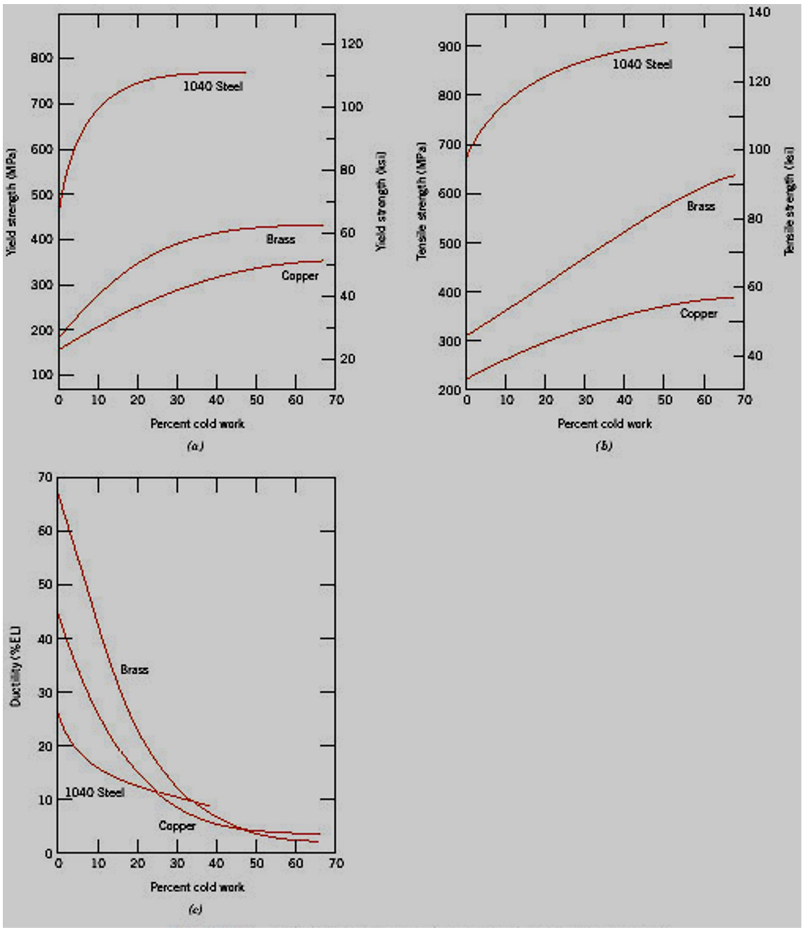
As cold work is increased

- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (%*EL* or %*AR*) decreases.



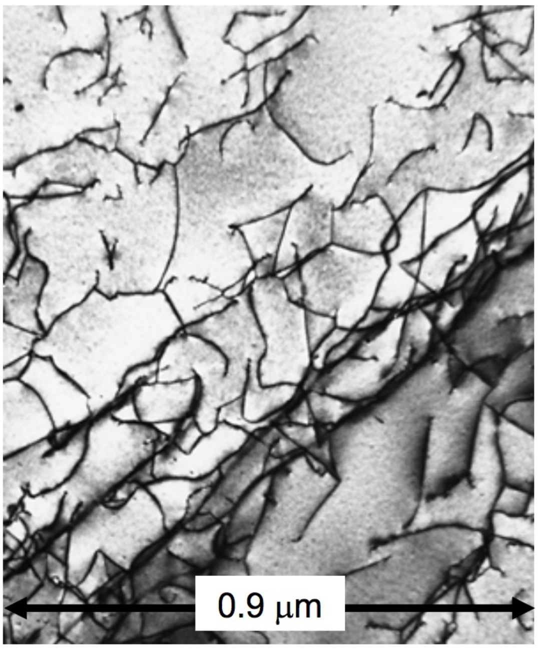
- Figure demonstrates effect of cold work on steel, brass and copper

- Loading to plastic deformation, unloading and then reloading ➔ requires more applied load or stress to yield ➔ metal becomes stronger



Why more stronger ?

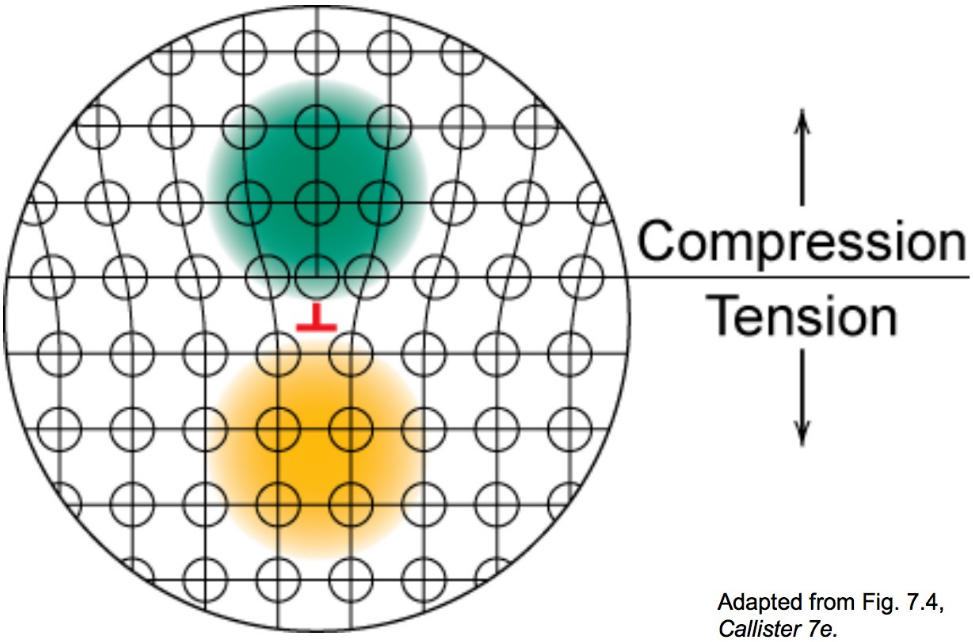
On the average, dislocation-dislocation strain interactions are repulsive. Dislocations are entangled with another during cold work.



- Dislocation density increases due to
  - Deformation or cold work
  - Dislocation multiplication
  - Formation of new dislocations

- Net result ➔ motion of dislocation is hindered by the presence of other dislocations ➔ higher imposed stress is needed to deform a metal

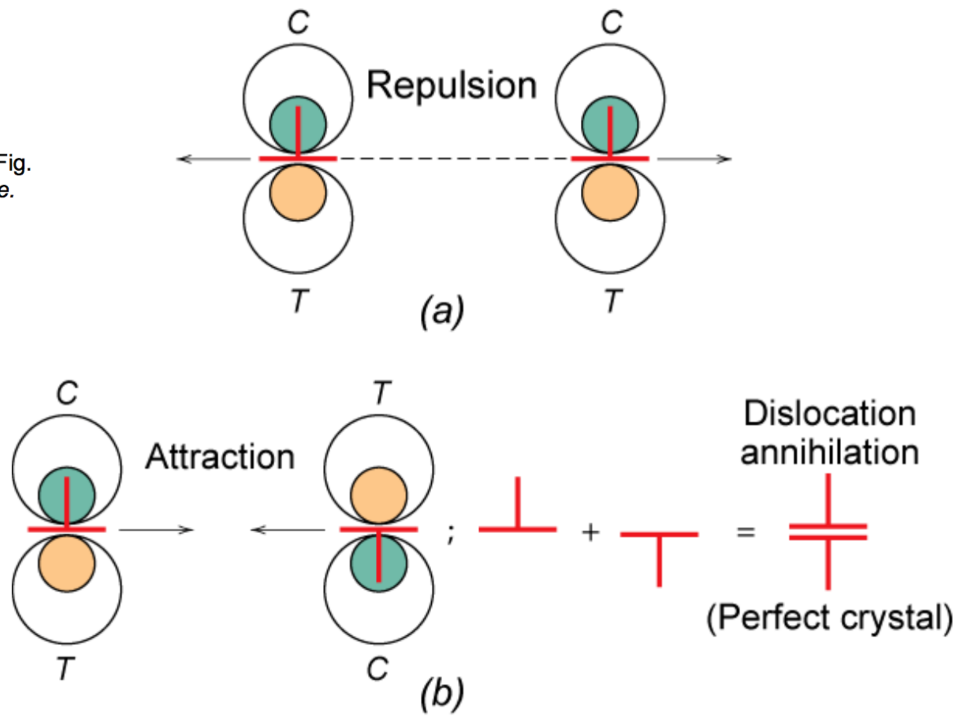
Stress Concentration at Dislocations



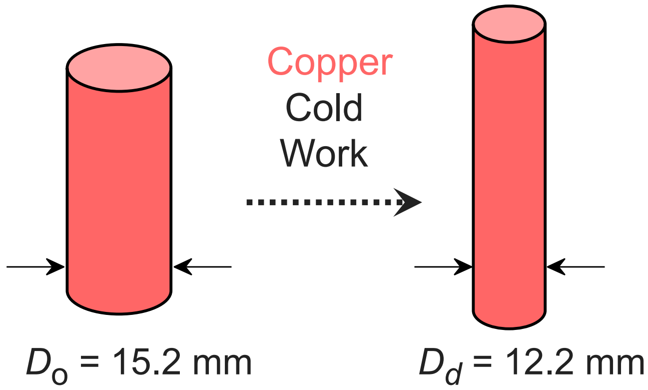
Adapted from Fig. 7.4, *Callister 7e.*

Effects of Stress at Dislocations

Adapted from Fig. 7.5, *Callister 7e.*



- What are the values of yield strength, tensile strength & ductility after cold working Cu?

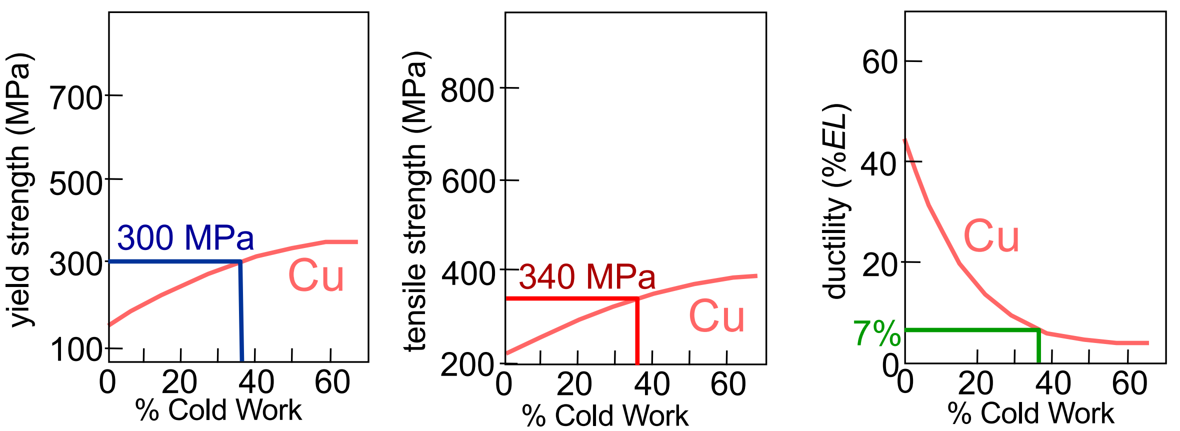


$$\%CW = \frac{\frac{\pi D_o^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_o^2}{4}} \times 100$$

$$= \frac{D_o^2 - D_d^2}{D_o^2} \times 100$$

$$\%CW = \frac{(15.2\,\text{mm})^2 - (12.2\,\text{mm})^2}{(15.2\,\text{mm})^2} \times 100 = 35.6\%$$

- What are the values of yield strength, tensile strength & ductility for Cu for %CW = 35.6%?

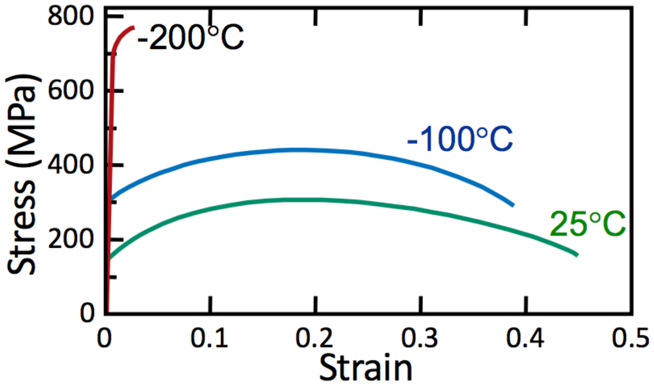


σ_y = 300 MPa | *TS* = 340 MPa | %*EL* = 7%

Adapted from Fig. 8.19, *Callister & Rethwisch 4e.* (Fig. 8.19 is adapted from *Metals Handbook: Properties and Selection: Iron and Steels*, Vol. 1, 9th ed., B. Bardes (Ed.), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979, p. 276 and 327.)

