TALAT
Training in Aluminium Application Technologies

TALAT Lecture 1251

Mechanical Working and Forming of Shapes

14 pages, 14 Figures

Advanced level

prepared by **M H Jacobs**
Interdisciplinary Research Centre in Materials
The University of Birmingham, UK

Objectives:

Outline of the metallurgical principles of mechanical working and forming of shapes from aluminium.

Prerequisites:

Basic knowledge of physics and chemistry. Familiarity with the contents of TALAT lectures 1201 through 1205.

Date of Issue: 1999

1251 Mechanical Working and Forming of Shapes

Contents (14 Figures)

1251.01 Background to Mechanical Working and Forming

This involves the conversion of a cast ingot to a wrought product by processes which are carried out at high temperatures or at room temperature and which might involve reheating the material to restore ductility.

Two main aspects must be considered, which are (1) change of shape, and (2) change of microstructure and mechanical properties. We will deal with these in turn.

1251.01.01 Change of Shape

As an example, consider the production of flat rolled products. If we start with a cast ingot of a suitable alloy which is 5m long and 300mm thick, this slab can be converted to foil which may be 7µm (.007mm) thick. Neglecting any change in width that occurs, the length of foil produced from this ingot is about 200km. The change of shape is expressed by measurement of strain. In the particular example, the total reduction in thickness can be expressed as

$$\frac{\text{Original thickness - Final thickness}}{\text{Original thickness}} \times 100\ \% = 99.998$$

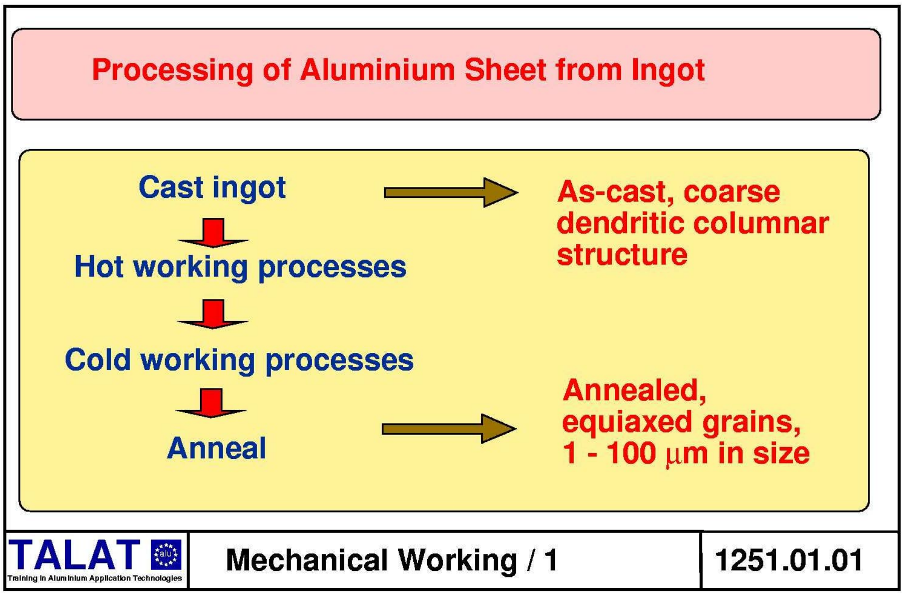
This is called nominal strain or engineering strain.

Another way of expressing the thickness strain is

$$\log_n \frac{\text{Original thickness}}{\text{Final thickness}} = 10.7$$

This is called true strain.

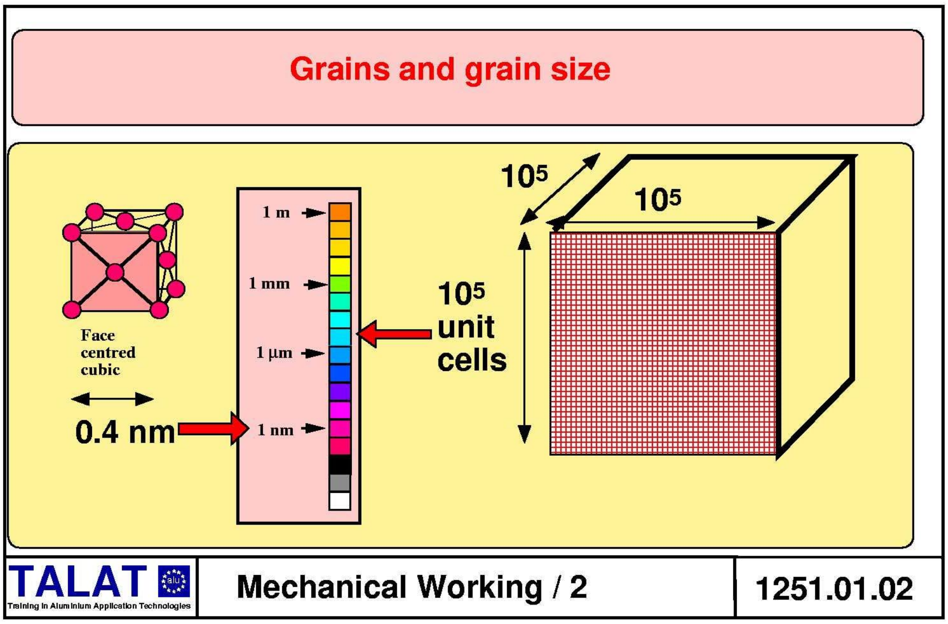
Such large strains cannot be achieved in a single operation. The usual route is to start with hot working processes followed by cold working and annealing, **Figure 1251.01.01**.



