

Material Sc. (MM1101) ASSINGMENT

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Topic:- Deformation of materials

- Recovery, recrystallisation and grain growth

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Contents:

- 1.Introduction
- 2.Terminologies
- 3.Annealing
- 4.Cold working
- 5.Recovery
- 6.Recrytallization
- 7.Grain growth

Introduction

The dynamic phenomenon of recovery , recrystallization and grain growth play a very important role in physical metallurgy, chemistry of the solid state Physics. Hence this review for the benefits for the teachers and students of the above mentioned disciplines.

Humpherys and Hatherly have stated that: “Recrystallization is related to annealing phenomena which happen during thermomechanical processing of materials has accepted as being mutually of technological importance and scientific interest.The phenomena include most widely studied in metals and there be vast literature spanning over about 150 years. Metallurgical research in this field is for metal forming processes for better products.”

Dierk Raabe [1] of Max-Planck Institute fuer Eisenforschung, Dusseldorf, Germany has written an excellent article in his book, Physical metallurgy, Fifth Edition, 2291-2397 (2014) on Recovery and Recrystallisation: phenomenon, Physics, Models, and Simulation.

He has mentioned the earliest investigators who had worked on deformation of metals and related phenomena. The works of Kalirher[2], Sorby[3] 1886 and 1887, Stead[4] 1898, Rosenhain[5] 1914, Ewing and Rosenhain [6] 1899a and 1899b, Alterhum[7] 1922, Carpenter and Elam[8] 1920, Czochoralski[9] 1927, Burgers and Louwerse [10] 1931 and Burgers [11] 1941.

Surprisingly , the excellent work of ErichSchmidt and Walter Boas[12] 1935/1950 has not been mentioned.

Terminologies:-

“The mechanism in which metals and alloys repair the structural damage caused by deformation, and incidentally through the resulting changes in the physical as well as mechanical properties and fix mechanisms which are induced by thermal treatment, are term as annealing, recovery, recrystallisation and grain growth.

We will define these terminologies one by one.

Annealing:

The term annealing is a very general term used in heat treatments of metals and alloys. It includes any cycle of heating and cooling of metallic materials, irrespective of temperatures, rates and terms involved in the cycle.

Depending upon the material being treated and the object of treatment, annealing operations may involve any of a very broad range of heating rates, soaking temperatures and soaking times and cooling rates. These methods can be used for stress-relieving, recrystallization and grain growth.

The purpose of annealing is to eliminate partially or completely the strain hardening produced by earlier mechanical forming operations, so that it can be put into service in relatively soft, ductile condition.

It must be realized that annealing involves recrystallization in which a combination of cold working and subsequent heating causes new stress-free crystals in a matrix which is itself stress free.

A full annealing treatment is a process intended to reduce the metal treated to its softness possible condition.

The term “annealing” is generally used, without qualifications or further description, as full anneal.

Cold Working:

Cold working is plastically deforming a material at a temperature below its recrystallization temperature. A material's recrystallization temperature is the temperature at which new grains with low dislocation density begin to replace the high dislocation density grains.

Cold working is a useful strengthening mechanism by virtue of strain hardening, but cold working is also useful for shaping materials.

In this experiment metal specimens were cold rolled, a form of cold working in which a metal specimen is forced through two rolls that have a gap in between each other. Cold rolling is often used commercially in order to produce sheet metal, plates, and bars.

Topic : Recovery Of Crystalline Material

Definition

The physical processes that fall under the designations of recovery, recrystallization and grain growth are often difficult to distinguish in a precise manner. Doherty *et al.* (1998) stated:

"The authors have agreed that ... recovery can be defined as all annealing processes occurring in deformed materials that occur without the migration of a high-angle grain boundary"

Thus the process can be differentiated from recrystallization and grain growth as both feature extensive movement of high-angle grain boundaries.

If recovery occurs during deformation (a situation that is common in high-temperature processing) then it is referred to as 'dynamic' while recovery that occurs after processing is termed 'static'. The principal difference is that during dynamic recovery, stored energy continues to be introduced even as it is decreased by the recovery process - resulting in a form of dynamic Equilibrium.