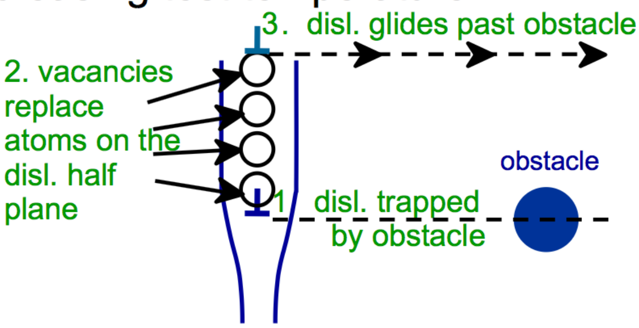
σ-ε Behavior vs. Temperature

- Results for polycrystalline iron:



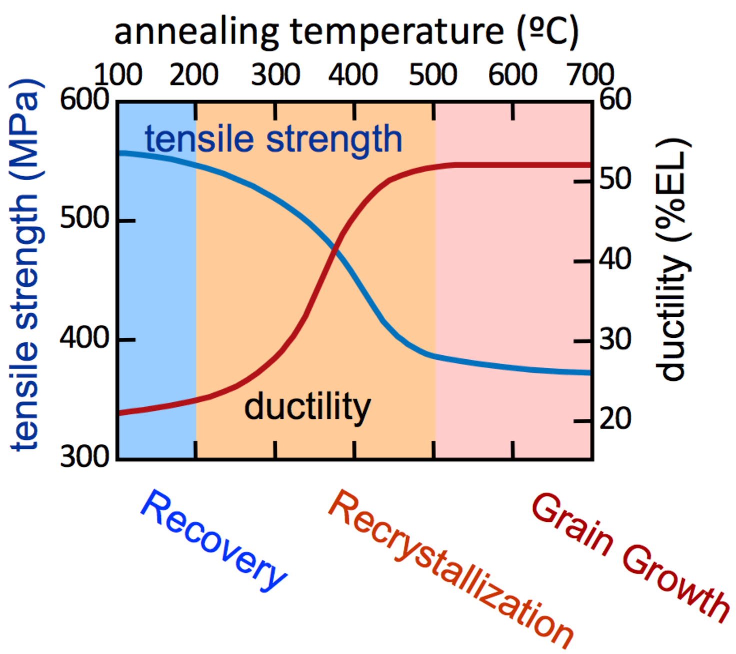
Adapted from Fig. 6.14, *Callister 7e.*

- σ_y and *TS decrease* with increasing test temperature.
- *%EL increases* with increasing test temperature.
- Why? Vacancies help dislocations move past obstacles.



Effect of Heating After %*CW*

- 1 hour treatment at *Tanneal*... decreases *TS* and increases %*EL*.
- Effects of cold work are reversed!



- 3 Annealing stages to discuss...

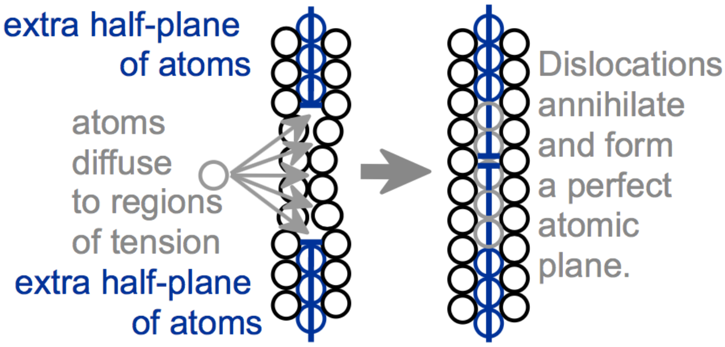
Adapted from Fig. 7.22, *Callister 7e.* (Fig. 7.22 is adapted from G. Sachs and K.R. van Horn, *Practical Metallurgy, Applied Metallurgy, and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)

Recovery

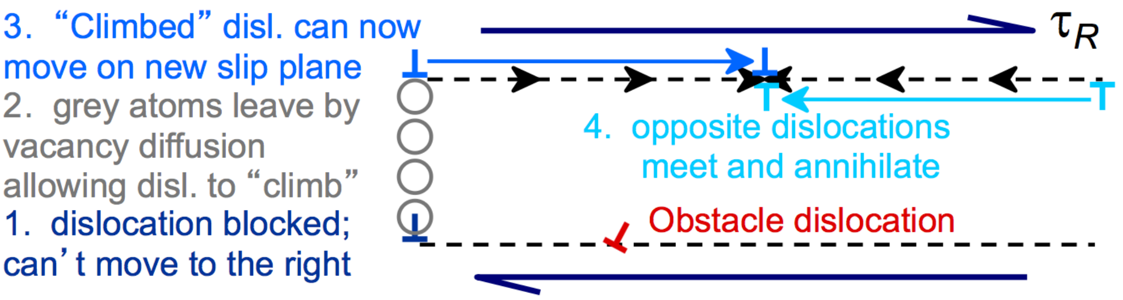
Annihilation reduces dislocation density.

- Scenario 1

  Results from diffusion

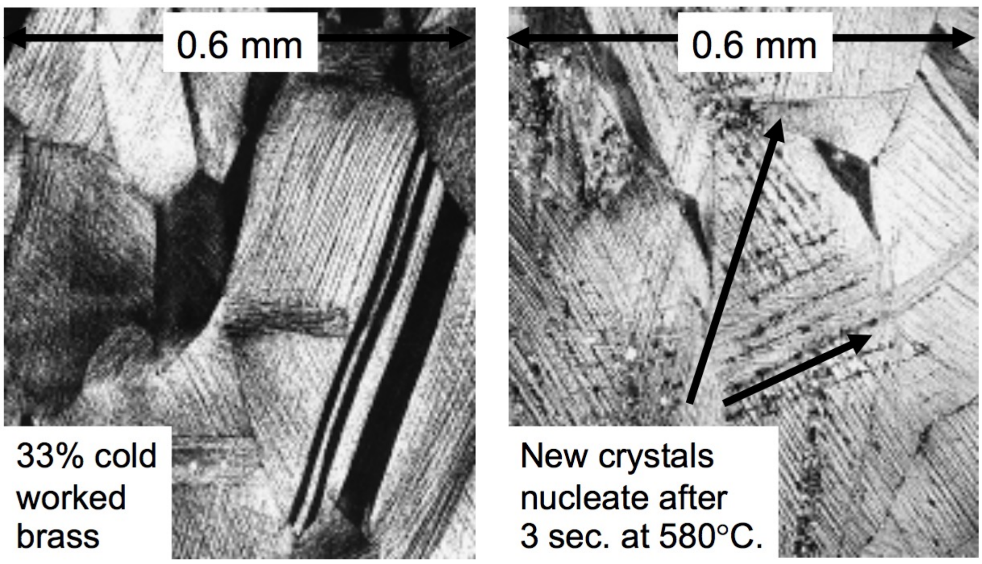


- Scenario 2



Recrystallization

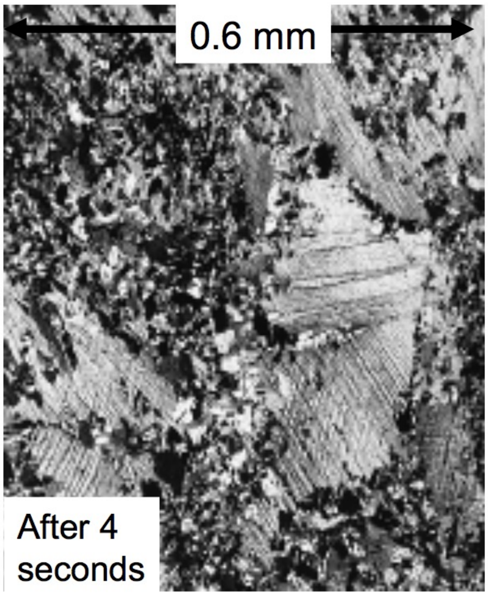
- New grains are formed that:
  - -- have a small dislocation density
  - -- are small
  - -- consume cold-worked grains.

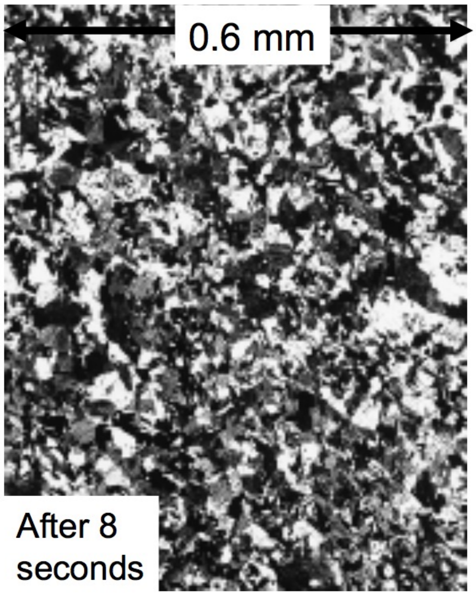


Adapted from Fig. 7.21 (a),(b), *Callister 7e.* (Fig. 7.21 (a),(b) are courtesy of J.E. Burke, General Electric Company.)

Further Recrystallization

- All cold-worked grains are consumed.

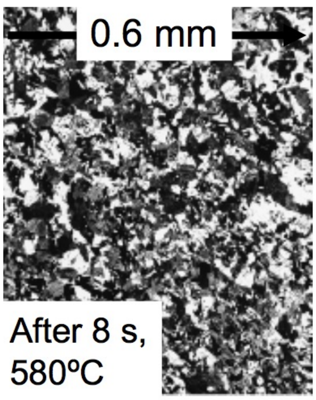


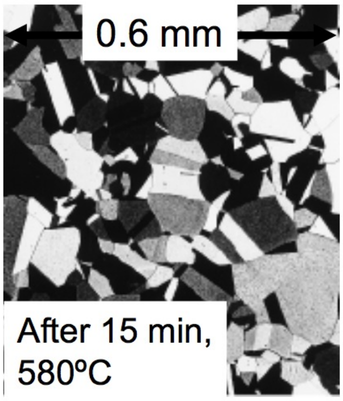


Adapted from Fig. 7.21 (c),(d), *Callister 7e.* (Fig. 7.21 (c),(d) are courtesy of J.E. Burke, General Electric Company.)

Grain Growth

- At longer times, larger grains consume smaller ones.
- Why? Grain boundary area (and therefore energy) is reduced.





Adapted from Fig. 7.21 (d),(e), *Callister 7e.* (Fig. 7.21 (d),(e) are courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation:

exponent typ. ~ 2

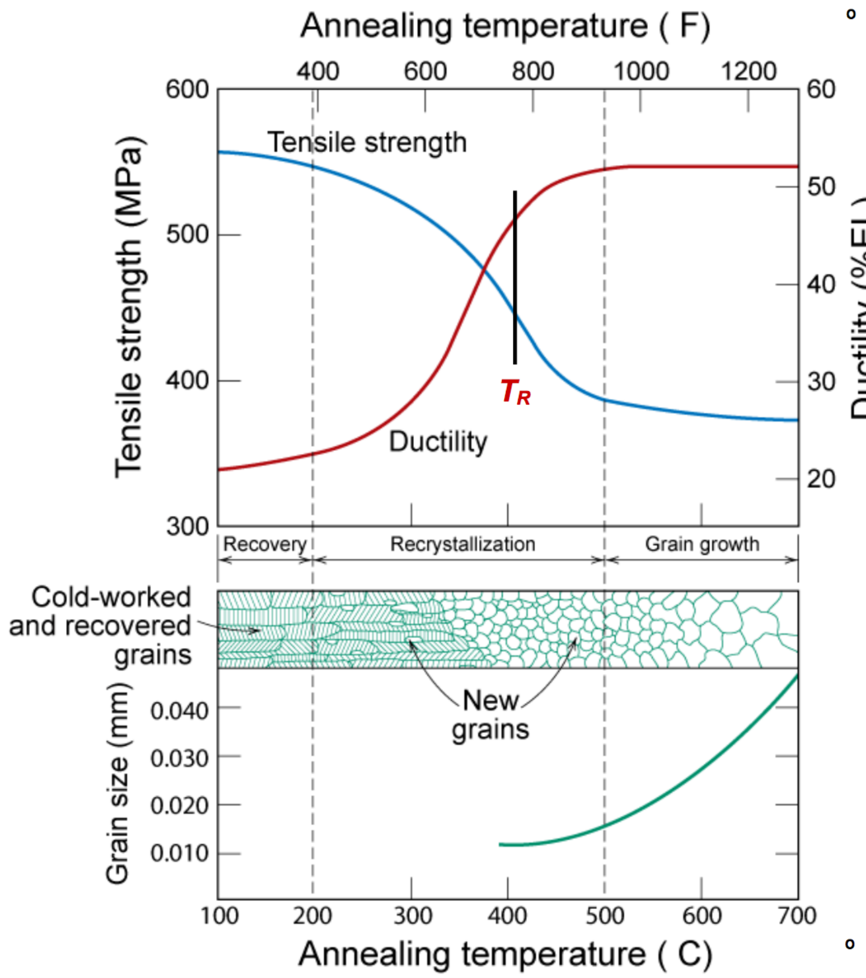
grain diam. at time t.

$$d^n - d_o^n = Kt$$

coefficient dependent on material and *T*.

elapsed time

Ostwald Ripening



T_R = recrystallization temperature

Adapted from Fig. 7.22, *Callister 7e.*

Recrystallization Temperature, T_R

T_R = recrystallization temperature = point of highest rate of property change

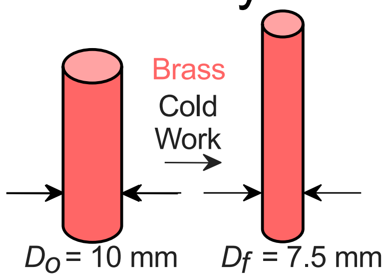
1. T_m => $T_R \approx$ 0.3-0.6 T_m (K)
2. Due to diffusion → annealing time→ T_R = f(t) shorter annealing time => higher T_R
3. Higher %CW => lower T_R – strain hardening
4. Pure metals lower T_R due to dislocation movements
   - Easier to move in pure metals => lower T_R

Diameter Reduction Procedure - Problem

A cylindrical rod of brass originally 10 mm (0.39 in) in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 380 MPa (55,000 psi) and a ductility of at least 15 %*EL* are desired. Furthermore, the final diameter must be 7.5 mm (0.30 in). Explain how this may be accomplished.