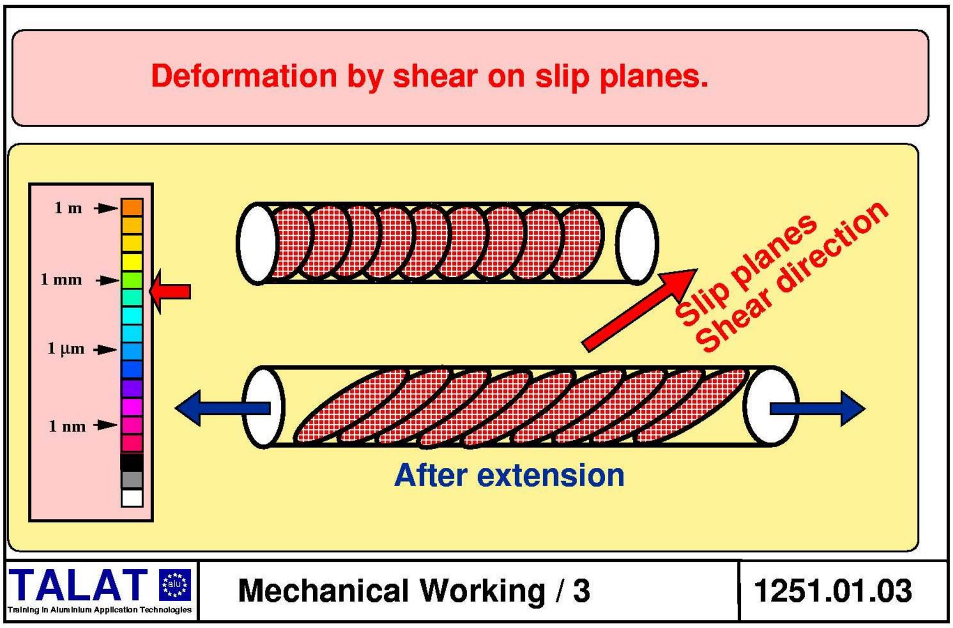
1251.01.02 Change of Microstructure and Mechanical Properties

The ability to undergo large plastic deformation is one of the most useful attributes of metals. Metals with a face-centred cubic (fcc) crystal structure usually exhibit good, isotropic ductility as a direct consequence of three sets of active slip planes. In this respect, aluminium and its many alloys are excellent examples of a material that is readily formed into complex shapes.

Metals usually consist of large numbers of individual grains or crystals; that is, they are polycrystalline, see **TALAT lecture 1201**. A typical grain or crystal after hot working, plus cold working and annealing will be of diameter, say, 40µm thus contains many millions of unit cells, see **Figure 1251.01.02**.



In the cast condition, the initial crystals grow from the liquid phase and the resultant microstructure is usually coarse, see TALAT lecture 1201. When the metal is deformed, each grain deforms by the movement of line defects in the crystal lattice; deformation is by ***slip*** on ***slip planes*** along the ***shear direction***, see **Figure 1251.01.03**. These defects are known as ***dislocations***, **Figure 1251.01.04**. The dislocations move on certain crystallographic planes in the crystals (close-packed planes) which are known as ***slip planes***, see again **TALAT lecture 1201**. The movement of a single dislocation produces a shear strain and the combined motion of hundreds of thousands of dislocations produces the total strain.



