I. OBJECTIVE OF THE EXPERIMENT

We will study the behavior of metal, and learn to interpret it to harden or soften metal alloys.

II. PHENOMENOLOGY OF PLASTIC DEFORMATION

When a body is exposed to external stress, it responds either by moving, or by deforming. Depending on the magnitude of the stresses applied, there are two types of possible deformations:

1) For low stresses, the strain is proportional to the applied stress (Hooke’s law) and comes back to its original position when the stress is removed. This is called elastic deformation.

2) For stresses higher than a certain limit (elastic limit), the strain is no longer proportional to the applied stress, and when the stress goes back to zero, the solid is still deformed. This is called plastic deformation.

Some materials are more apt to deform plastically than others. In general, metals are quite capable of deforming plastically, which explains their very important place in history. In contrast, rock is brittle and hard. People left the Stone Age for the Bronze Age, since stone is hard and breakable, whereas bronze is malleable and can be used to make all sorts of objects and weapons.

In order to study the plastic properties of materials, we can perform different types of tests. For example, the one we will use here is the tensile test.

**Tensile Test**

This is a test during which we will pull on a specimen at constant speed.

We will write the force $F$ as a function of the stretching $\Delta l$ of the sample; or better, the stress $\sigma = F/S$ as a function of the strain $\varepsilon = \Delta l/l_0$ (Fig. 1).

with $S_0$ = area of the cross-section of the sample

$l_0$ = initial length of the sample

There are many different norms (DIN, ISO ...) regarding the geometric properties of the sample, depending on the material to study.
We get a curve called \textit{tensile curve} of the tested material. This curve can be split into three zones.

\begin{itemize}
  \item **zone I:** elastic domain, reversible deformation, linear relationship between stress $\sigma$ and strain $\varepsilon$
    
    Hooke's law $\sigma = E\varepsilon$
    
    where $E$ = elastic modulus or Young modulus
  \item **zone II:** plastic domain, irreversible deformation
    
    the stress is no longer proportional to the strain
    
    When we remove the stress, there is a remnant strain $\varepsilon_r$, \\
  \item **zone III:** necking and breakage
    
    Necking is due to localized and catastrophic plastic deformation of the sample
\end{itemize}

The limit between the elastic and plastic domain is called elastic limit. Since it's hard to define it experimentally, we prefer to use the value $\sigma_{0.2}$, the value of the stress applied when the remnant strain is only of 0.2%.

We define the breaking stress as the maximal stress that can be applied on a given tensile curve, and the breaking strain as the maximal plastic deformation.

Elastic deformation can easily be explained by the elasticity of the atomic bonds. The reversible property comes from the fact that the atomic structure remains unchanged. Therefore, plastic deformation can only be explained by a modified internal structure of the metal, but how precisely?
III. INTERPRETATION PF PLASTIC DEFORMATION

Plastic deformation appears almost always as shear strain. Let's consider the shear strain of a monocrystal of cubic structure on the atomic scale (fig. 2).

Under a shear stress $\sigma$, the crystal can only deform elastically by tilting of the vertical atomic layers (fig. 4b). In this case, Hooke’s law leads to the following relationship between stress and strain

$$\sigma = G\varepsilon$$

where $G$ = elastic shear modulus

$$\varepsilon = \tan \gamma = \text{strain, or shearing}$$

Plastic deformation will only appear if the stress increases sufficiently, at which point there will be an irreversible slipping of the atomic planes (fig. 4c). For this to happen, the atomic bonds of two neighboring planes must be cut and reattached after having moved on part of the crystal with respect to the other.

However, by calculating the stress required to get this slipping, we get values that are approximately 1000 times too large, i.e. an elastic limit of the order of $10^{-11} G$ ($G$ = shear modulus). However, experimentally, the stresses observed are of the order of $10^{-3}$ to $10^{-4} G$.

In order to explain this paradox of the elastic limit, G.I. Taylor and E. Orowan, as well as M. Polanyi proposed simultaneously in 1934 that plastic deformation could be due to the motion of lattice defects along the shear direction. These defects, called dislocations are be able to move at stresses much lower than the theoretical shear stress.