Process

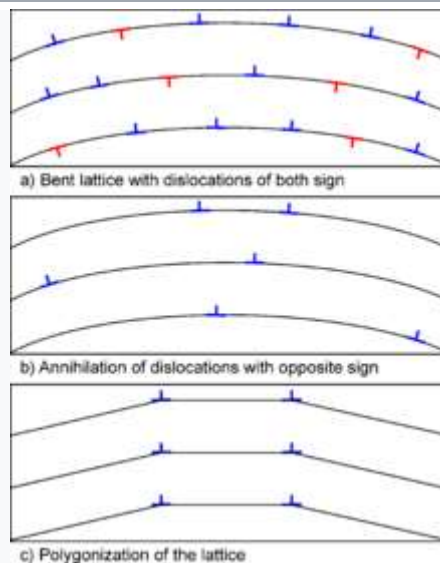


Fig 1. The annihilation and reorganisation of an array of edge dislocations in a crystal lattice

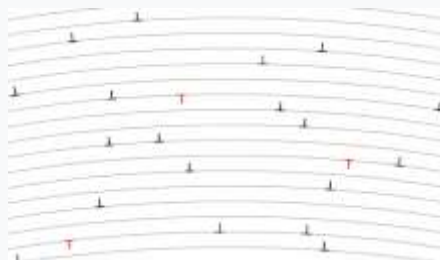


Fig 2. Animation of the annihilation and reorganisation of edge dislocations in a crystal lattice

Deformed structure

A heavily deformed metal contains a huge number of dislocations predominantly caught up in 'tangles' or 'forests'. Dislocation motion is relatively difficult in a metal with a low stacking fault energy and so the dislocation distribution after deformation is largely random. In contrast, metals with moderate to high stacking fault energy, e.g. aluminium, tend to form a cellular structure where the cell walls consist of rough tangles of dislocations. The interiors of the cells have a correspondingly reduced dislocation density.

Annihilation

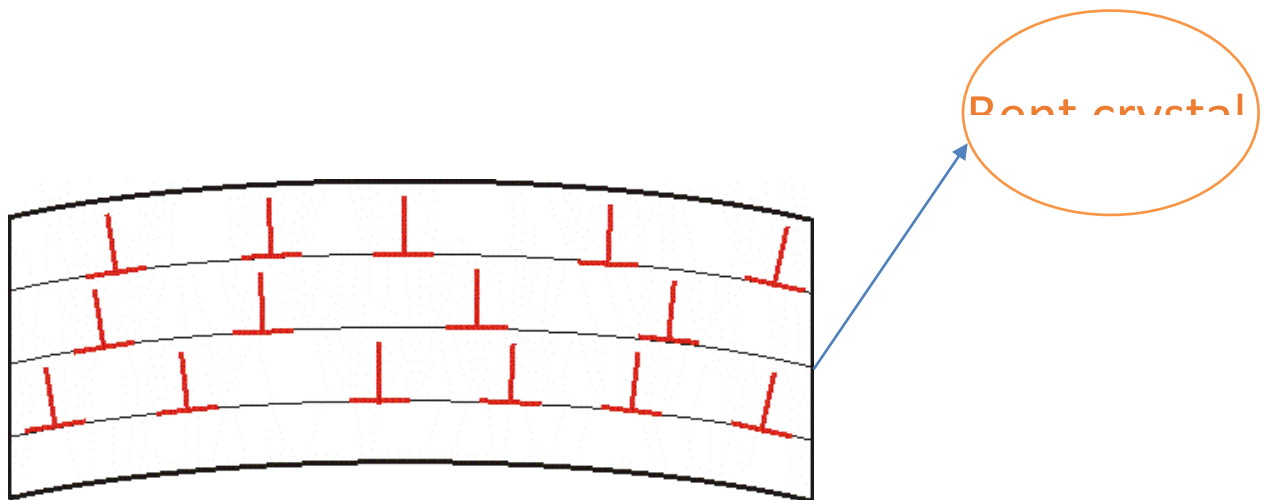
Each dislocation is associated with a strain field which contributes some small but finite amount to the materials stored energy. When the temperature is increased - typically below one-third of the absolute melting point - dislocations become mobile and are able to glide, cross-slip and climb. If two dislocations of opposite sign meet then they effectively cancel out and their contribution to the stored energy is removed. When annihilation is complete then only excess dislocation of one kind will remain.