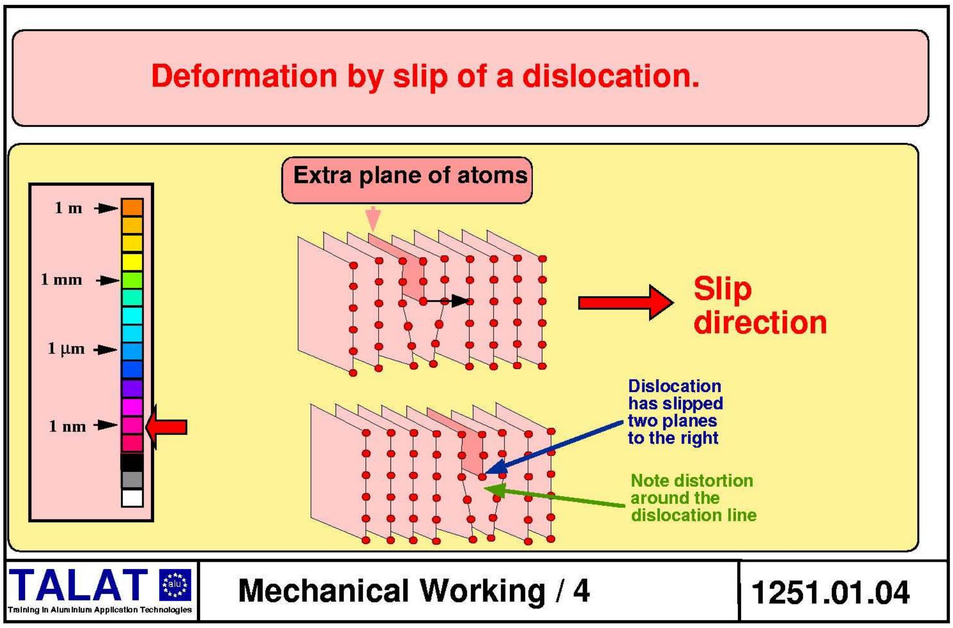


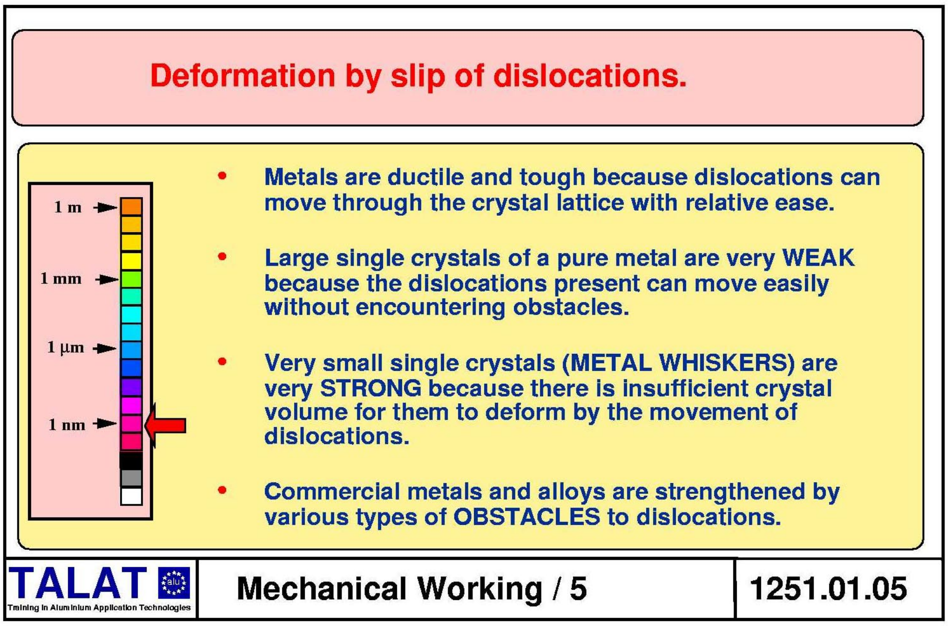
Figure 1251.01.05 lists four points that emphasise the importance of dislocations and the ease with which they slip under the influence of an applied stress:

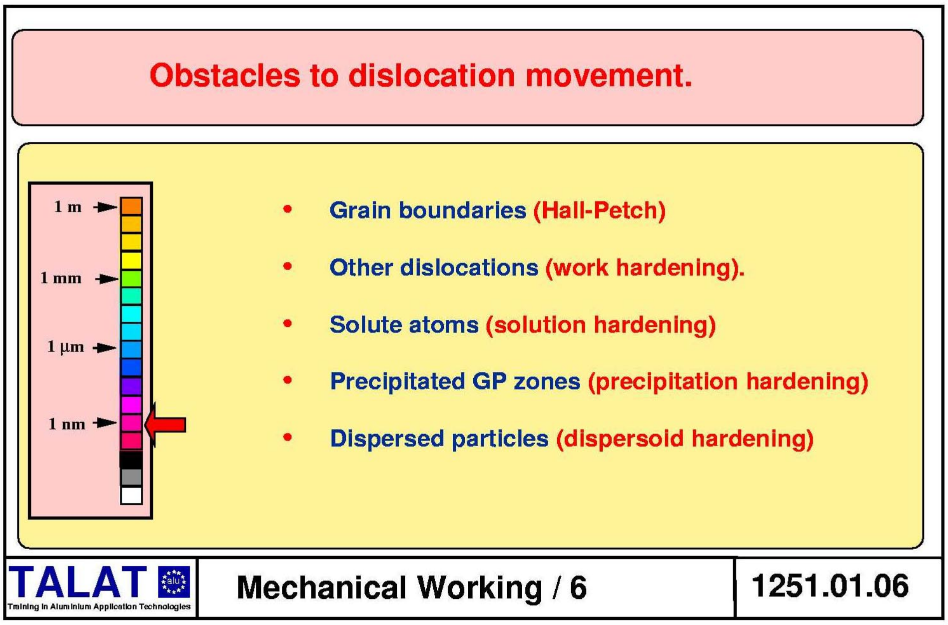
Metals, especially those with a cubic crystal structure, are ductile and tough because dislocations can move through the crystal lattice with relative ease.

