In the name of God

Technical English Language

for Materials Engineering and Metallurgy

Lesson 3: Mechanical Metallurgy

Taught by:

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1. Dislocations

In materials science, a dislocation is a crystallographic defect, or irregularity, within a crystal structure. The presence of dislocations strongly influences many of the properties of materials. The theory of dislocations was originally developed by Vito Volterra in 1905. Some types of dislocations can be visualized as being caused by the termination of a plane of atoms in the middle of a crystal. In such a case, the surrounding planes are not straight, but instead bend around the edge of the terminating plane so that the crystal structure is perfectly ordered on either side. There are two primary types of dislocations: edge dislocations and screw dislocations. Mixed dislocations are intermediate between these. In Fig. 1, the Transmission Electron Micrograph of dislocations in titanium alloy is shown. Dislocation types include:

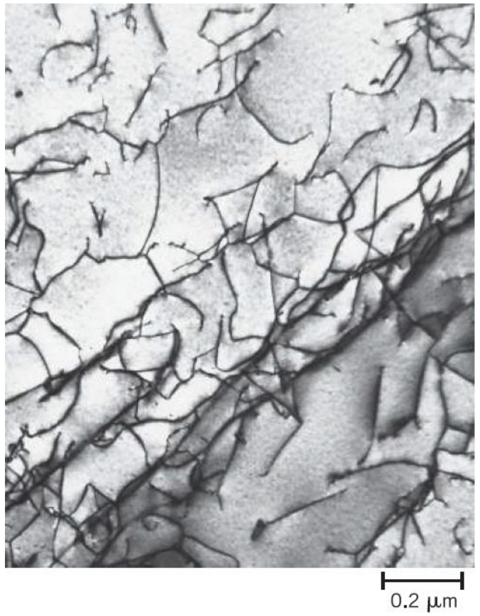

Fig. 1. A transmission electron micrograph of a titanium alloy in which the dark lines are dislocations, 50,000×.

- ***Edge Dislocations***

An edge dislocation is a defect where an extra half-plane of atoms is introduced mid way through the crystal, distorting nearby planes of atoms. When enough force is applied from one side of the crystal structure, this extra plane passes through planes of atoms breaking and joining bonds with them until it reaches the grain boundary.

- ***Screw Dislocations***

A screw dislocation is much harder to visualize. Imagine cutting a crystal along a plane and slipping one half across the other by a lattice vector. A screw dislocation is a dislocation in which atomic planes form a spiral ramp winding around the line of the dislocation.

- ***Mixed Dislocations***

In many materials, dislocations are found where the line direction and Burgers vector are neither perpendicular nor parallel. These dislocations are called mixed dislocations, consisting of both screw and edge character.

2. Strengthening Mechanisms

Plastic deformation occurs when large numbers of dislocations move and multiply so as to result in macroscopic deformation. In other words, it is the movement of dislocations in the material which allows for deformation. If we want to enhance a material's mechanical properties (*i.e.* increase the yield and tensile strength), we simply need to introduce a mechanism which prohibits the mobility of these dislocations. Whatever the mechanism may be, work hardening, grain boundary strengthening, solid solution strengthening/alloying, precipitation hardening and *etc*, they all hinder dislocation motion and render the material stronger than previously.

The stress required to cause dislocation motion is orders of magnitude lower than the theoretical stress required shifting an entire plane of atoms, so this mode of stress relief is energetically favorable. Hence, the hardness and strength (both yield and tensile) critically depend on the ease with which dislocations move. Dislocations may be pinned due to stress field interactions with other dislocations and solute particles, or physical barriers from grain boundaries and second phase precipitates. There are four main strengthening mechanisms for metals; however the key concept to remember about strengthening of metallic materials is that it is all about preventing dislocation motion and propagation. For a material that has been strengthened, the amount of force required to start irreversible deformation (plastic deformation) is greater than it was for the original material.

In amorphous materials such as polymers, amorphous ceramics (glass), and amorphous metals, the lack of long range order leads to yielding via mechanisms such as brittle fracture, crazing, and shear band formation. In these systems, strengthening mechanisms do not involve dislocations, but rather consist of modifications to the chemical structure and processing of the constituent material.