Solution

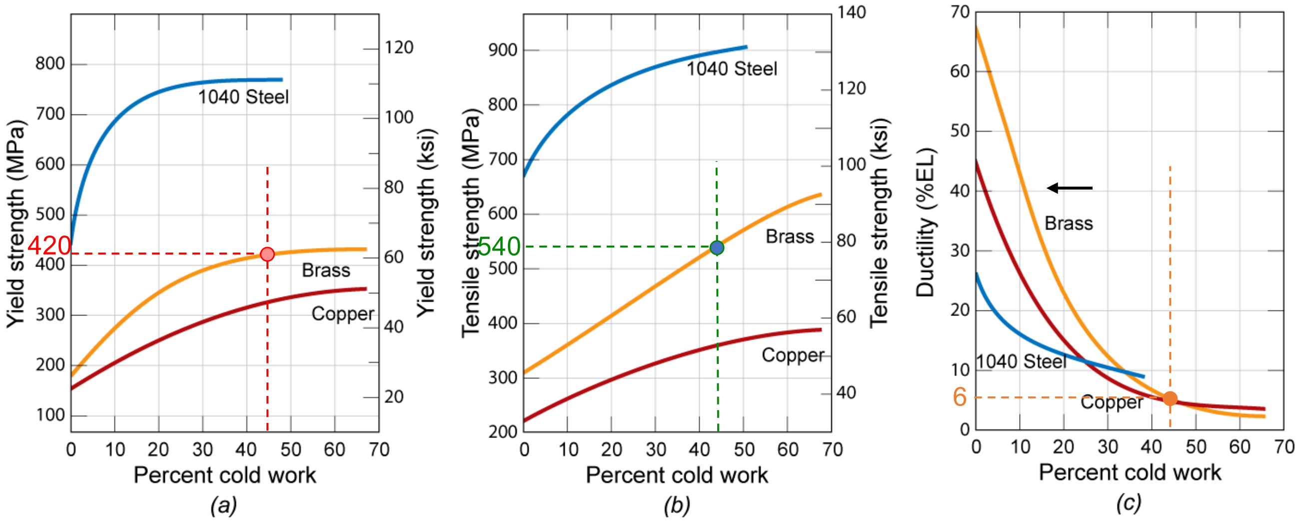
What are the consequences of directly drawing to the final diameter?



$$\%CW = \left(\frac{A_o - A_f}{A_o}\right) x\,100 = \left(1 - \frac{A_f}{A_o}\right) x\,100$$

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_o^2/4}\right) x\,100 = \left(1 - \left(\frac{7.5}{10}\right)^2\right) x\,100 = 43.8\%$$

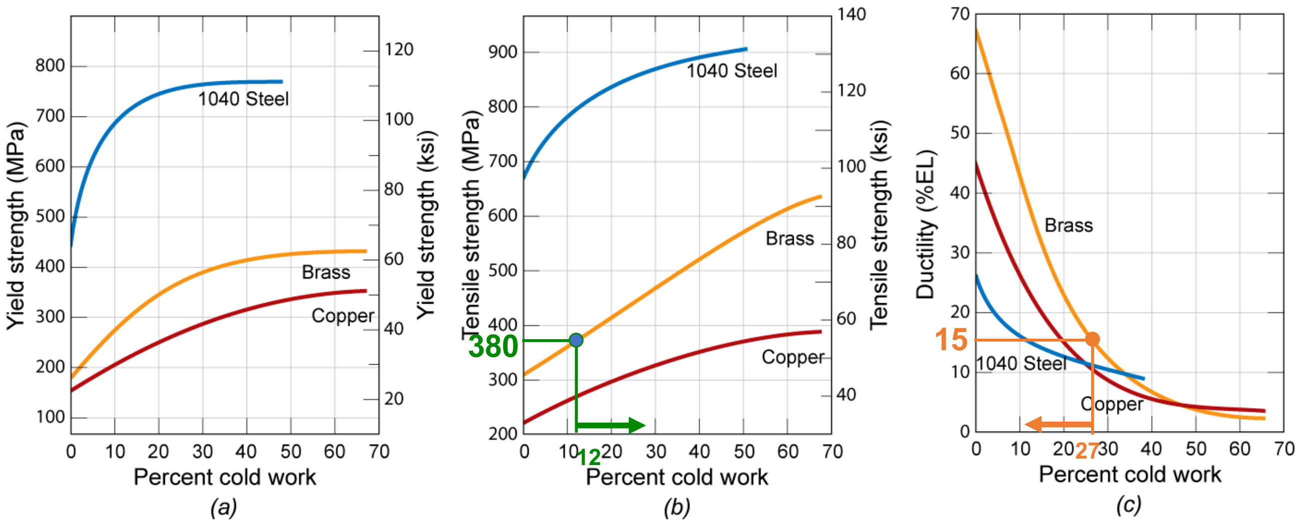
Solution



Adapted from Fig. 8.19, *Callister & Rethwisch 4e.*

- For %CW = 43.8%
  - σ_y = 420 MPa
  - *TS* = 540 MPa   > 380 MPa
  - %*EL* = 6   < 15
- This doesn't satisfy criteria… what other options are possible?

Solution



Adapted from Fig. 8.19, *Callister & Rethwisch 4e.*

For *TS* > 380 MPa → > 12 %CW

For %*EL* > 15 → < 27 %CW

∴ our working range is limited to 12 < %CW < 27

Solution

Cold work, then anneal, then cold work again

- For objective we need a cold work of 12 < %CW < 27
  - We'll use 20 %CW
- Diameter after first cold work stage (but before 2nd cold work stage) is calculated as follows:

$$\%CW = \left(1 - \frac{D_{f2}^2}{D_{02}^2}\right) x\, 100 \;\Rightarrow\; 1 - \frac{D_{f2}^2}{D_{02}^2} = \frac{\%CW}{100}$$

$$\frac{D_{f2}}{D_{02}} = \left(1 - \frac{\%CW}{100}\right)^{0.5} \;\Rightarrow\; D_{02} = \frac{D_{f2}}{\left(1 - \frac{\%CW}{100}\right)^{0.5}}$$

$$\text{Intermediate diameter} = D_{f1} = D_{02} = 7.5\,\text{mm} \Big/ \left(1 - \frac{20}{100}\right)^{0.5} = \boxed{8.39\,\text{mm}}$$

Solution

Stage 1: Cold work – reduce diameter from 10 mm to 8.39 mm

$$\%CW_1 = \left(1 - \left(\frac{8.39\,\text{mm}}{10\,\text{mm}}\right)^2\right) x\, 100 = 29.6$$

Stage 2: Heat treat (allow recrystallization)

Stage 3: Cold work – reduce diameter from 8.39 mm to 7.5 mm

$$\%CW_2 = \left(1 - \left(\frac{7.5}{8.49}\right)^2\right) x\, 100 = 20 \quad \overset{\text{Fig 8.19}}{\Rightarrow} \quad \begin{array}{l} \sigma_y = 340\,\text{MPa} \\ TS = 400\,\text{MPa} \\ \%EL = 24 \end{array}$$

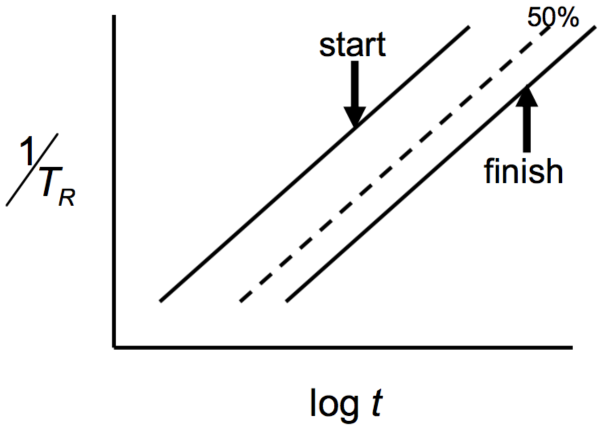
Therefore, all criteria satisfied

Rate of Recrystallization

$$\log R = -\log t = \log R_0 - \frac{E}{kT}$$

$$\log t = C + \frac{B}{T}$$

$$\text{note}: R = 1/t$$



- Hot work → above T_R
- Cold work → below T_R
- Smaller grains
  - stronger at low temperature
  - weaker at high temperature

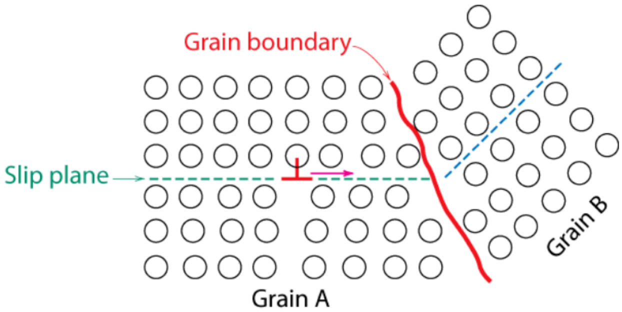
Summary

- Dislocations are observed primarily in metals and alloys.
- Strength is increased by making dislocation motion difficult.
- Particular ways to increase strength are to:
  - --decrease grain size
  - --solid solution strengthening
  - --precipitate strengthening
  - --cold work
- Heating (annealing) can reduce dislocation density and increase grain size. This decreases the strength.

4 Strategies for Strengthening:

3.Grain size reduction Strengthening Mechanism

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with Increasing angle of misorientation.
- Smaller grain size: more barriers to slip.



Adapted from Fig. 7.14, *Callister 7e.*
(Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

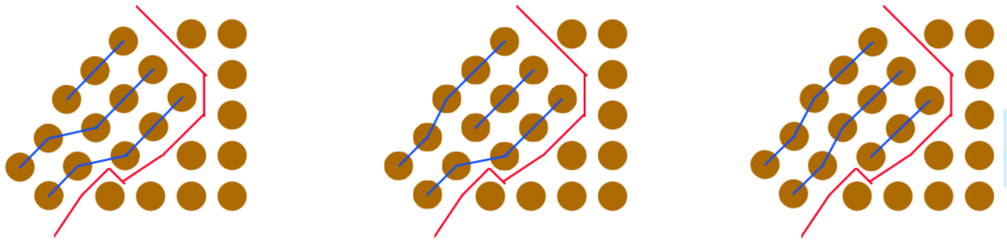


Figure 1. Representation of a Dislocation Stopped by a Grain Boundary (Red Line).

- Hall-Petch Equation: For many materials, Yield strength varies with grain size as

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

d: average grain diameter

σ_0 and k_y are material constants

Hall-Petch equation is not valid for very large and extremely small grain materials

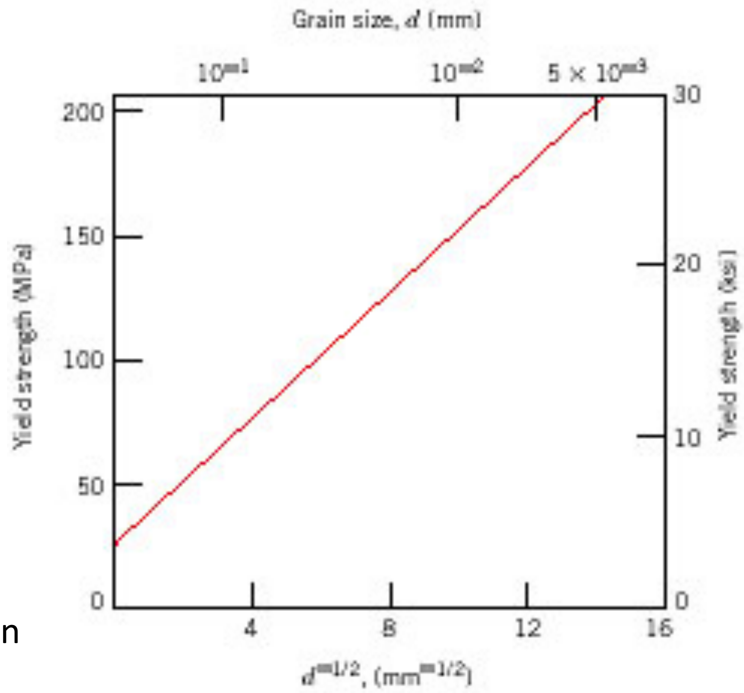
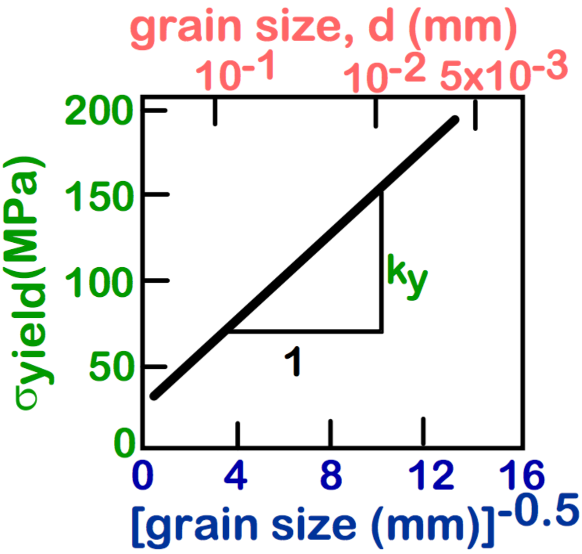


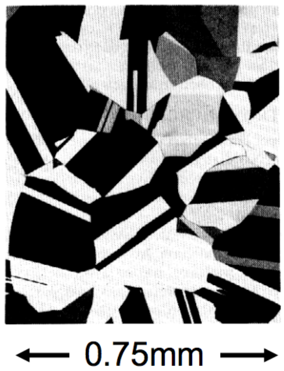
Figure 7.15 shows strength variation for brass

Example: Grain Size Strengthening

- 70wt%Cu-30wt%Zn brass alloy

- Data:





$$\sigma_{yield} = \sigma_o + k_y d^{-1/2}$$

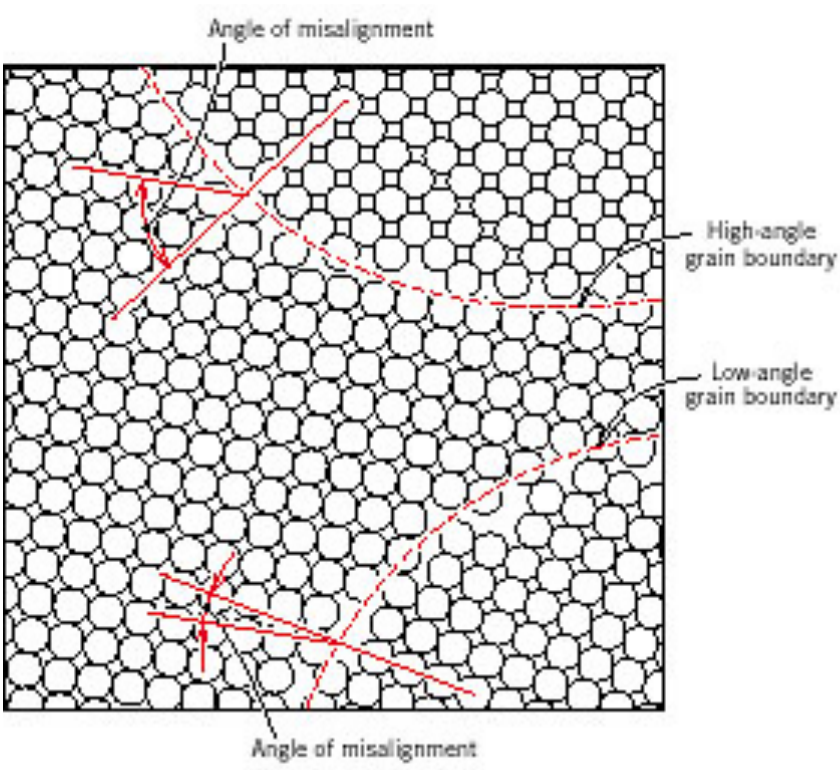


FIGURE 4.7 Schematic diagram showing low- and high-angle grain boundaries and the adjacent atom positions.