Rearrangement

After annihilation any remaining dislocations can align themselves into ordered arrays where their individual contribution to the stored energy is reduced by the overlapping of their strain fields. The simplest case is that of an array of edge dislocations of identical Burger's vector. This idealized case can be produced by bending a single crystal that will deform on a single slip system (the original experiment performed by Cahn in 1949). The edge dislocations will rearrange themselves into tilt-boundaries, a simple example of a low-angle grain boundary. Grain boundary theory predicts that an increase in boundary misorientation will increase the energy of the boundary but decrease the energy per dislocation. Thus, there is a driving force to produce fewer, more highly misoriented boundaries. The situation in highly deformed, polycrystalline materials is naturally more complex. Many dislocations of different Burger's vector can interact to form complex 2-D networks.

□

POLYGONIZATION



Statistically stored edge dislocations in a crystal, which has undergone cold work. Excess on sign of dislocations leads to a bent crystal.

POINTS ON POLYGONIZATION:

- *During recovery polygonization takes place.*
- *In this process, dislocations of the same sign arrange themselves in a low energy configuration.*
- *This leads to the formation of sub-grain boundaries or low-angle grain boundaries.*
- *In the example considered formation of low angle tilt grain boundary is shown (starting with an excess of positive edge dislocations).*
- *If we start with an excess of screw dislocations, we will obtain a low-angle twist boundary.*
- *An interesting point is that during this process, statistically stored (random) dislocations 'become' structural dislocations.*

Topic:-

RECRYSTALLIZATION

Recrystallization is the process of nucleation and growth of new strain free crystals, which replace all the deformed crystals of the worked material.

It starts on heating to temperatures in the range of $0.3-0.5T_m$, which is above the recovery range. There is no crystal structure change during recrystallization.

As such, recrystallization is not a phase transformation in strict sense. The free energy change during recrystallization arises from the excess strain energy of the deformed material as compared to the undeformed material.

The strain energy difference between the cold-worked and the strain-free material is known as the **driving force of recrystallization**.

Nucleation may not occur in recrystallization.

As existing grain boundary with local differences in dislocation density on either side may simply migrate into the region of higher dislocation density. The recrystallization temperature is arbitrarily defined as that temperature at which 50% of the material recrystallizes in 1hr.

Emperical laws of recrystallization:-

- The higher is the degree of deformation, the lower is the recrystallization temperature.

- The finer is the initial grain size, the lower is the recrystallization temperature.
- Increasing the amount of cold work and decreasing the initial grain size produce finer recrystallized grains.
- The higher is the temperature of cold working, the less is the strain energy stored in the material. The recrystallization temperature is correspondingly higher
- The recrystallization rate increases exponentially with temperature.

The recrystallization temperature is strongly dependent on the **pureity of the material**.

Pure material recrystallized around $0.3T_m$ and impure materials may recrystallized around $(0.5-0.6)T_m$

Eg.: Aluminium of 99.999% purity recrystallizes as 75 degree Celsius.

During recrystallization the impurity atoms segregated at the grain boundaries retard their motion and obstruct the processes of nucleation and growth.

This solute drag effect can be exploited in raising the recrystallization temperature. In applications where the increased strength of a cold worked material is to be maintained at the service temperature without letting it to recrystallize.

Recrystallization is also slowed down in presence of second phase particles. When the particle lies in the migrating boundary during recrystallization, the grain boundary area is less by an amount equal to cross sectional area of the particle.

When the boundary moves out, it has to pull away from the particle and there by create new boundary area equal to the cross-section of the particle. The increase in energy manifests itself as a *pinning action of the particle* on the boundary.

Consequently, the rate of recrystallization decreases.