Large single crystals of a pure metal are very WEAK because the dislocations present can move easily without encountering obstacles.

Very small single crystals (METAL WHISKERS) are very strong because there is insufficient crystal volume for them to deform by the movement of dislocations.

Commercial metals and alloys are strengthened by various types of OBSTACLES to the movement of dislocations.





Obstacles to dislocation movement, **Figure 1251.01.06**, include one or more of the following:

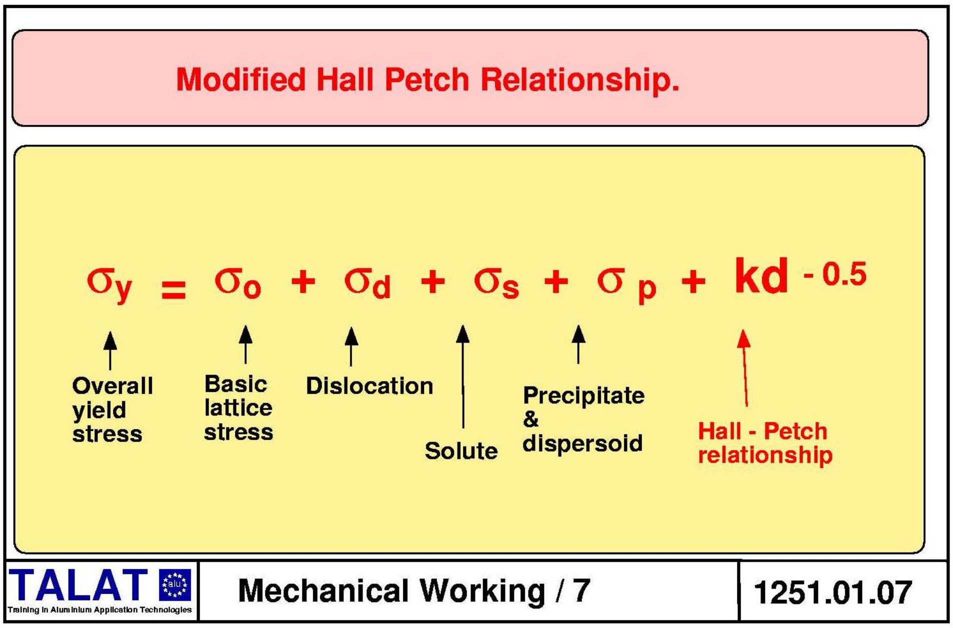
(1) Grain boundaries
(2) Other dislocations (work hardening)
(3) Solute atoms (solution hardening)
(4) Precipitated GP zones (precipitation hardening)
(5) Dispersed particles (dispersoid hardening).

Some or all of these may contribute to the strength of a metal or alloy, **Figure 1251.01.07**:

$$\sigma_y \quad = \quad \sigma_o + \sigma_d + \sigma_s + \sigma_p + kd^{-0.5} \qquad (1)$$

where

σ_y	=	overall yield stress
σ_o	=	stress due to basic lattice
σ_d	=	stress due to dislocations interactions
σ_s	=	stress due to resistance to dislocation movement caused by solute atoms (size effect)
σ_p	=	stress due to obstacles resented as precipitate particles and dispersoid particles



The effect of grain size is given by the Hall-Petch relationship

$$\sigma \quad = \quad \text{Constant} + kd^{-0.5}$$, where d is the grain size (mean diameter).

During deformation at <u>room temperature</u> the number of dislocations increases and it becomes increasingly difficult for dislocations to move through the lattice, i.e. the metal ***work hardens*** or ***strain hardens***. This means that higher loads are required to continue deformation and the metal loses ductility, eventually leading to cracking and failure. At the atomistic level the situation is complex and the theory of dislocations has been developed to a high degree in order to understand the details of the mechanisms involved [1]. During deformation, slip is very active and moving dislocations on intersecting slip planes will give rise to jogs which, in themselves, make only a small contribution to hindering dislocation movement and associated work hardening; of move importance is the interaction between opposing strain fields that surround dislocations, which gives rise to tangles or ‘forests’ of dislocations, **Figure 1251.01.07**.