3. Fracture

In most structural failures, final fracture is usually abrupt after some sort of material or design flaw (such as a material defect, improper condition, or poor design detail) that is aggravated by a crack growth process that causes the crack to reach a critical size for final fracture. The cracking process occurs slowly over the service life from various crack growth mechanisms such as fatigue, stress-corrosion cracking, creep, and hydrogen-induced cracking. Each of these cracking mechanisms has certain characteristic features that are used in failure analysis to determine the cause of cracking or crack growth. In contrast, the final fracture is usually abrupt and occurs from cleavage, rupture, or intergranular fracture (which may involve a combination of rupture and cleavage).

✓ *Fracture mechanism*

Fracture mechanisms are termed "ductile," although these terms must be defined on either a macroscopic or microscopic level. This distinction is important, because a fracture may be termed "brittle" from an engineering (macroscopic) perspective, while the underlying metallurgical (microscopic) mechanism could be termed either ductile or brittle. For metallurgists, cleavage is often referred to as brittle fracture and dimple rupture is considered ductile fracture. However, these terms must be used with caution, because many service failures occur by dimple rupture, even though most of these failures undergo very little overall (macroscopic) plastic deformation from an engineering point of view.

The majority of structural failures are of the more worrisome type, brittle fracture, and these almost invariably initiate at defects, notches, or discontinuities. Cracks resulting from machining, quenching, fatigue, hydrogen embrittlement, liquid-metal embrittlement, or stress corrosion also lead to brittle fracture. In fact, the most prevalent initiator of brittle fracture is the fatigue crack. In contrast, service failure by macroscopic ductile failure is relatively infrequent (although the microscopic mechanisms of ductile fracture can ultimately lead to macroscopic brittle fracture).

4. Fatigue

Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue may culminate into cracks and cause fracture after a sufficient number of fluctuations.

Fatigue damage is caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain. If any one of these three is not present, a fatigue crack will not initiate and propagate. The plastic strain resulting from cyclic stress initiates the crack; the tensile stress promotes crack growth (propagation). Although compressive stresses will not cause fatigue, compressive loads may result in local tensile stresses. Microscopic plastic strains also can be present at low levels of stress where the strain might otherwise appear to be totally elastic.

✓ ***Fatigue mechanism***

During fatigue failure in a metal free of cracklike flaws, microcracks form, coalesce, or grow to macrocracks that propagate until the fracture toughness of the material is exceeded and final fracture occurs. Under usual loading conditions, fatigue cracks initiate near or at singularities that lie on or just below the surface, such as scratches. sharp changes in cross section, pits, inclusions, or embrittled grain boundaries.

Microcracks may be initially present due to welding, heat treatment, or mechanical forming. Even in a flaw-free metal with a highly polished surface and no stress concentrators, a fatigue crack may form. If the alternating stress amplitude is high enough, plastic deformation (*i.e.*, long-range dislocation motion) takes place, leading to slip steps on the surface. Continued cycling strains lead to the initiation of one or more fatigue cracks. Alternately, the dislocations may pile up against an obstacle, such as an inclusion or grain boundary, and form a slip band, a cracked particle, decohesion between particle and matrix, or decohesion along the grain boundary.

The initial cracks are very small. Their size is not known well because it is difficult to determine when a slip band or other deformation feature becomes a crack. Certainly, however, cracks as small as a fraction of a micron can be observed using modern metallographic tools such as the scanning electron microscope or scanning tunneling microscope. The microcracks then grow or link up to form one or more macrocracks.

- ✓ ***Fatigue failure process***

The fatigue failure process can be divided into five stages:

I. Cyclic plastic deformation prior to fatigue crack initiation;
II. Initiation of one or more microcracks;
III. Propagation or coalescence of microcracks to form one or more macrocracks;
IV. Propagation of one or more macrocracks;
V. Final failure.

5. Creep

Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly 0.5 T_m, where T_m is the absolute melting temperature.

