MECHANISM OF SLIP & TWINNING

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**Keywords:** deformation behavior of materials, mechanism of plastic deformation, slip bands, twin bands, ductile failure, intergranular fracture, shear failure, slip planes, crystal deformation, dislocations in ceramics.

**Prerequisite Knowledge:** elementary knowledge of: metal structure, specimen preparation, measurement of mechanical properties of materials, examination of microstructure of a polished surface with a metallurgical microscope.

**Objectives:** To demonstrate the mechanisms of deformation in bcc, fcc, and hcp-structure metals and alloys and in some ceramics as well. To examine the deformed microstructures (slip lines and twin boundaries) in different grains of metallic and ceramic specimens. To study visually the deformed macrostructure (slip and twin bands) of metals and alloys.

**Background:** Two of the most important mechanisms of plastic deformation are slip and twinning. Slip, which is the principal one, can be considered as a result of a distorted boundary, a line imperfection called dislocation, between two perfect regions of a space lattice, figure 1. Two types of dislocation segments are identified: edge dislocation, which causes axial strains in the space lattice, figure 2; and screw dislocation which causes the lattice to experience shear strains and to distort through a helical path, figure 3. The passage of a dislocation through a crystal results in the relative motion of one part of the crystal past the other part; this process is called slip. Figure 4-a shows a slip resulting from the movement (right to left) of a pure edge dislocation, and figure 4-b shows a slip resulting from the movement (front to back) of a pure screw dislocation through a simple cubic lattice. Slip occurs on the planes of the densest pack of atoms and in the direction of least distance between atoms. For example, in a face-centered-cubic (fcc) lattice, slip occurs on the four planes of ABC type, (111) planes, and in the direction of the diagonals of cube faces or the three sides of triangle ABC, <110> directions, figure 5. Slip planes and directions for some type of structures are shown in table 1. In a monocrystalline specimen under axial loading, figure 6-a, if the slip plane is oriented parallel with or at a right angle to the axis of loading, figures 6-b and 6-c, the crystal will fail with no plastic deformation at all. When the orientation lies between the above two extreme cases, figure 6-d, the fracture is preceded by an appreciable plastic deformation. The closer in value the angle of slope of the slip plane is to 45°, the less load P is required to start the slip and the greater the plastic deformation is before the
failure. In a polycrystalline specimen under axial loading, slip occurs first in
grains whose slip planes are oriented at an angle of 45° with respect to the
direction of applied force, while adjacent grains are affected by elastic
deformation only. Surface examination of a deformed material under the
optical microscope reveals a series of lines arising from steps on the surface
called slip lines; this is shown in experiments number 1 and 2 for metallic
and ceramic specimens. Also, these slip planes open up on the surface of the
specimen as slip bands; this is shown in experiment number 3. The other
mechanism of deformation is twinning. Twinning is the result of identical
motions of atoms of a plurality of rows parallel to a twinning plane in the
original lattice. The twin plane is a boundary which separates two
orientations that are mirror images of one another. In other words, twinning
is formed by a uniform shearing of atoms parallel to the twin boundary,
figure 7. The strained part of the crystal becomes a mirror image of the zone
free from twin crystals with respect to the twinning plane. When the polished
surface of such a material is subjected to etching, usually the regions on both
sides of the twin boundary will be attacked differently because of a difference
in the atomic configurations. Hence, viewed under a reflected-light
microscope the surface will show dark and bright parallel regions (twin
boundaries) within each grain. Similar to slip bands, twin bands could be
viewed on the surface of the specimen. Examples of twin boundaries and
bands are shown in experiments number 4 and 5. Twinning occurs along
with the slippage. The fraction of deformation by twinning is greater in
hexagonal-lattice metals and in deformation occurring at great speed, as
explosion stamping or extrusion.