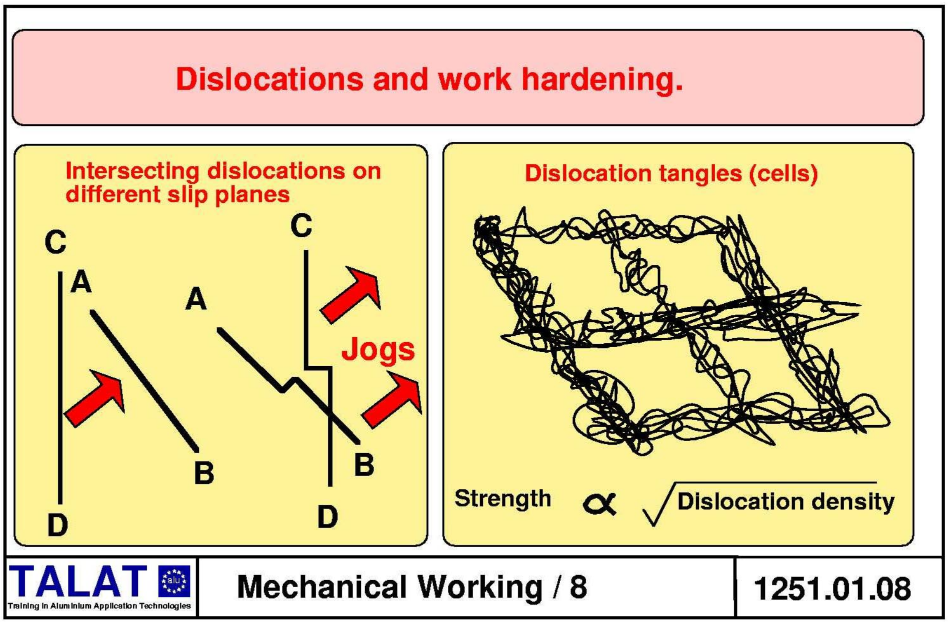
During work hardening in which dislocation forests are formed, the flow stress σ is given by

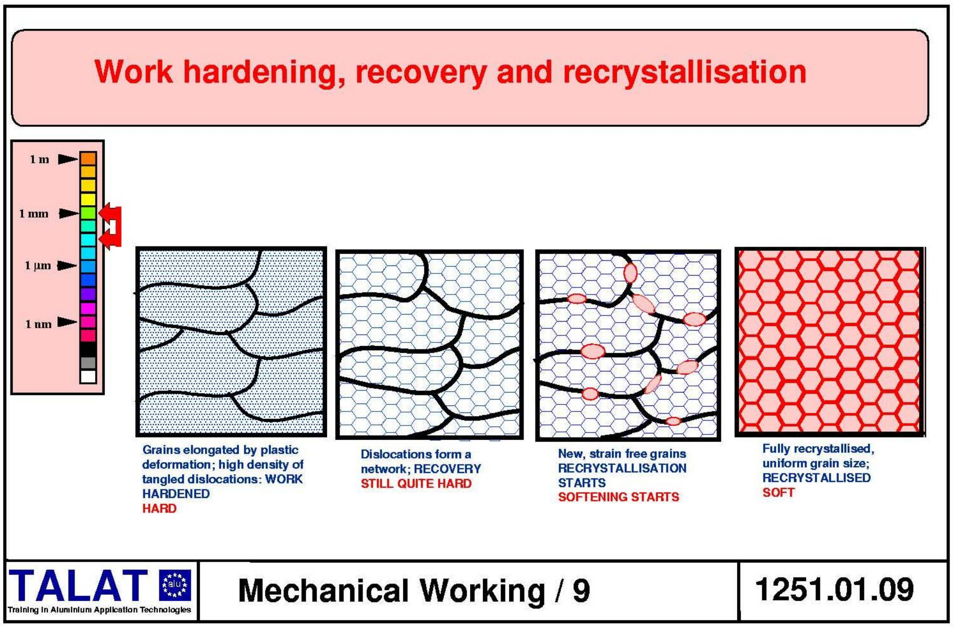
$$\sigma \quad = \quad \text{constant} \times \sqrt{(\text{dislocation density})} \qquad (2)$$

Dislocations may be removed by heating the cold worked metal to a moderately high temperature (***annealing***) which causes the metal to soften and restores ductility. The changes in microstructure which occur during annealing are referred to as ***recovery*** and ***recrystallisation***, see TALAT **lecture 1201**.

During deformation at elevated temperatures, restoration processes may occur. These are called ***dynamic recovery*** or ***dynamic recrystallisation***. In aluminium alloys, the former is more likely to occur. As a result of these processes, the metal does not strain harden as much as it does at room temperature and consequently lower loads are required to deform the material. But, under these conditions, the speed of deformation, or ***strain rate***, becomes an important parameter of the process.