Figure 3 represents an edge dislocation on the atomic scale. The dislocation is the limit of an extra half-plane of atoms, introduced in the crystal like a wedge. The edge of this half-plane of atoms makes a line. Dislocations are therefore linear defects of crystalline nature. We actually can see them as lines in electron transmission microscopes (fig. 4).
Note that it took more than twenty years for the existence of dislocations to be confirmed by observations under an electron transmission microscope. The first time these black lines were interpreted as the contrast of dislocations was in 1956, by Hirsch, Horne and Whelan at the Cavendish Laboratory of Cambridge, and independently by Bollmann in Geneva.

![Image of dislocations](image)

**Fig. 4:** Observation of dislocations in a classic electron microscope. Due to the diffraction contrast, dislocations appear as black lines. Aluminum sample, M. Carrard, EPFL thesis 1985 (Mag. 15000x)

Under a shear stress, these lines of dislocations move easily, since for each elementary jump, only one line of atomic bonds must be broken, compared to a full plane in our previous theory. While moving, they irreversibly displace the different parts of the crystal with respect to one another (fig. 5). The motion of a dislocation is often compared to that of a caterpillar (fig. 5), or of a fold on a rug. For a crystal, the “fold” translates into the presence of an extra half plane of atoms. This is an edge dislocation (fig. 5)

![Diagram of dislocations](image)

**Fig. 5:** Motion of an edge dislocation in a crystal

Another type of dislocation is represented in figure 6. It can be described by a tear moving through a sheet of paper, the dislocation line moving from front to back. It is parallel to the shear stress. This is called a **screw dislocation**.
Connection between motion of dislocations and plastic deformation

We have seen that the motion of dislocations implies a plastic deformation. It must therefore be possible to establish a relationship between their motion and the deformation they cause. Let’s start by considering a parallelepipedic crystal ($L_1, L_2, L_3$) (Fig. 7), that is cut across by a straight edge dislocation.

Fig. 6: Motion of a screw dislocation in a crystal

Fig. 7: Plastic deformation due to an edge dislocation
Once the dislocation has gone through the entire crystal, it causes a plastic deformation $\varepsilon$ given by

$$\varepsilon = \frac{b}{L_2}$$

If the dislocation only moves by a distance $u$ ($u = \Delta l$), the strain can be given by

$$\varepsilon = \frac{b \cdot u}{L_2} = \frac{b}{S} \cdot u \quad S = L_1 L_2$$

If we now suppose that $N_m$ parallel dislocations moved in the same direction (on the same or parallel planes) an average distance $u$, the strain created after their motion is given by:

$$\varepsilon = \frac{N_m}{S} \cdot b \cdot u$$

We can then introduce the notion of dislocation density $\Lambda_m$, defined by:

$$\Lambda_m = \frac{N_m}{S}$$

Notice that this value expresses the average number of emerging dislocations per unit surface.

We then have:

$$\varepsilon = \Lambda_m \cdot b \cdot u$$

And if we further suppose that all dislocations move at the same speed $v$, we can express the deformation speed by:

$$\dot{\varepsilon} = \Lambda_m \cdot b \cdot v$$

This is called **Orowan's equation**

We notice that the plastic deformation speed is directly linked to the dislocation's speed. Dislocations are the plastic strain carriers, the same way that electrons are charge carriers.

**Remarque:** For charge carrier (electrons), the current density is written:

$$j = \rho \cdot q \cdot v$$

where $\rho$ = carrier density $\leftrightarrow \Lambda_m$

$q$ = electric charge $\leftrightarrow b$ = plastic charge

$v$ = carrier speed $\leftrightarrow v$

**IV. HARDENING OF AN ALLOY**

Dislocations move under the influence of rather small forces. How can we harden a material, i.e. heighten its elastic limit? In other words, how can we block dislocations?

Crystal defects attract or repel each other. This way, a dislocation can be attracted or repelled by a foreign atom (solid solution) or better, a group of foreign atoms (precipitate). Hardening via precipitation manifests itself through a higher elastic limit. Dislocations are blocked when they hit a precipitate (fig. 8).
Fig. 8: Precipitates (groups of foreign atoms) block dislocations and thus stop plastic deformation.