Exp. # 1: Slip Lines in Metals
Equipment: UTM, Metallurgical Microscope, Specimen Preparation Station,
4 copper (fcc), one iron (bcc)
PROCEDURE: 1) One side of the specimens of copper and iron is ground and
polished. 2) Measure the hardness of one of the copper specimens.
3) Examine the microstructures of the polished surfaces with a metallurgical
microscope. 4) Keep one of the specimens of copper in the UTM in such a way
that the polished surface is not in contact with the grips and deform the
specimen approximately 10 percent in compression. 5) One specimen of
copper is lightly etched and operation 4 is repeated to observe the change in
deformed structures from grain to grain, figure 8. 6) Repeat operations 4 and
5 on iron specimen, figure 9. 7) The remaining two specimens of copper are
deformed 5 percent and 20 percent, respectively. 8) Examine the
microstructures of the polished surfaces of the deformed specimens. 9)
Measure hardness of copper specimens. Plot hardness vs percent
deformation for copper specimens, figure 10, and conclude why does hardness
change as a function of percent deformation?
Exp. # 2: Dislocation in Ceramic by Etch Pit Pattern
Equipment: Reflected light microscope, Sodium Chloride crystal, anhydrous methyl alcohol, ether, blade
PROCEDURE: 1) Cleave the sodium chloride crystal with a single-edge razor blade. A slight press given to the blade placed on the crystal surface will bring about cleavage if the blade is properly oriented with respect to the cleavage planes. In sodium chloride these are (100). 2) Dip the crystal in anhydrous methyl alcohol and keep it there for a few seconds. 3) Take out the crystal, wash it in ether, and quickly dry it on a filter paper. 4) Put the specimen on a glass slide, mount the latter on the stage of the microscope and observe the etch pit patterns, figure 11.

Exp. # 3: Slip Bands
Equipment: Tensile specimen of mild steel, furnace, UTM
PROCEDURE: 1) Select a tensile specimen of mild steel. 2) Fully anneal the specimen and then polish the surface. 3) Load it in tension at a rate of 0.05 in/min. 4) Study the surface pattern just as the yield load is reached (Slip plane opens up on the surface as a band with an angle of 45° with respect to the load axis), figure 12.

Exp. # 4: Twin Boundaries
Equipment: Alpha-brass specimen, reflected-light microscope, etching solution, specimen preparation station
PROCEDURE: 1) The specimen is ground and polished to a mirror like surface. 2) Wash the specimen thoroughly with water and dry it with alcohol. 3) Immerse the specimen with polished surface upward in the etching solution for about 2 seconds. 4) Locate the specimen on the glass slide and mount the slide on the microscope stage and view it in the reflected light, figure 13.

Exp. # 5: Twin Bands
Equipment: A CPH-structure specimen such as zinc, specimen preparation station, UTM, reflected-light microscope.
PROCEDURE: 1) Select a CPH-structure metal such as magnesium, titanium, or zinc. 2) Cut the specimen about 8-in long and obtain a metallographic polish on the surface. 3) Place the specimen in a tensile stress and slowly load it while viewing the surface reaction (Twin planes appear as broad lines).

<table>
<thead>
<tr>
<th>structure</th>
<th>slip plane</th>
<th>slip direction</th>
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<tbody>
<tr>
<td>fcc</td>
<td>{111}</td>
<td>&lt;110&gt;</td>
</tr>
<tr>
<td>bcc</td>
<td>{101}, {112}</td>
<td>&lt;111&gt;, &lt;11\overline{1}&gt;</td>
</tr>
<tr>
<td>hcp</td>
<td>{0001}, {1010}</td>
<td>&lt;11\overline{2}0&gt;</td>
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Table 1: Slip planes and slip directions for some type of structures
References:

Figure 1. The lattice distortion at the boundary between two perfect regions in a slip.

Figure 2. The regions of tension (light) and compression (dark) around an edge dislocation in a simple cubic lattice.
Figure 3. (a) A simple cubic lattice before slip, (b) the lattice traces a helical path in a screw-dislocation slip.

Figure 4. (a) Slip resulting from a pure edge dislocation, (b) Slip resulting from a pure screw dislocation.
Figure 5. Slip planes and their directions in an fcc crystal lattice.

Figure 6. Effect of orientation of slip plane upon character of deformation of monocrystals.

Figure 7. The formation of a twin in a tetragonal lattice.
Figure 8. Slip lines in a plastically deformed copper, 200X.

Figure 9. Slip lines in a plastically deformed iron, 300X.
Figure 10. Variation of hardness vs deformation.

Figure 11. Etch pit pattern (slip bands) in sodium chloride, 375 X.
Figure 12. Slip band of a deformed mild steel that makes a $45^\circ$ angle with the tensile load axis.

Figure 13. Twin boundaries as dark and bright regions within each grain in an $\alpha$-brass specimen, 400X.