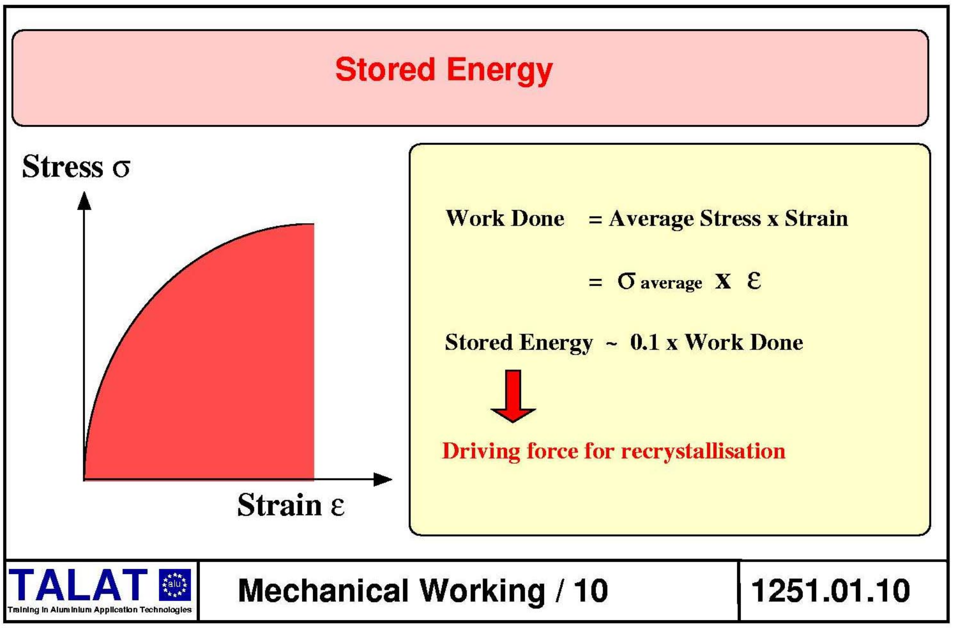
Several different techniques must be used to observe the microstructural features referred to above. In order to observe dislocations, it is necessary to use transmission electron microscopy (TEM) A thin foil of the material is prepared and inserted in an electron microscope, and dislocations are revealed by diffraction contrast, see TALAT lecture 1204, section **1204.05 Appendix**. In aluminium alloys after a moderate amount of deformation, the dislocations are not uniformly distributed but instead they form cells, with walls of tangled dislocations and interior regions of low dislocation density, see **Figure 1251.01.08**. Typically, these cells have a diameter of the order of 1µm. When recovery occurs, the cell walls become clean boundaries and the units are then referred to as ***subgrains***. However, when a large amount of cold work is followed by annealing, new grains are formed by the process of ***recrystallisation***, **Figure 1251.01.09**.





The driving force for recrystallisation is the ***stored energy*** caused by the presence of dislocations, **Figure 1251.01.10**.

The ***dislocation density*** can be expressed as the total length of dislocation lines in a unit volume of the material. For annealed material this may be about $10^{10}m^{-2}$ and for heavily cold worked material the dislocation density rises to about $10^{15}m^{-2}$.



The ***response of a metal to stress*** at constant temperature, **Figure 1251.01.11** may be expressed as:

$$\sigma = k\,\varepsilon^{n}\,\dot{\varepsilon}^{m} \qquad (3)$$

where σ = stress
ε = strain
$\dot{\varepsilon}$ = strain rate
n = strain hardening exponent
m = strain rate sensitivity.