- High-angle grain boundaries
  - Dislocations may not traverse grain boundaries during deformation
  - A stress concentration ahead of a slip plane in one grain may activate sources of new dislocation in an adjacent grain.

- Small-angle grain boundaries
  - Not effective in interfering because of slight misalignment

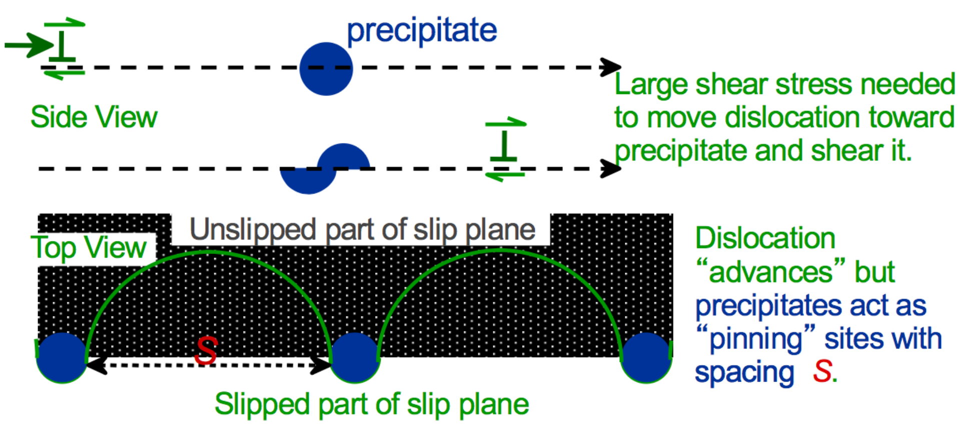
- Twin boundaries
  - Effectively block slip and increase the strength of the material

- Boundaries between two different phases
  - Impediment (obstacle/barrier) to movements of dislocations
  - Important in strengthening complex alloys

4. Precipitation and Dispersion Strengthening Mechanisms

- Hard precipitates are difficult to shear.

  Ex: Ceramics in metals (SiC in Iron or Aluminum).



- Result: $\sigma_y \sim \frac{1}{S}$

4. Aging and Precipitation strengthenning

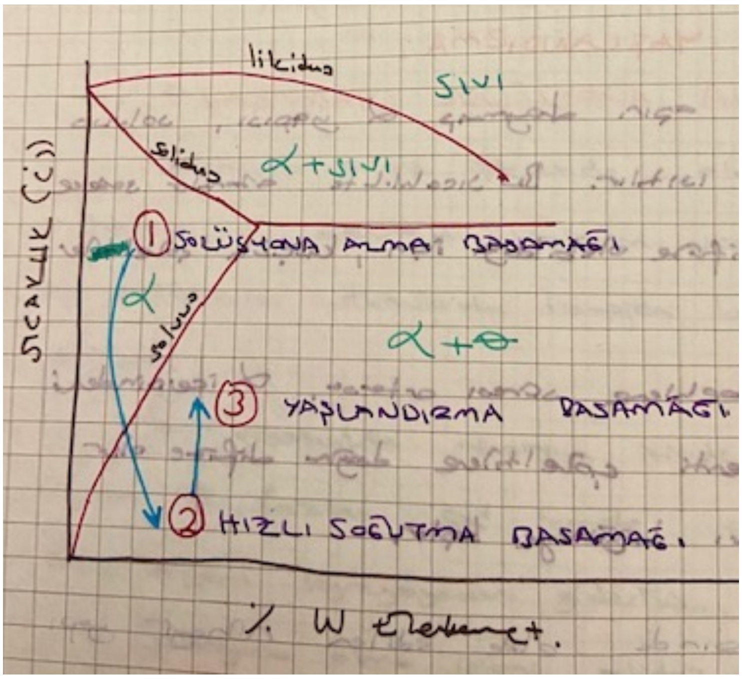
Üniform olarak dağılmış nanoboyutlu koherent parçaların daha yumuşak ve sünek matriks içine çökelmesi esasına dayanır. Yaşlanma ile malzemenin akma sınırı çok kolay ısıl işlemler yardımıyla malzeme yoğunluğu artmadan yükseltilebilir. Örneğin alüminyumun akma dayanımı 20.000 psi'dan 60.000 psi'a çıkarılabilir (3 katına).

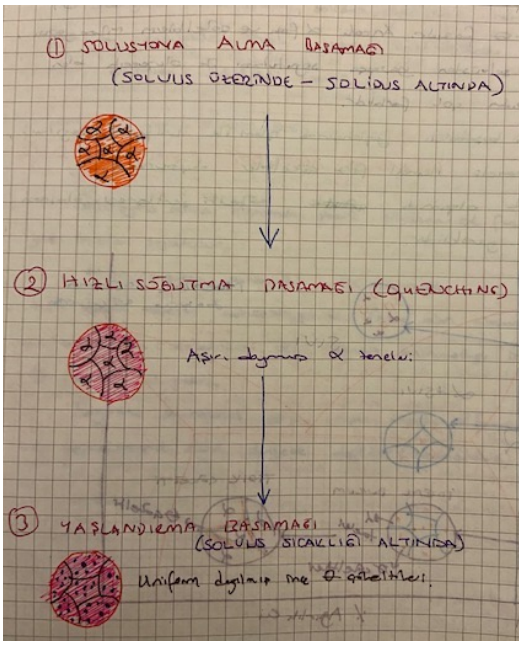
Aging (YAŞLANMA) ISIL İŞLEMİ

1. Basamak: Solüsyona alma (Solution treatment)
2. Basamak: soğutma (quenching)
3. Basamak: Yaşlandırma (Aging)

1. Solüsyona alma işleminde alaşım solvus sıcaklığı üzerinde ve ötektoid dönüşüm sıcaklığının altında bir sıcaklıkta tutularak homojen bir alfa α katı fazı oluşturması sağlanır. Bu basamakta alaşımın içinde daha önceden çökelmiş tüm (θ) fazları alfa içinde çözülür ve yapıdaki segregasyonlar giderilir.
2. Soğutma: Solüsyona alma işleminden sonra tamamen alfa (α) fazı içeren yapı hızlı soğutulur. Hızlı soğutma sırasında α içerisinde katı çözelti çözünürlüğünden fazla olan alaşımların çekirdeklenerek çökelmesi için zaman tanınmadığı için (θ) fazları oluşmaz. Soğuma sonrası yapı aşırı doymuş (α) fazıdır ve termodinamik olarak dengede değildir (kararsız yapı).
3. Yaşlandırma aşamasında aşırı doymuş (α) yapısı, solvus sıcaklığının altına ısıtılır. Bu sıcaklıkta atomlar sadece küçük mesafelerde difüze olabildiği için küçük çökeltiler oluşur. Bu sıcaklıkta bekleme süresi artarsa α içerisindeki fazla alaşım elementi çözeltilere doğru difüze olur ve çözelti parçacıkları büyümeye başlar. Yaşlandırma sonrası elde edilen nihai yapı $\alpha + \theta$ fazıdır.

4. Aging and Precipitation strengthenning

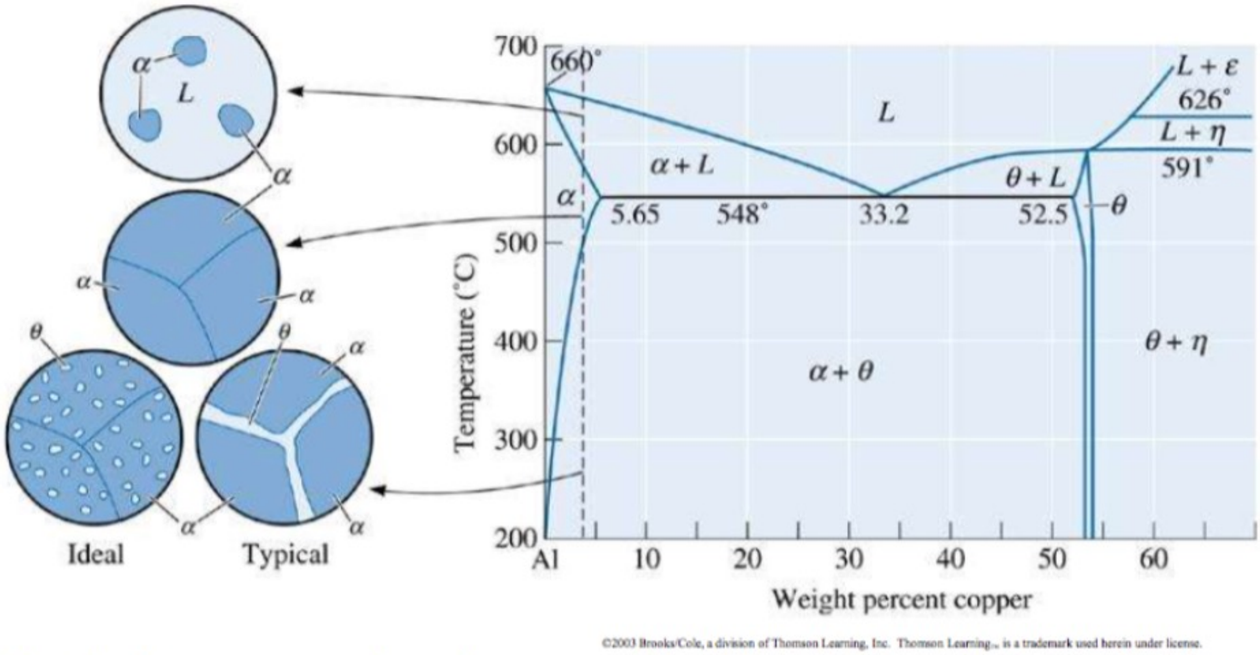




Aging (YAŞLANMA) Heat Treatment

1. Basamak: Solüsyona alma (Solution treatment)
2. Basamak: soğutma (quenching)
3. Basamak: Yaşlandırma (Aging)

4. Aging and Precipitation strengthenning

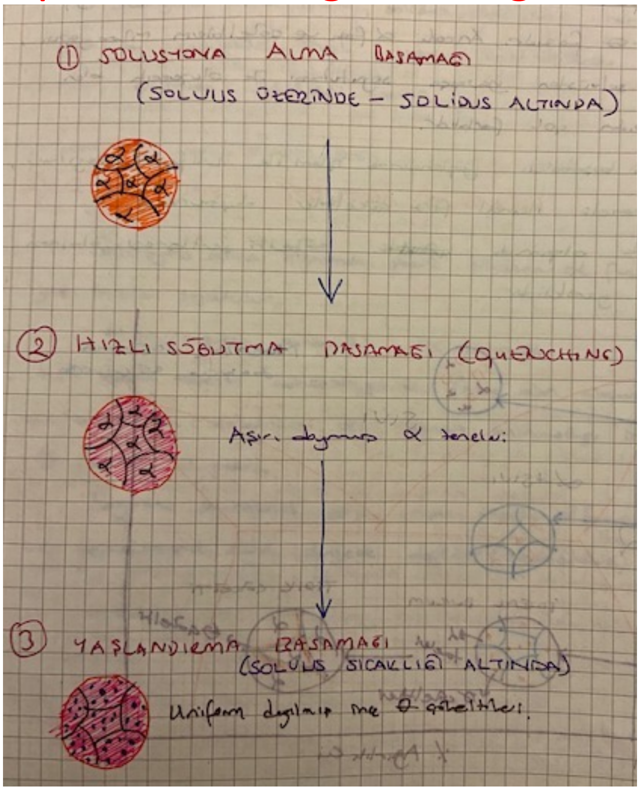


The aluminum-copper phase diagram and the microstructures that may develop curing cooling of an Al-4% Cu alloy.