Precipitates are groupings of foreign atoms that occur when making metal alloys, for example, adding 4% of copper in aluminum to make an Al-4%Cu basic alloy used for aviation. The copper precipitates, or more precisely the Al$_2$Cu, efficiently block the dislocations, preventing plastic deformation of the plane wings.

In conclusion, if one wants to harden a metal, one must introduce elements of an alloy that will block dislocations. If on the other hand, one wants to soften a metal to be able to deform it (e.g. bending sheet metal to the appropriate shape), one must dissolve the precipitates in a heat range where the solubility is greater.

The solubility range of an alloy in a metal, as well as the existence area of different precipitates, of type Al$_2$Cu compound, is given in the appropriate phase diagram.

The phase diagram shows the alloy composition on the x-axis, and the temperature on the y-axis. The areas drawn out represent the different equilibrium phases of the system. Figure 9 represents, as an example, the phase diagram for Al-Si.

For instance, an Al-Si 0.7% alloy will be liquid over 660 °C, a mix of liquid and solid at 630 °C, a solid solution between ~620 °C and ~490 °C, and will contain silicon Si below ~490 °C.

A solid solution is a state where the atoms of the solutions, here Si, replace Al atoms randomly, like salt would in salt water. Precipitates appear when there is an over saturation, similarly to salt in saturated water. The difference in microstructure of an alloy containing precipitates at a lower temperature is shown schematically in figure 10.

Fig. 9: Phase diagram of Al - Si.
Fig. 10: Schematic representation of an alloy in a homogeneous solid solution, and one containing precipitates

V. SUGGESTED EXPERIMENTS

An industrial grade Anticorodal 110 alloy (i.e. Al-0.7%Si-0.6%Mg—...) is used for a metallic construction. Since the alloy is hard and not ductile as received, we would like to soften it to form certain components (bending sheet metal, ...)

The goal is to do tensile tests on samples:
- as received
- softened: heated for 1h at 550 °C
- softened and hardened: heated for 1h at 550 °C, then again for ~20 minutes at 250 °C.

Experimental procedure:
Heat up the oven at 550 °C (see fig. 12). Once hot, place 5 out of the 6 received samples in the oven for 1h.
In the mean time, perform a tensile test on the received sample.
After 1h, quench the samples, i.e. cool them down abruptly by letting them fall in the tray filled with water.
Measure on of the samples.
Let the oven door open while cooling it down. The temperature indicated by the thermocouple rises quickly when the door is closed, so you should wait for the temperature to drop under 200 °C before closing it. Then, set the temperature to 250 °C, and wait for the oven to reach it.
Place the remaining samples in the oven, and remove them for measuring after 15, 20 and 25 minutes respectively. Be sure to quench the samples when taking them out.
There is an extra sample that can be used to repeat any measurement that could have failed, or perform an extra measurement.
Plot the tensile curves, and determine:
- the Young modulus \( E \)
- the elastic limit \( \sigma_{0.2} \)
- the maximal stress before breaking \( \sigma_{rup} \) and the maximal strain \( \varepsilon_{rup} \)

Note that the jerky line of the softened sample is due to the Portevin-Le Chatelier effect.

Doing a tensile test:
Before starting, measure the sample’s cross section.
Place the sample in the tensile machine, and tighten the clamps. The center of the sample need to be low enough to be able to attach the sample.
Attach the strain captor to the sample (fig. 11). Make sure the two arms are parallel before starting. To help you do so, use the alignment prop. Make sure to remove the prop before starting the test.
Be careful when tightening the screws on the sample. A screw not tight enough will slide during the measurement, while a screw too tight will damage the sample and distort the results. To start the tensile test, follow the instructions on location very precisely. Data is collected using the program Plotter_XY on the computer. The strength captor has a sensibility of 0.934 mV/N (if not indicated differently on the installation), and the deformation captor, 1 V/mm. However, if we account for the lever, this sensibility becomes 0.2 V/mm.

![Fig. 11: Setup of the sample](image1.jpg)

![Fig. 12: Image of the oven](image2.jpg)