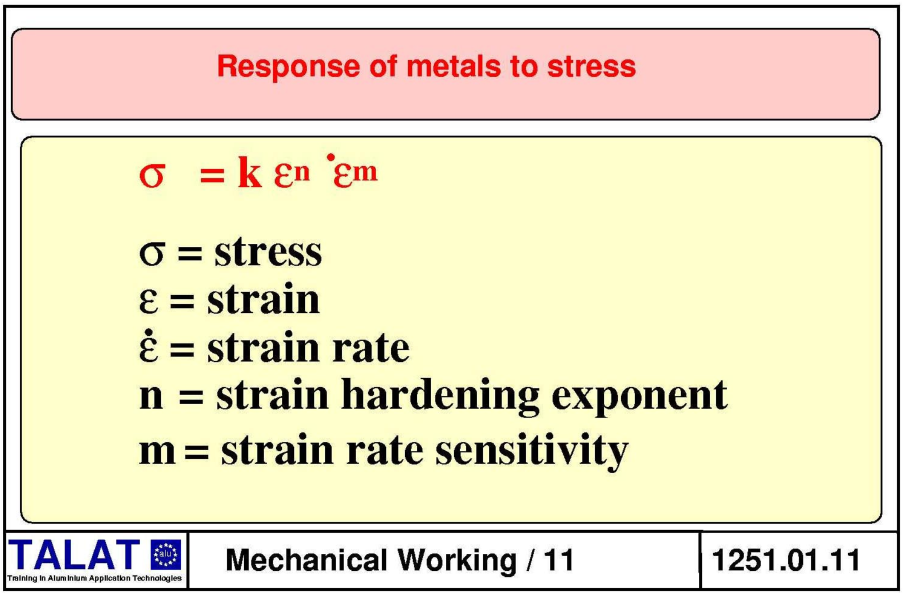
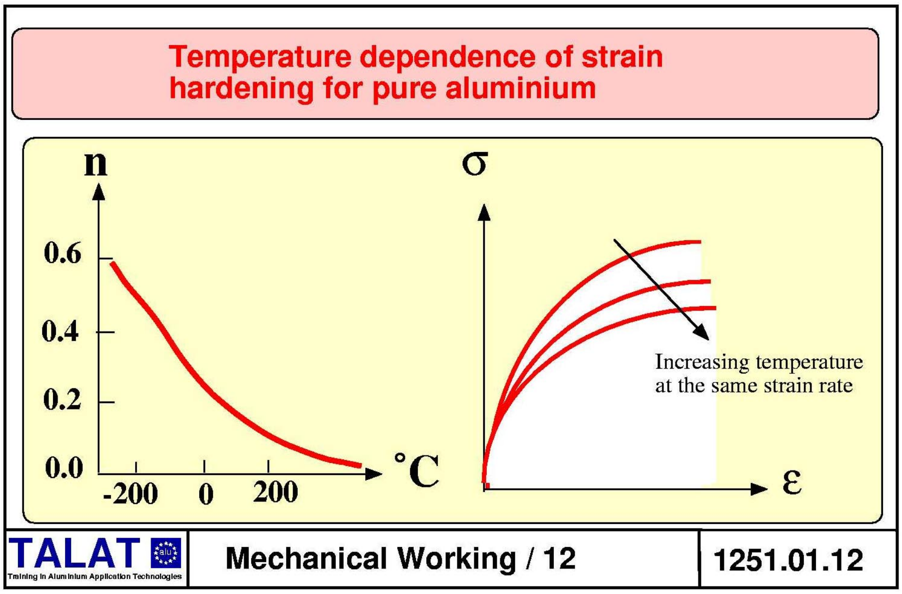
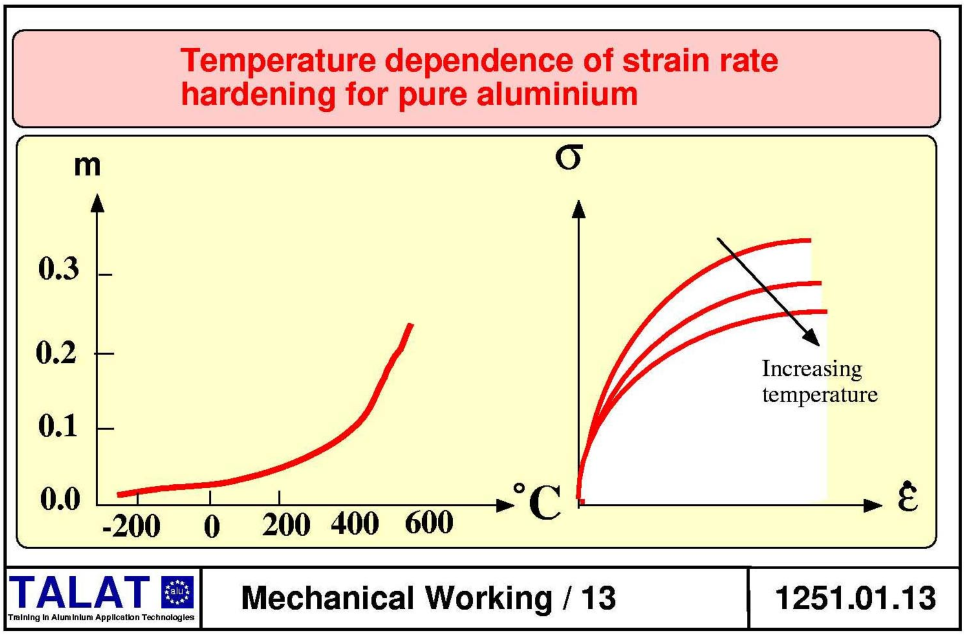
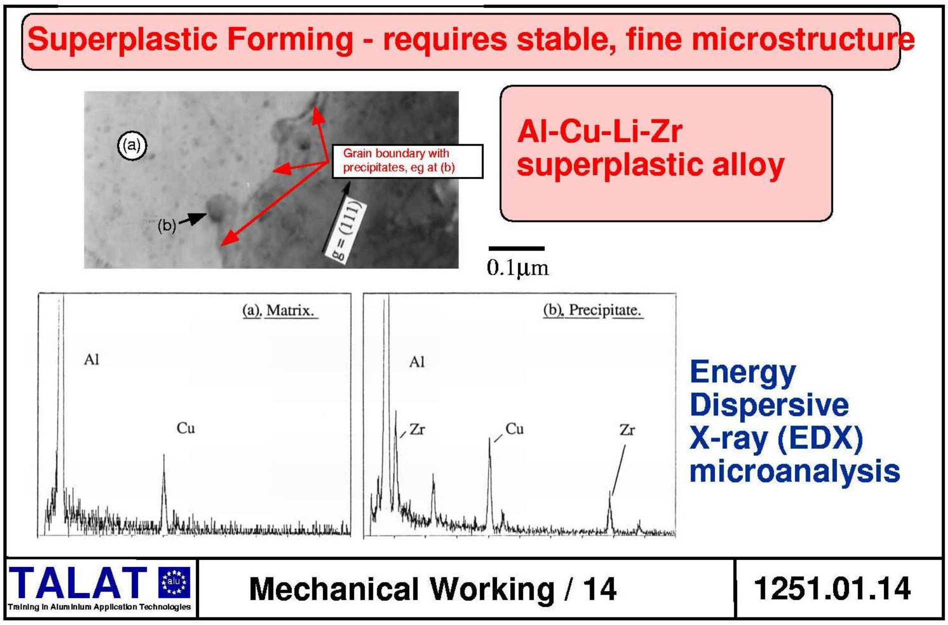