Grain growth

In materials science, **grain growth** is the increase in size of grains (crystallites) in a material at high temperature. This occurs when recovery and recrystallisation are complete and further reduction in the internal energy can only be achieved by reducing the total area of grain boundary. The term is commonly used in metallurgy but is also used in reference to ceramics and minerals.

Importance of grain growth

Most materials exhibit the Hall-Petch effect at room-temperature and so display a higher yield-stress when the grain size is reduced (assuming abnormal grain growth has not taken place). At high temperatures the opposite is true since the open, disordered nature of grain boundaries means that vacancies can diffuse more rapidly down boundaries leading to more rapid Coble creep. Since boundaries are regions of high energy they make excellent sites for the nucleation of precipitates and other second-phases e.g. Mg–Si–Cu phases in some aluminium alloys or martensite platelets in steel. Depending on the second phase in question this may have positive or negative effects.

Rules of grain growth

Grain growth has long been studied primarily by the examination of sectioned, polished and etched samples under the optical microscope. Although such methods enabled the collection of a great deal of empirical evidence, particularly with regard to factors such as temperature or composition, the lack of crystallographic information limited the development of an understanding of the fundamental physics. Nevertheless, the following became well-established features of grain growth:

1. Grain growth occurs by the movement of grain boundaries and not by coalescence (i.e. like water droplets)
2. Boundary movement is discontinuous and the direction of motion may change suddenly.
3. One grain may grow into another grain whilst being consumed from the other side
4. The rate of consumption often increases when the grain is nearly consumed
5. A curved boundary typically migrates towards its centre of curvature
6. When grain boundaries in a single phase meet at angles other than 120 degrees, the grain included by the more acute angle will be consumed so that the angles approach 120 degrees.

Driving force

The boundary between one grain and its neighbour (grain boundary) is a defect in the crystal structure and so it is associated with a certain amount of energy. As a result, there is a thermodynamic driving force for the total area of boundary to be reduced. If the grain size increases, accompanied by a reduction in the actual number of grains per volume, then the total area of grain boundary will be reduced.

The local velocity of a grain boundary at any point is proportional to the local curvature of the grain boundary, i.e.:

$$V=M*s*K$$

where v is the velocity of grain boundary, M is grain boundary mobility (generally depends on orientation of two grains), s is the grain boundary energy and K is the sum of the two principal surface curvatures. For example, shrinkage velocity of a spherical grain embedded inside another grain is

$$v=(M*s^2)/R$$

where R is radius of the sphere. This driving pressure is very similar in nature to the Laplace Pressure that occurs in foams.

In comparison to phase transformations the energy available to drive grain growth is very low and so it tends to occur at much slower rates and is easily slowed by the presence of second phase particles or solute atoms in the structure.

Self-similarity



Click to see the animation. Geometry of a single growing grain is changing during grain growth. This is extracted from a large scale phase-field simulation. Here surfaces are "grain boundaries", edges are "triple junctions" and corners are vertexes or higher-order junctions. For more information please see.

An old-standing topic in grain growth is the evolution of the grains size distribution. Inspired by the work of Lifshitz and Slyozov on Ostwald ripening, Hillert has suggested that in a normal grain growth process the size distribution function must converge to a self-similar solution, i.e. it becomes invariant when the grain size is scaled with a characteristic length of the system that is proportional to the average grain size .

Several simulation studies, however, have shown that the size distribution deviates from the Hillert's self-similar solution.^[2] Hence a search for a new possible self-similar solution was initiated that indeed led to a new class of self-similar distribution functions. Large-scale phase field simulations have shown that there is indeed a self-similar behavior possible within the new distribution functions. It was shown that the origin of the deviation from Hillert's distribution is indeed the geometry of grains specially when they are shrinking.

Factors hindering growth

If there are additional factors preventing boundary movement, such as Zener Pinning by particles, then the grain size may be restricted to a much lower value than might otherwise be expected. This is an important industrial mechanism in preventing the softening of materials at high temperature.

Inhibition

Certain materials especially refractories which are processed at high temperatures end up with excessively large grain size and poor mechanical properties at room temperature. To mitigate this problem in a common sintering procedure, a variety of dopants are often used to inhibit grain growth.