4. Aging and Precipitation strengthenning

Aging (YAŞLANMA) Heat Treatment

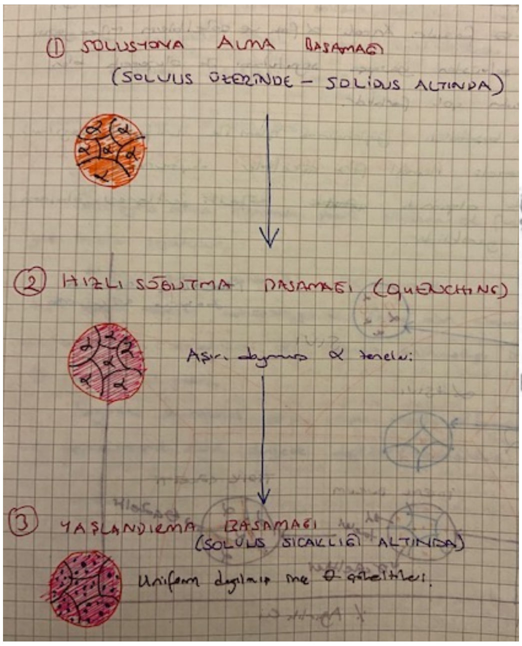
1. Basamak: Solüsyona alma (Solution treatment)
2. Basamak: soğutma (quenching)
3. Basamak: Yaşlandırma (Aging)

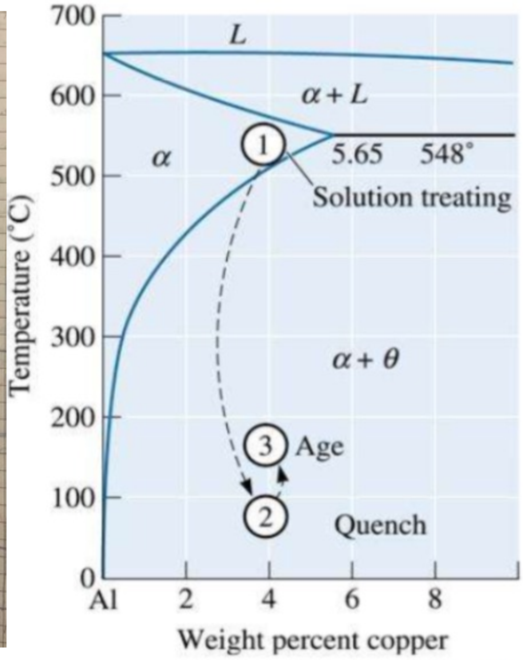


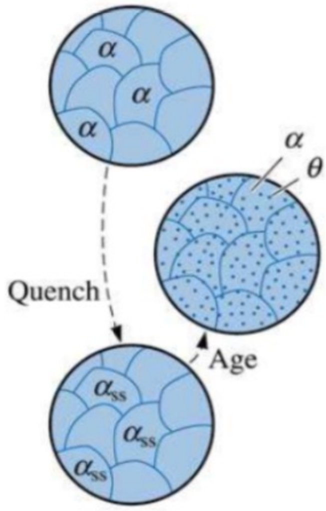
Aşırı doymuş alfa taneleri

Homojen dağılmış ince deta çökeltileri

4. Aging and Precipitation strengthenning

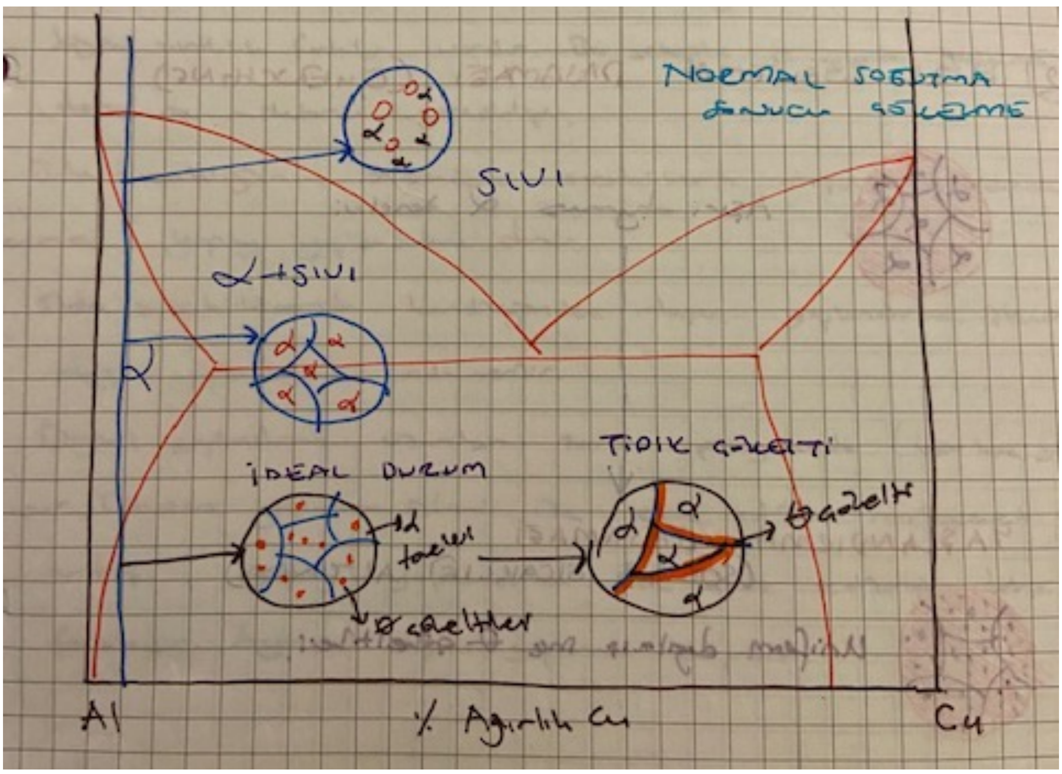






4. Aging and Precipitation strengthenning

Al-Cu

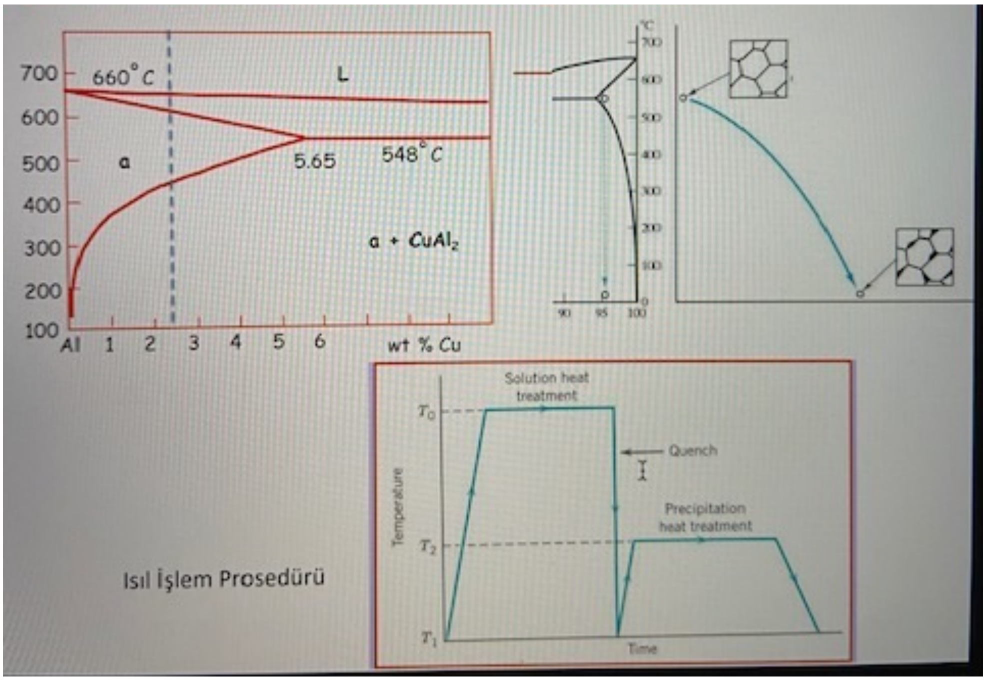


4. Aging and Precipitation strengthenning

- Çökelme sertleşmesi veya yaşlandırma sertleşmesi, yapıda, yüksek sıcaklıkta çözünebilen, düşük sıcaklıklarda sınırlı bir çözünürlüğe sahip olan ikinci bir fazın olmasını gerektirir.
- Mikroyapıda çökelen ikincil faz tanelerinin dayanımı artırmak için kullanıldığı yöntemlerden birisidir.
- Çok küçük ve sert olan bu taneler dislokasyonların hareketini zorlaştırmakta ve böylece de dayanımın artmasını sağlamaktadır.
- Çökelme sertleşmesinde şu faktörler önemlidir:
  - Tane boyutu ve hacim oranı
  - Tanenin şekli
  - Tane ve matris arasındaki sınırın türü(bağdaşıklık)
  - Tanenin mekanik dayanımı (elastik modülü, akma dayanımı)

4. Precipitation strengthenning

4. Yaşlanma veya Çökelme/Çökelti Sertleşmesi



4. Aging and Precipitation strengthenning

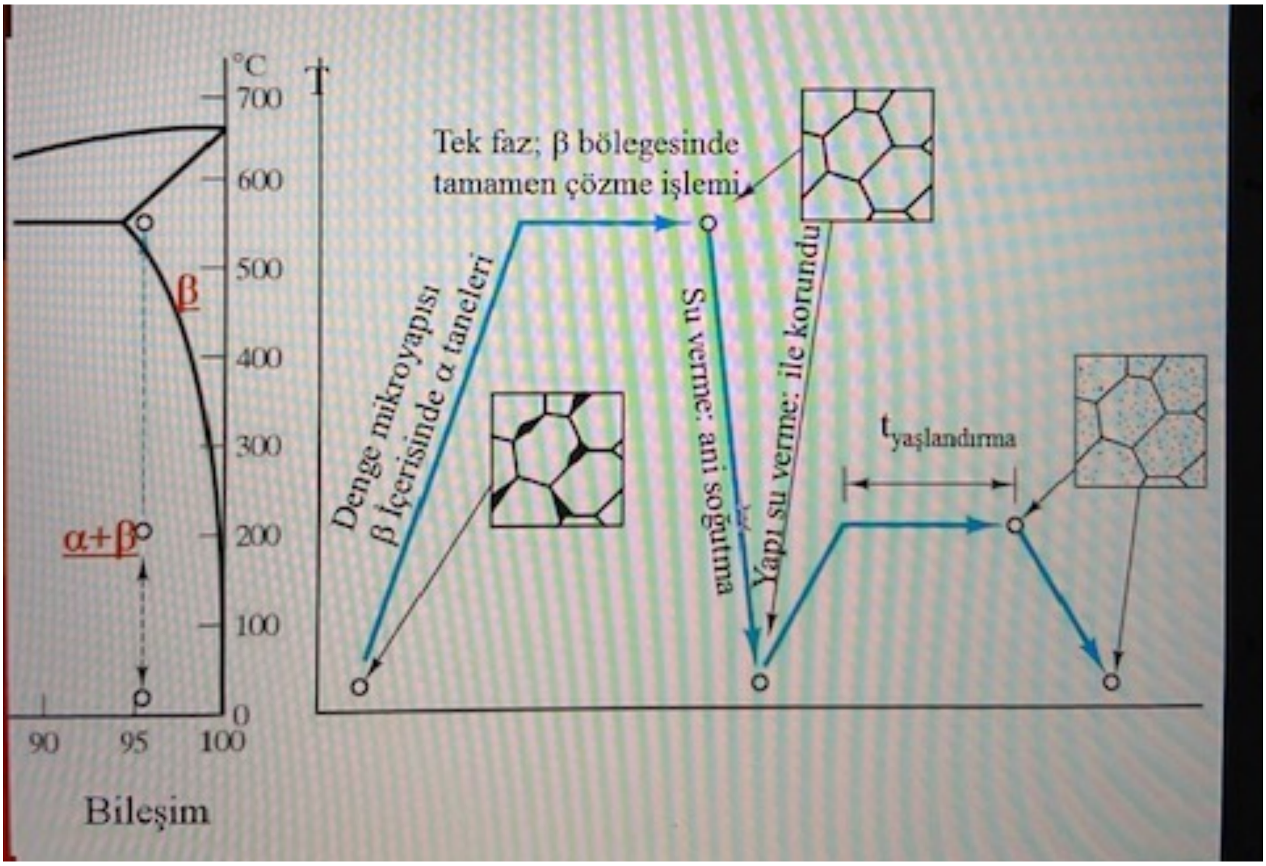
YAŞLANMA ISIL İŞLEMİ

1. Basamak: Solüsyona alma
2. Basamak: Soğutma
3. Basamak: Yaşlandırma

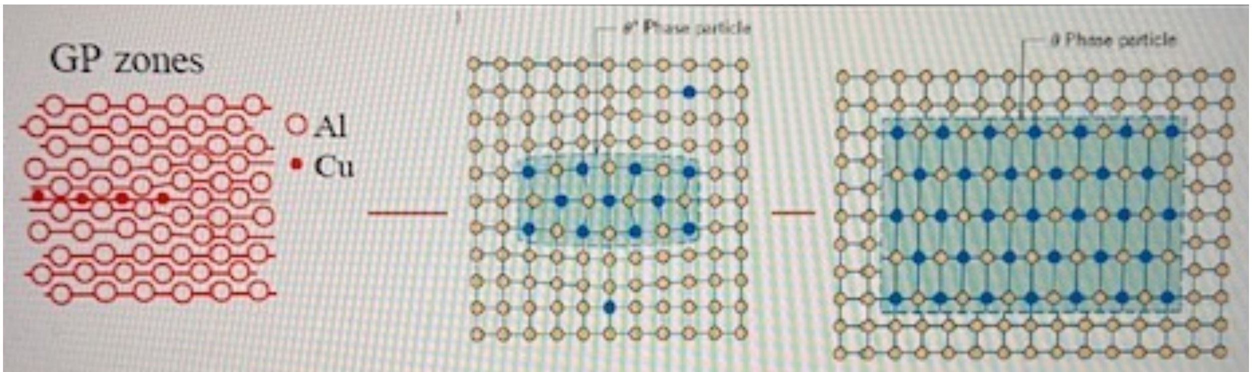
ÇÖKELME SERTLEŞMESİNİN AŞAMALARI

- **Çözündürme işlemi** (solution treatment): Malzeme tek faz bölgesine ısıtılarak çökelecek olan sert 2. faz, tek faz içerisinde tamamen çözülür.
- **Ani soğutma** (Quenching): Oda sıcaklığına ani soğutma ile 2. fazın çökelmesi engellenir ve aşırı doymuş katı çözelti elde edilir.
- **Yaşlandırma işlemi**(Aging)nde; aşırı doymuş katı çözelti, çözündürme sıcaklığından daha düşük olan yaşlandırma sıcaklığına tekrar ısıtılarak çok küçük bağdaşık (koherent) 2. faz tanecikleri çökeltilir. (Bu çökeltiler dislokasyonlara engel teşkil ederek malzemenin dayanımını arttırır).
- **Aşırı yaşlanma**: çökelmelerin çok büyüyerek bağdaşıklığın (koherentliğin) kaybolması (bu durum istenmez).