Figure 1251.01.12 and **Figure 1251.01.13** show schematically the temperature dependences of strain hardening and strain rate hardening in pure aluminium. These figures show that the strain rate sensitivity of pure aluminium increases significantly with temperature above 200°C. This reflects the importance of the dynamic recovery at high temperatures.





Note that aluminium alloys that are formable by superplastic deformation have strain rate sensitivities > 0.5. A stable, fine scale microstructure is required for superplastic deformation, by which ductilities of several hundreds of percent are possible. This requires special alloy compositions, containing Zirconium which provides particles which pin grain boundaries, **Figure 1251.01.14**.



In heat treatable aluminium alloys, the effective hardening precipitates are very small and it is necessary to use TEM to observe these directly, see TALAT **lecture 1204** on precipitation hardening. Also the small sub-micron ***dispersoid particles*** present in some alloys are observable only by TEM.

Other features of the microstructure may be observed by optical microscopy – these include the ***grain size***, the ***degree of recrystallisation***, the ***grain aspect ratio*** and coarse intermetallic particles.

Yet another aspect of the microstructure is concerned with the ***orientations*** of the grains. During deformation involving crystallographic slip, rotations occur leading to the lining up of crystals in preferred directions. The non-random distribution of orientations is known as ***preferred orientation*** or ***crystallographic texture***. The preferred orientation developed during deformation is known as a ***deformation texture*** and when the material is subsequently recrystallised, a new preferred orientation is formed which is a ***recrystallisation texture***. The presence of texture in wrought products influences ***directionality*** of mechanical properties, an important example in aluminium process technology being the control of ***earring*** in canstock material used for the production of beverage cans.

Preferred orientation is usually measured by X-ray diffraction methods.

Another source of directionality, particularly in some of the strong aluminium alloys in plate form, is associated with ***grain morphology***. Flat, elongated grains account for lower ductility, lower toughness and lower stress corrosion resistance in the short transverse direction.

In the deformation and heat treatment of aluminium alloys, ***particles of intermetallic compounds*** play an important role especially in relation to the recrystallisation behaviour. Large particles, with diameters of the order of 1µm or more, create strain concentrations during deformation and can act as nucleation sites for recrystallisation. On the other hand, small particles (dispersoids) interact with moving grain boundaries and can prevent grain growth.

The above considerations relate generally to deformation and we can now consider briefly some specific working processes, flat rolling, extrusion, forging and sheet metal forming processes.

1251.02 Forming Processes

1251.02.01 Flat Rolling

The first stage in the process is ***hot rolling***. Slabs are pre-heated to a temperature of up to ~500°C, depending on the alloy composition and the rolling to plate with a thickness of ~7mm is often carried out without reheating, so that the temperature falls during deformation.

A typical rolling mill for this stage is a large 4-high reversing mill, with work rolls of about 1m diameter and back-up rolls of about 1.5m diameter.

Cold Rolling is carried out on a variety of mills depending on the alloy and the dimensions of the strip - a single 4-high mill, tandem mill or cluster mill (Sendzimir) can be used. In the case of very thin strip, the application of front and back tension is important.

1251.02.02 Extrusion

The advantage of the extrusion process is that complicated cross section products can be made in a single operation. It is a hot forming process carried out on large and expensive extrusion presses. For large extruded sections, the loading capacity of the press may be about 7000t.

1251.02.03 Forging

Forging of aluminium alloys is carried out at high temperatures in the region of 400°C. While the main outlet for aluminium forgings has been the aerospace industry, commercial products now occupy a significant portion of the market.

Examples of commercial products are suspension units for trucks, wheels, components for racing cars, etc.

1251.02.04 Sheet Metal Forming Processes

These are usually carried out at room temperature. The processes involved are bending, stretch forming and deep drawing. The range of products is enormous, ranging from aircraft fuselages to beer cans. Currently, efforts are being made to introduce aluminium alloys into car bodies. The room temperature formability of aluminium alloys is not as good as that of some competitive materials such as low-carbon steels.

For the forming of complex shapes in a single operation, superplastic forming offers possibilities. Aluminium alloys have been developed for superplastic forming applications.

1251.03 References

1. R E Smallman, *Modern Physical Metallurgy*, Fourth Edition, Butterworth Heinemann, 1985.

1251.04 List of Figures