✓ ***Creep stages***

Several aspects in creep are important. First, in creep diagram (strain versus time, Fig. 2) three regions are delineated: Change Stage I, or primary creep, which denotes that portion where the creep-rate (plastic strain-rate, $\dot{\varepsilon} = d\varepsilon/dt$), is changing, with increasing plastic strain or time. Analogously, under constant strain-rate conditions, the metal hardens, resulting in increasing flow stresses. Often, in pure metals, the strain-rate decreases or the stress increases to a value that is constant over a range of strain. The phenomenon is termed Stage II, secondary, or steady-state creep. Eventually, cavitations and/or cracking increase the apparent strain-rate or decrease the flow stress. This regime is termed Stage III, or tertiary creep, and leads to fracture. Sometimes, Stage I leads directly to Stage III and an "inflection" is observed.

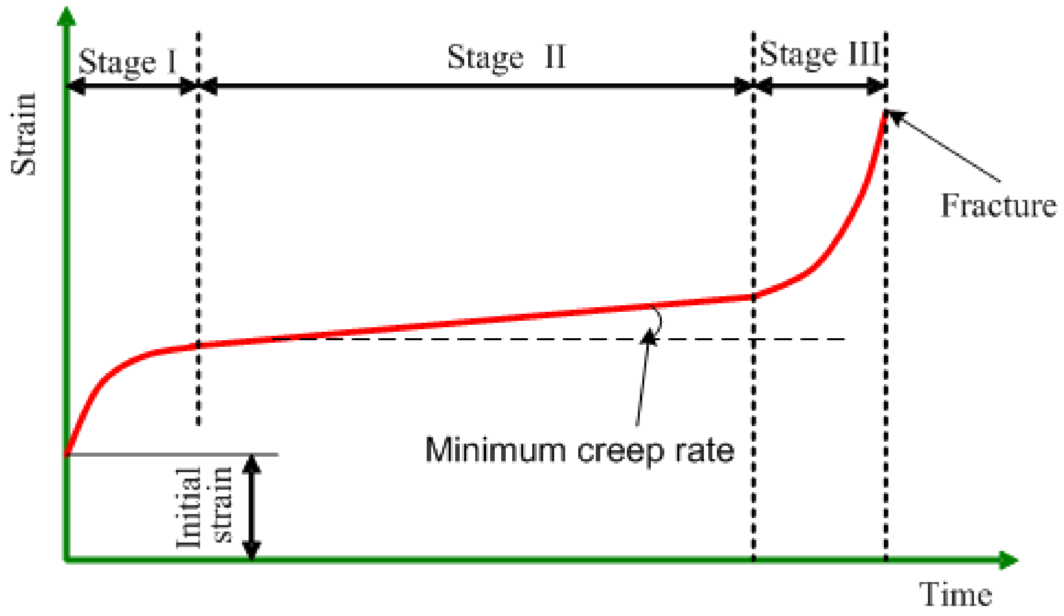

Fig. 2. Typical strain-time curve of a creep test.