4. Aging and Precipitation strengthenning

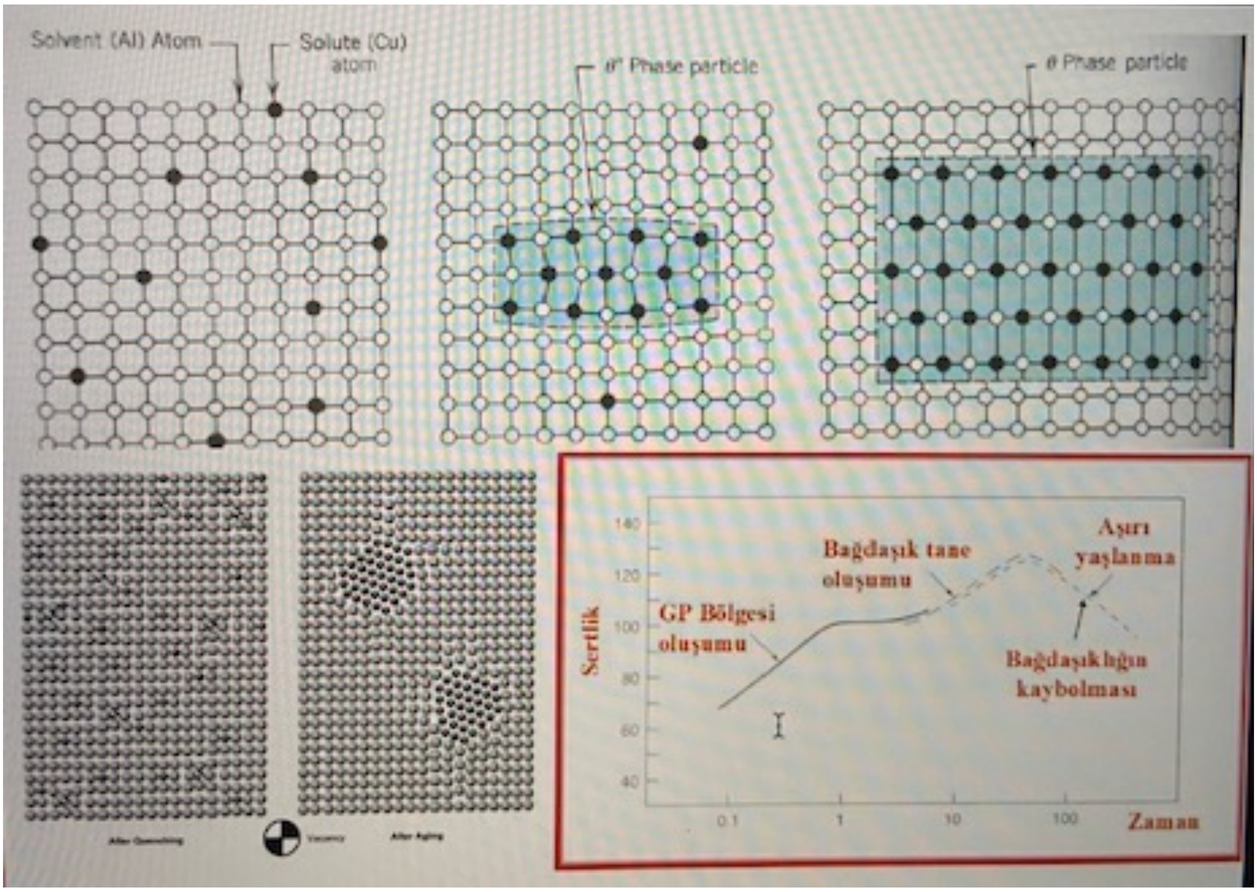


4. Aging and Precipitation strengthenning

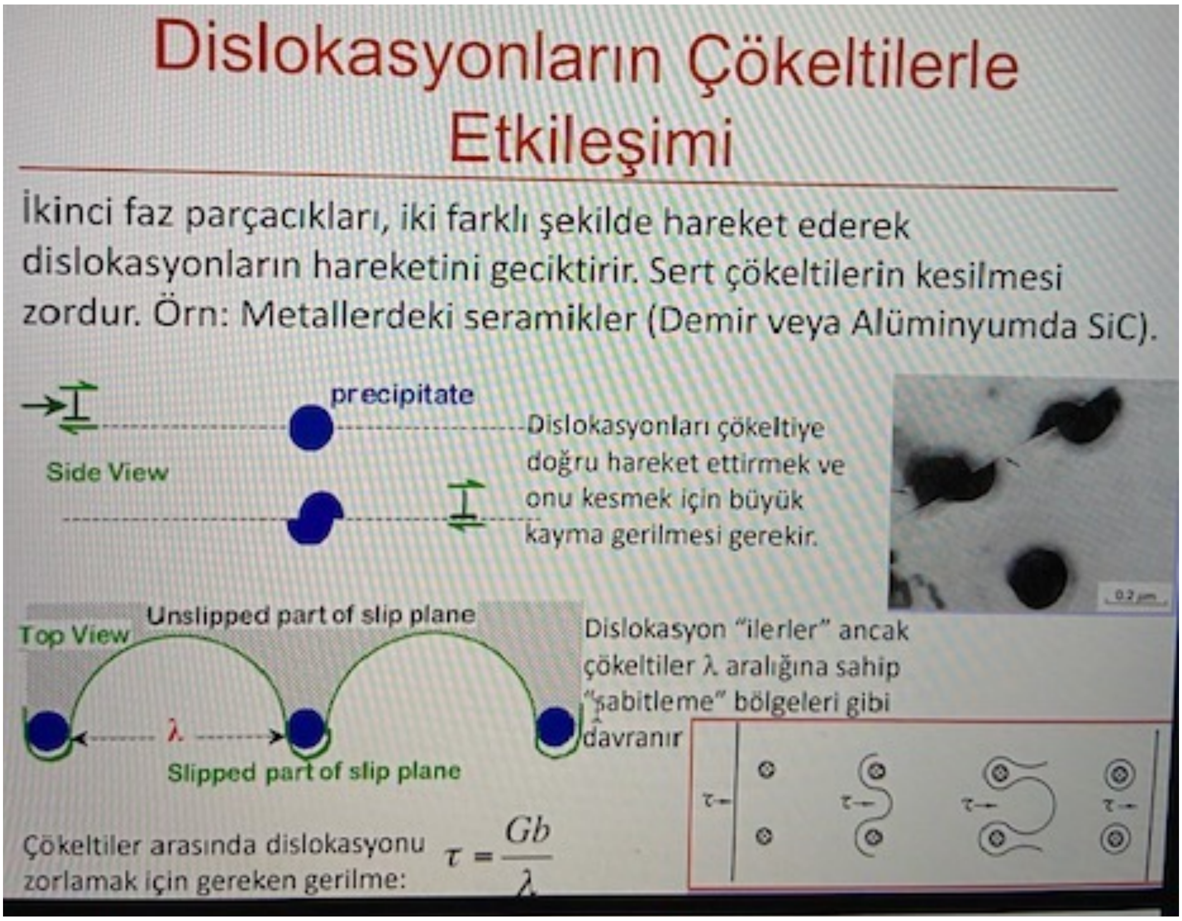


- Çökeltmenin ilk aşamasında, çok küçük koherent-GP bölgeler (Guinier preston zones) oluşur,
- GP bölgeleri genelde dislokasyon altındaki boşluklarda çekirdeklenir (sistemin enerjisini düşürmek için) ve dislokasyon hareketlerini engeller.
- Bu bölgeler, daha büyük bağdaşık (koherent) çökeltilere dönüşür. Bağdaşık çökeltiler kafesi aşırı gererek dayanım artışı oluştururlar.
- Daha sonra sıcaklığın veya zamanın gerekenden yüksek tutulması halinde tane büyümesi gerçekleşir. Dayanım düşmeye başlar.

4. Aging and Precipitation strengthenning



4. Aging and Precipitation strengthenning



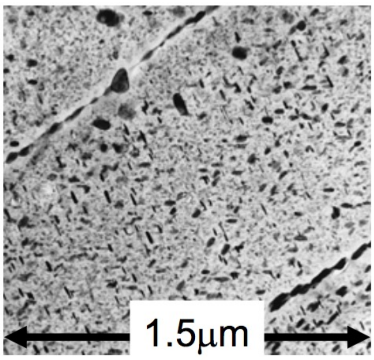
4. Aging and Precipitation strengthenning

Precipitation Strengthening

- Internal wing structure on Boeing 767

Adapted from chapter-opening photograph, Chapter 11, *Callister 5e.* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

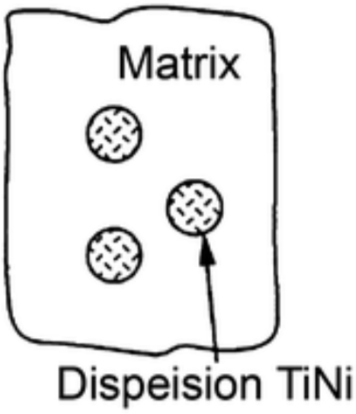
- Aluminum is strengthened with precipitates formed by alloying.



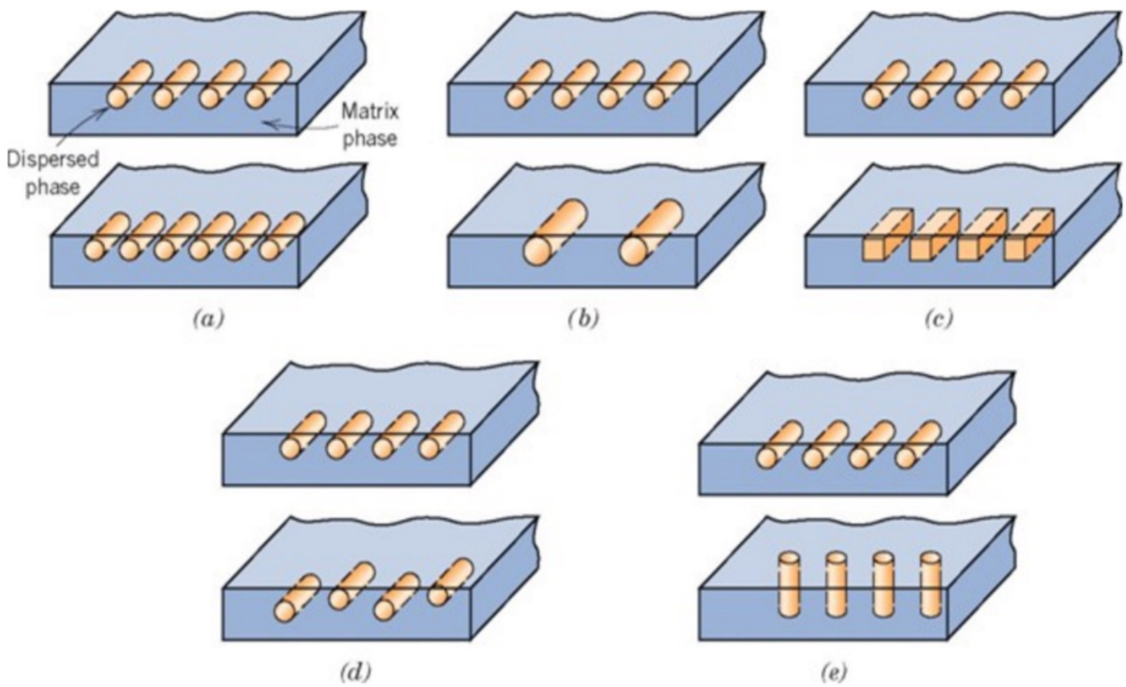
Adapted from Fig. 11.26, *Callister 7e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

5. Dispersion Strengthening

- **Dispersion strengthening** is a well known procedure used for improving the hardness of metallic materials.
- Dispersion-strengthened means of strengthening materials where in very small particles (usually less than 0.1 µm) of a hard yet inert phase are uniformly dispersed within a load-bearing matrix phase
- Dispersed phase may be metallic or nonmetallic,generally oxide materials are used.



5. Dispersion Strengthening



5. Dispersion Strengthening

- Dispersion strengthened alloys can be considered as composites because there is little or no interaction between the two components and the reinforcement is not soluble in the metal matrix.

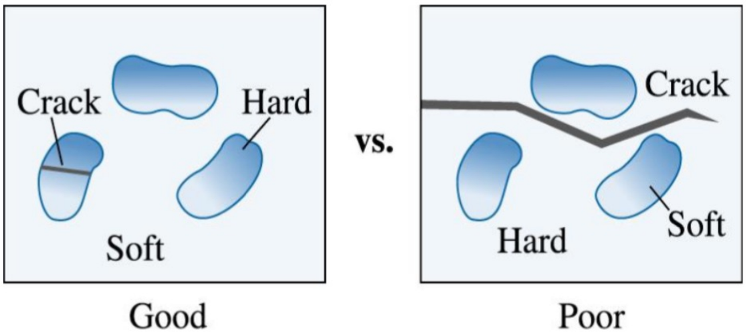
5. Dispersion Strengthening

- **Dispersoids** can be introduced by a variety of methods but "Mechanical Alloying" was a breakthrough enabling obtaining of a homogeneous dispersoid distribution.
- The dispersoids are usually 10-250 nm diameter oxide particles and are introduced by physical means rather than chemical precipitation.
- They are located within the grains and at grain boundaries but are not coherent with the matrix as in precipitation hardening.
- The dispersed particles are sufficiently small in size to impede dislocation movement and thus improve yield strength as well as stiffness.

5. Dispersion Strengthening

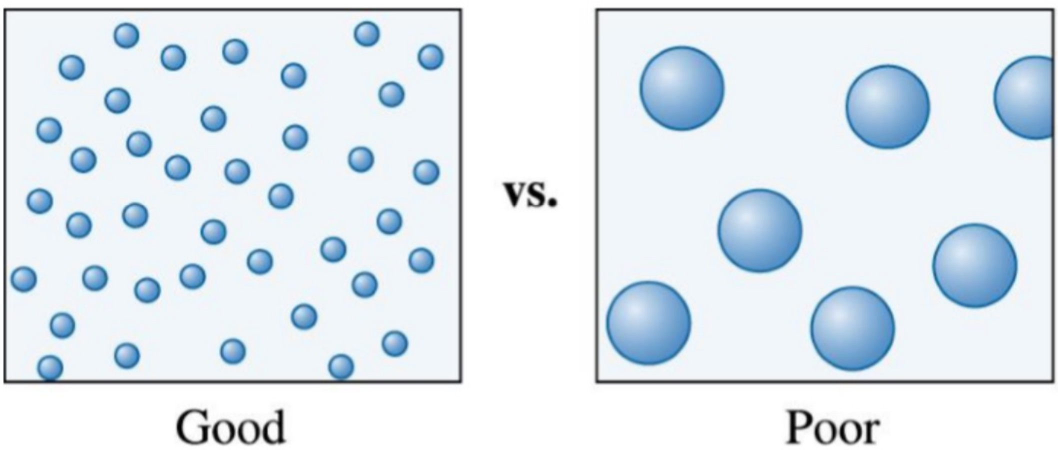
Requiring of good dispersion hardening

✓ Dispersed phase should be hard and discontinuous to prevent crack or load coming on material.



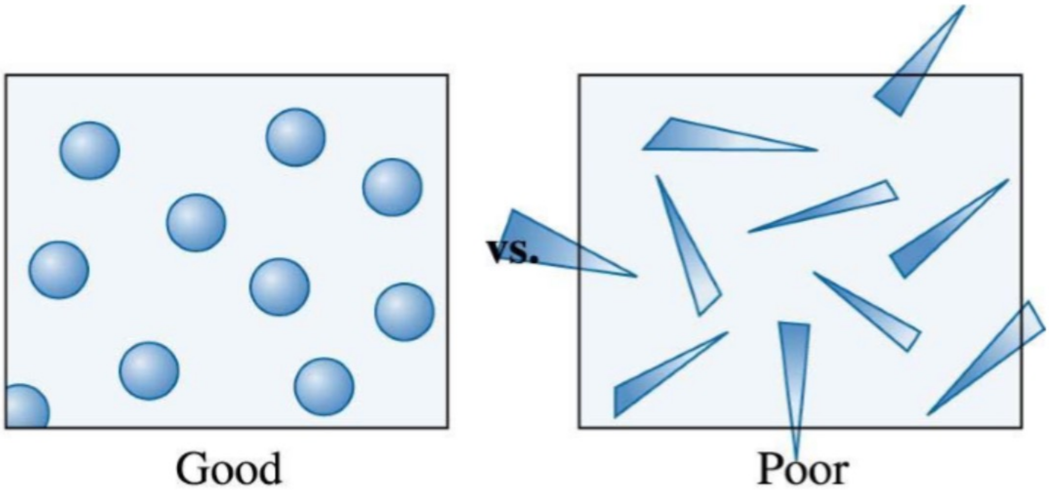
5. Dispersion Strengthening

✓Dispersed phase should be small and much because of increasing number of absorbing atoms.



5. Dispersion Strengthening

✓Dispersed phase's particles should be spherical form instead of acicular form to absorb occuring fructure and not to occur any crack or fructure in material.



5. Dispersion Strengthening

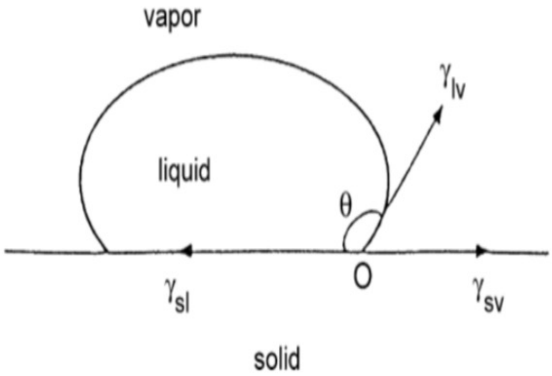
WETTABILITY

In dispersion hardening, wettabilty is more important to generate a strong enough interfaceto allow effective transfer and distributionof a load fromthe matrix to the reinforcement.

Wettability can be define as the ability of a liquid to spread on a solid surface and represent the extent of initimate contact between a liquid and a solid. It can be describe by the angle of contact between a drop of liquid resting on a solid substrate.

The contact angle at equilibrium, θ, is determine by the following equation, often referred to as the Young –Dupre equation:

5. Dispersion Strengthening



$\gamma_{sv} = \gamma_{sl} + \gamma_{lv}.\cos\theta$ (Eqs :

$Wa = \gamma_{lv} + \gamma_{sv} - \gamma_{sl}$ (Eqs :

(Wa: work of adhesion)
Combine Eqs (1) and (2);

$Wa = \gamma_{lv}.(1+\cos\theta)$

1. θ = 0, for perfect wetting
2. θ = 180, no wetting, and for
3. 0 < θ <180, ther will be partially wetting.

Dispersion Hardening big and small Particles

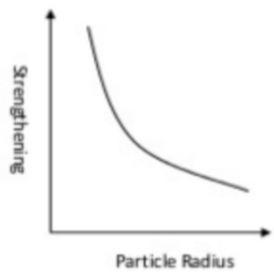
Strengthening effect can be estimated as:

$$\Delta\sigma \approx 6G(\frac{r}{b})^{0.5} f^{0.5} \varepsilon^{1.5}$$

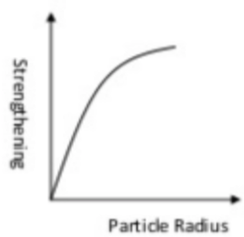
G – Shear Modulus
r – Particle radius
b – Burgers vector
f – volume fraction of particles
ε - strain field factor

$$\lambda = \frac{4(1-f)r}{3f}$$

f – volume fraction of particles
r – particle radius



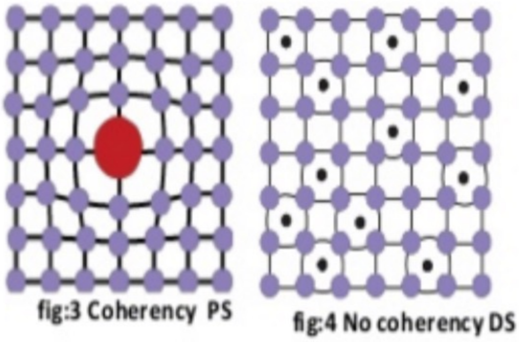
Curve for small particles



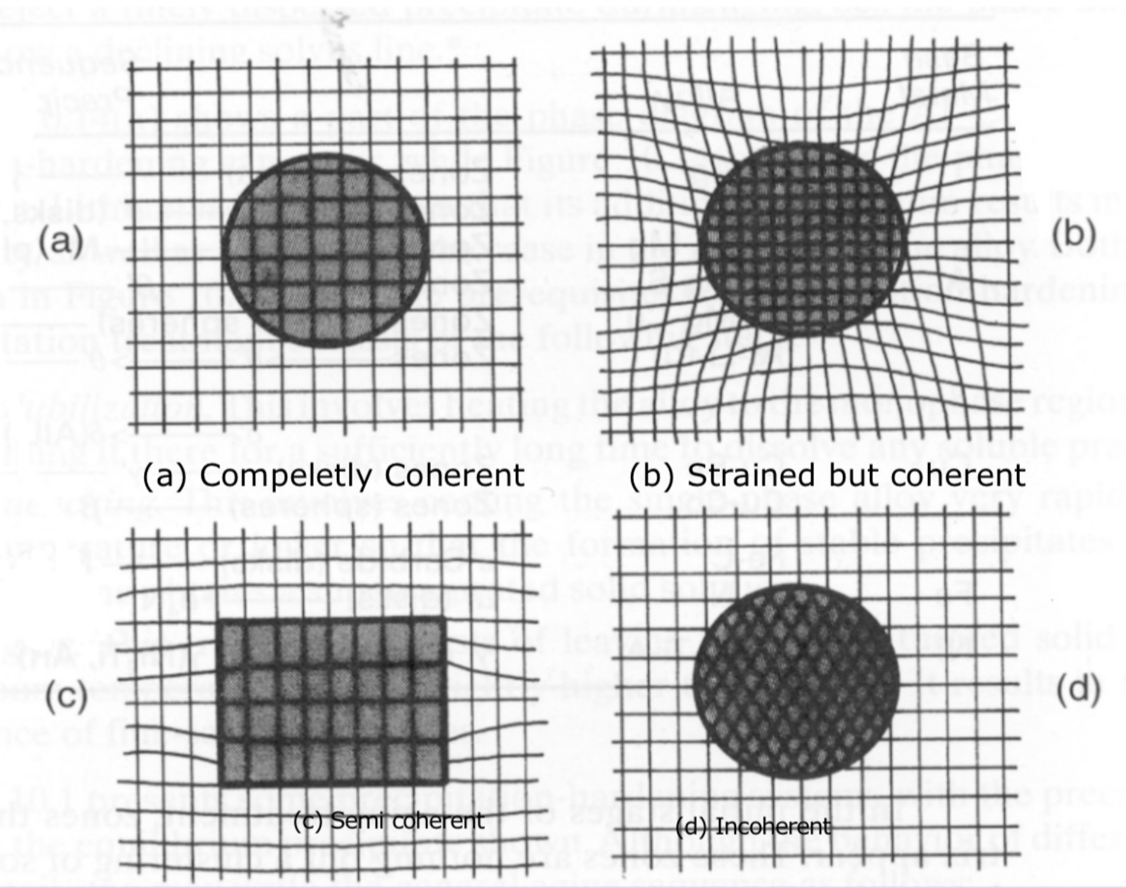
Curve for big particles

Difference Between Precipitation and Dispersion Strengthening

- Coherency ocur in PS but No coherency presense in DS.
- DS stable at all temperatures but PS is not stables
- Time factor not important for DS but PS time factor important
- Any alloy can be made in case DS
- In DS chemical stability is increase than PS
- PS-isotropic and DS-Anisotropic



Coherency: Misfit between particles and matrix produces strain field→ **improving strength.**



Advantage And Disadvantages

Advantages:

- Higher creep resistance
- Higher temperature sustain
- Automotives industries
- Aerospace areas
- Sporting good industries

Disadvantages:

- Not use for only higher strength purpose
- Uniform distrubition of the particles

Dispersion strengthened (higher Tech..)

Similar to precipitation hardening

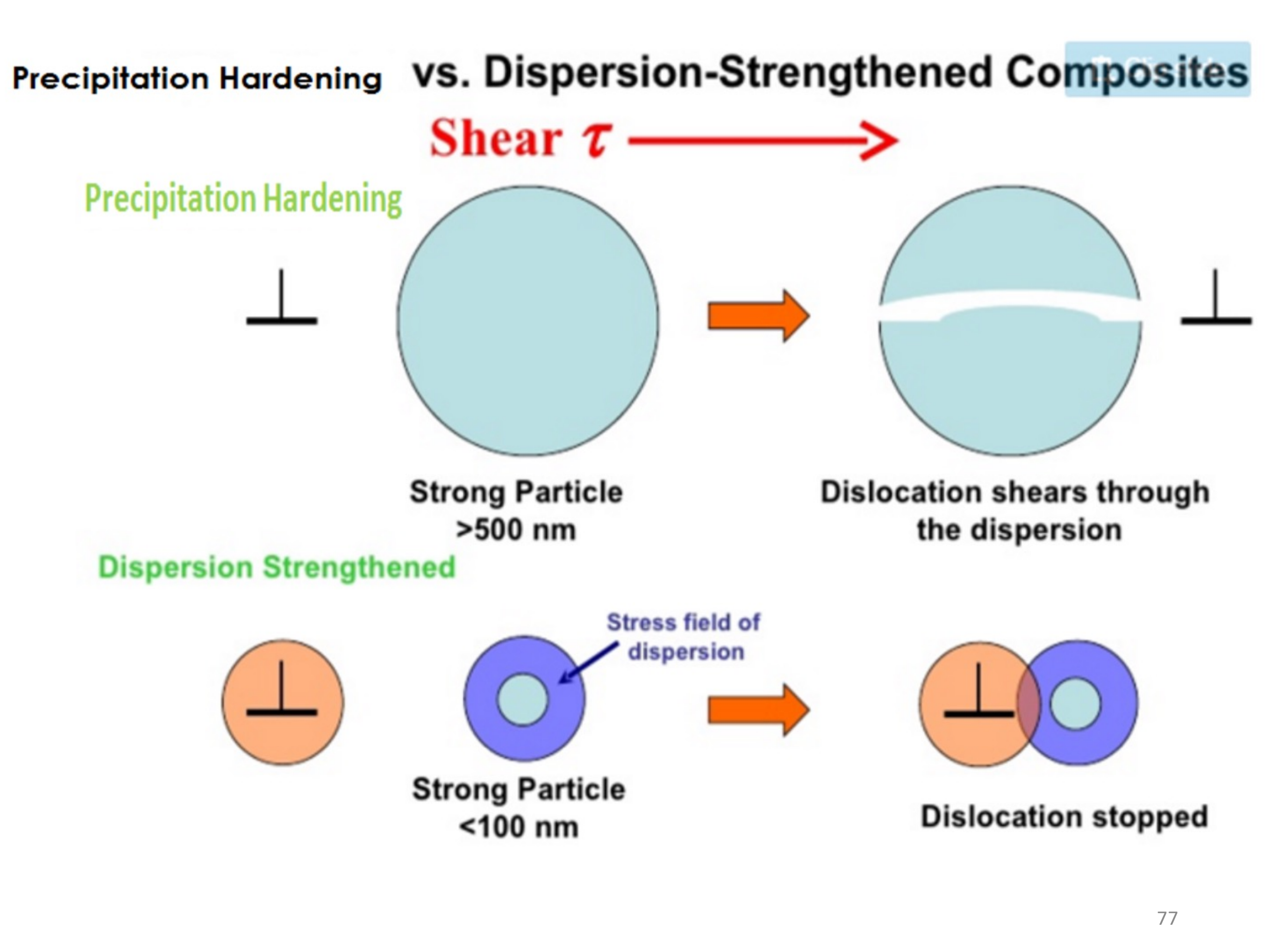
- Strengthening is not as good as for precipitation hardening at low temperatures
- At higher temperatures the properties are generally better.