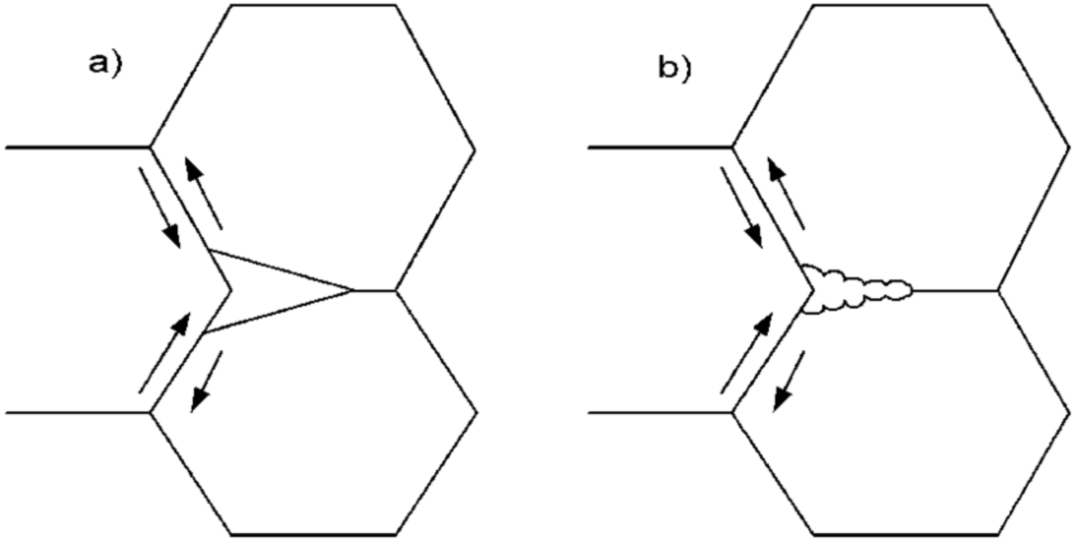

Fig. 3. Wedge (W-type) crack formed at the triple junctions by the creep.

Creep plasticity can lead to tertiary or Stage III creep and failure. It has been suggested that creep fracture can occur by W or Wedge-type cracking (Fig. 3), at grain-boundary triple points. Some have suggested that W-type cracks form most easily at higher stresses (lower temperatures) and larger grain sizes when grain-boundary sliding is not accommodated. In spite of, some have suggested that the Wedge-type cracks nucleate as a consequence of grain-boundary sliding.

- Choose the best choice using your knowledge of metallurgy and the details in the previous reading.

1. The study of plasticity is concerned with the ……..…….. between metal flow and ………… stress.

   a) forces, tensile b) interaction, required c) tension, compressive ✓ d) relationship, applied

2. Many creep-resistant alloys are in fact of the …………….. hardening type.

   a) propagation ✓ b) precipitation c) progression d) premature

3. Understanding of yielding in crystalline materials need to ………………. .

   a) fracture theory b) creep theory c) fatigue theory ✓ d) dislocation theory

4. The stiffness of a structure is of principal importance in many engineering applications. Stiffness is synonym with …………

   a) Inflexibility b) plasticity c) hardness ✓ d) elasticity

5. Cold working is done at a temperature below the value required for recrystallization, so no applicable ……….. takes place during deformation.

   a) reshaping b) crystallization ✓ c) recovery d) grain elongation

6. In which of the following phenomena the formation of new stress free and equiaxed crystals lead to lower strength and higher ductility:

a) recovery b) polymorphism c) nucleation ✓ d) recystaliztion

7. Hot tension test is a well-established method of ………... metal working. It can be performed at a known temperature (above $0.6T_m$) and deformation rate.

a) strengthening b) comparing c) stimulating ✓ d) simulating

8. The strength of fiberglass reinforced plastic is mainly …………… to the glass content of the material and the …………… of the glass fibers.

a) concerned, size ✓ b) related, arrangement c) traced, color d) subjected, arrangement

9. In many engineering systems, the overall ………… of the systems is directly limited by the capabilities of the component material.

a) damage ✓ b) performance c) deployment d) properly

10. At elevated temperatures metals ………. to fail by fracture ………… the crystal boundaries, while at low temperatures failure by trans-crystalline fracture is common.

a) try, across ✓ b) tend, along c) are prone, across d) are said, towards

6. Selected vocabulary

En	Fa	En	Fa
Catastrophic	فاجعه‌بار	Pile-up	تجمع
Coalesce	ادغام شدن	Relief	آزاد شدن
Creep	خزش	Screw dislocation	نابجایی پیچشی
Cavitation	ایجاد حفره	Scratch	خراش
Dislocation	نابجایی	Stain hardening	کرنش سختی
Dimple	گودی	Toughness	چقرمگی
Decohision	ناهمدوسی	Roughness	زبری
Fatigue	خستگی	Resilience	برجهندگی
Embrittlement	تردی	Necking	گلویی شدن
Irregularity	بی‌نظمی	Strengthening	استحکام‌بخشی
Initiate	آغاز شدن	Intergranular	بین دانه‌ای
Inclusion	آخال، ناخالصی	Transgranular	درون دانه‌ای
Notch	فاق، شیار	Rupture	گسیختگی
Propagation	اشاعه	Cleavage	ورقه ورقه شدن