Dispersion Strengthened Composites:

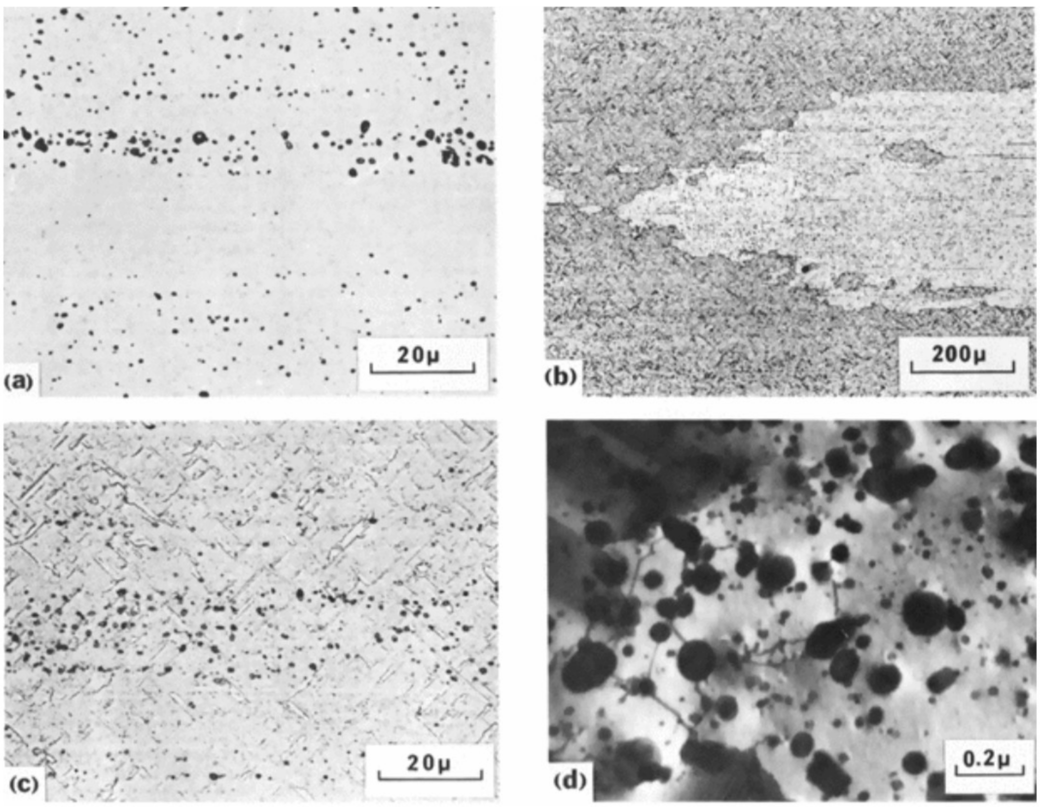
- Small particles (10 to 100nm)
- Matrix bears most of the applied load
- Particles hinder or impede motion of dislocations
- Plastic deformation is restricted
- İmproves yield and tensile strength.

Examples:

- Thoria dispersed nickel (Ni with up to 3 vol % ThO_2 particles)
- Sintered aluminium powder (Al matrix with Al_2O_3 coated Al Flakes)



Structure Of TD-NiC



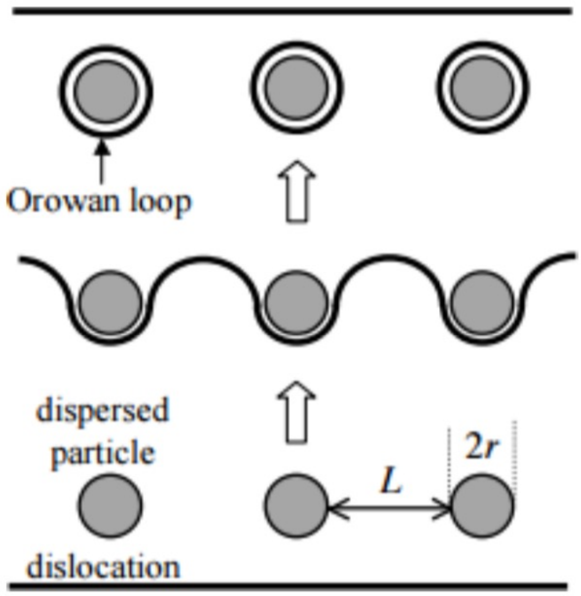
(a) Stringers of internal oxide (b) large, elongated grain morphology (c) annealing twins and (d) transmission micrograph of substructure

Absolutely Strong Obstacles

Orowan Mechanism:

- The dislocation bow out between two particles
- Yielding occurs when the bowed-out dislocation becomes semi-circular in shape.
- After the yielding, the dislocation leaves Orowan loops around the particles
- The formation of the Orowan loops makes the dislocation motion more and more difficult. This results in large work-hardening.

Orowan Mechanism

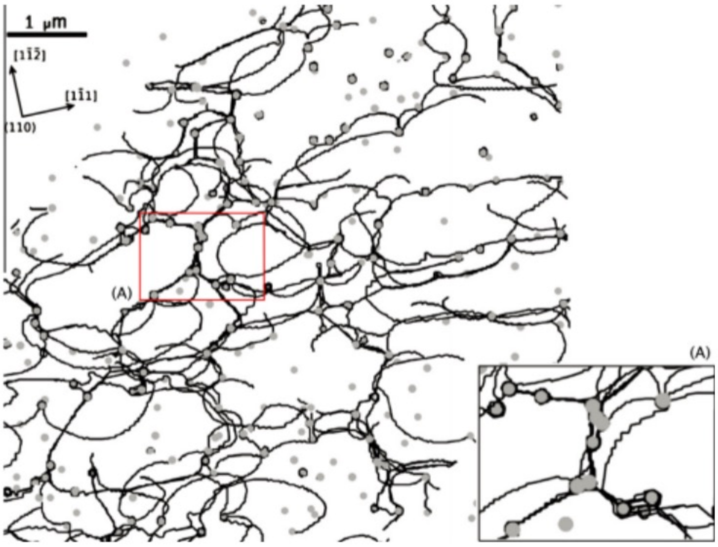


Orowan Mechanism For Dispersion Hardening

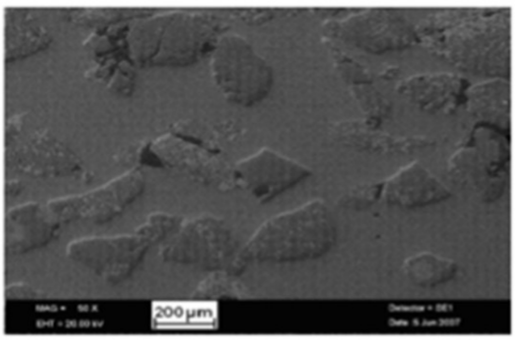
$$\tau = \frac{\mu b}{L}$$

CRSS for the Orowan mechanism (Orowan stress)

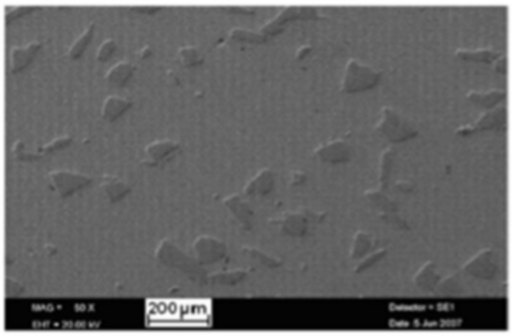
Orowan Mechanism



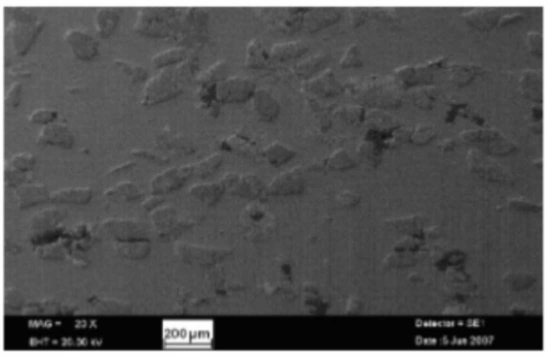
Simulated microstructure resulting from the interaction between a single slip system with a random distribution of carbides. s = 75 MPa and c = 1%. The thin foils extracted from the simulated volume have a thickness of 0.2 lm and are parallel to the dislocation glide plane. The enlargement (A) shows the formation of dipoles and multipoles aligned along the smallest carbide spacing.



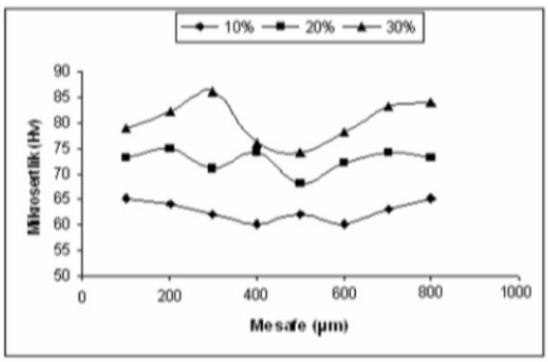
Al matrix 10 % B_4C reinforced composite



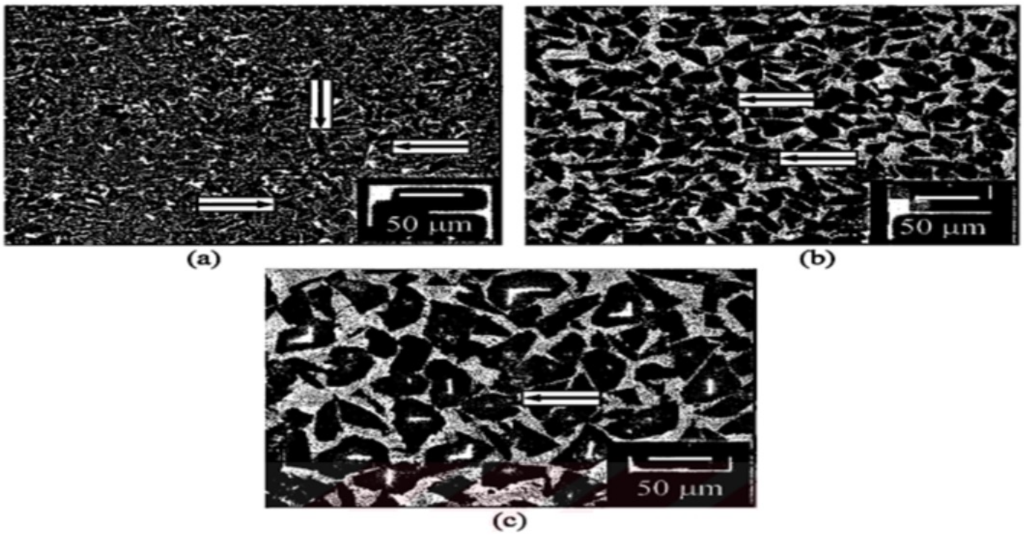
Al matrix 20 % B_4C reinforced composite



Al matrix 30 % B_4C reinforced composite



Al/B_4C composites samples of microhardness graphic



Microstructure of (a) 13 µm, (b) 23 µm, (c) 37 µm SiC reinforced materials Al matrix composite

Matris	SiC Takviye boyutu (µm)	Hacim Oranı (%)		
		SiC	Porozite	Matris
Saf Al	13	61.0±3.0	6.2±0.6	32.9±2.5
	23	60.2±0.7	6.1±2.7	33.7±2.06
	37	60.0±1.0	3.1±0.9	36.6±0.5

Malzeme	SiC Takviye boyutu (µm)	Basma Deneği			Eğme Deneyi	Darbe Deneği
		Basmada Akma Mukavemeti (N/mm^2)	Maksimum Basma Mukavemeti (N/mm^2)	Basmada % Kısalma Oranı	Eğme Mukavemeti (N/mm^2)	Spesifik Darbe enerjisi x 10^{-3} (j/mm^2)
Saf Al	13	267.1±22,2	381.4±40,2	5.6±1.5	311.4±27.6	28.9±3.5
	23	184.2±23,0	340.3±27,1	6.9±2.1	233.4±11.2	23.1±3.8
	37	112.1±21,7	296.0±22,5	13.1±3.0	183.3±6.0	8.8±0.8

Mechanical properties of produced composites

Thank you for your attention