Opportunities for X-ray Imaging of Plastically Deformed Metals

L. E. Levine
Metallurgy Division
National Institute of Standards and Technology
Gaithersburg, MD 20899-8553

The use of metals in modern society is so extensive that they have become an almost invisible backdrop to the world we live in. The combination of excellent mechanical, chemical, electrical and magnetic properties of metals (along with their relatively low price) makes them the materials of choice for a huge range of applications. Thus, the economic impacts of even incremental improvements in metals processing and forming are potentially immense. The automotive industry is an excellent case in point. Most of the weight of an automobile is metal and approximately 30 % of the vehicle weight is sheet metal that is shaped by stamping with dies. The design of these stamping dies is the largest single expense (excluding labor) for making a car. The reason for the high cost is that each stamping die must be redesigned and retested approximately 12 times before an acceptable part shape is obtained. Improvements to fuel economy require substituting new high-strength steels and aluminum alloys for the mild steel used today and this greatly exacerbates these problems since even more die redesigns are needed for these materials. Improved models of metals deformation are the key to reducing these costs considerably.

Although often thought of as a "low-tech" field, the plastic deformation of metals is phenomenally complex, with coupled processes covering the full range of length scales from the macroscopic down to individual atomic bonds. The changes in mechanical properties that occur during the plastic deformation of metals result from the complex interaction of huge numbers of mobile and immobile (trapped) line defects called dislocations. The immobile dislocations form three-dimensional cellular structures that evolve as the sample is deformed plastically. The dislocations interact via long range, 1/r, angle-dependent stress fields that become highly non-linear at short range. Even for the simplest possible systems, pure metal single crystals deformed in uniaxial tension, the underlying evolution of dislocation structures and the resulting changes in mechanical properties are beyond our current understanding. Including such complications as alloy chemistry, precipitation, grain structure, strain path, strain rate and temperature are not straightforward. Over the past ten years, international efforts to understand the underlying processes of plastic deformation have been expanding rapidly,[1] with major advances in atomistic simulations, 3D dislocation dynamics simulations, multiscale modeling, non-linear and statistical approaches, and new experimental techniques. Nevertheless, major gaps in our basic understanding exist and new experimental techniques capable of shedding light on these processes are necessary.

Figure 1 shows a TEM image of the dislocation cellular structure that formed within a pure Al single crystal during uniaxial tensile deformation of 15 % along an axis close to a <111> orientation. The walls of the cells are dense collections of dislocations and the differing gray shades of the cells reflect local changes in crystallographic orientation caused by the heterogeneous dislocation structure. The sizes, shapes, orientations and dislocation character of the cells and cell walls are very sensitive to the total strain and the tensile axis. Deformation occurs through the transport of mobile dislocations through this structure along specific crystallographic planes called slip planes. The slip process is extremely heterogeneous in both time and position. Figure 2 shows the surface of an Al single crystal deformed in uniaxial tension along an axis close to a <100> orientation.

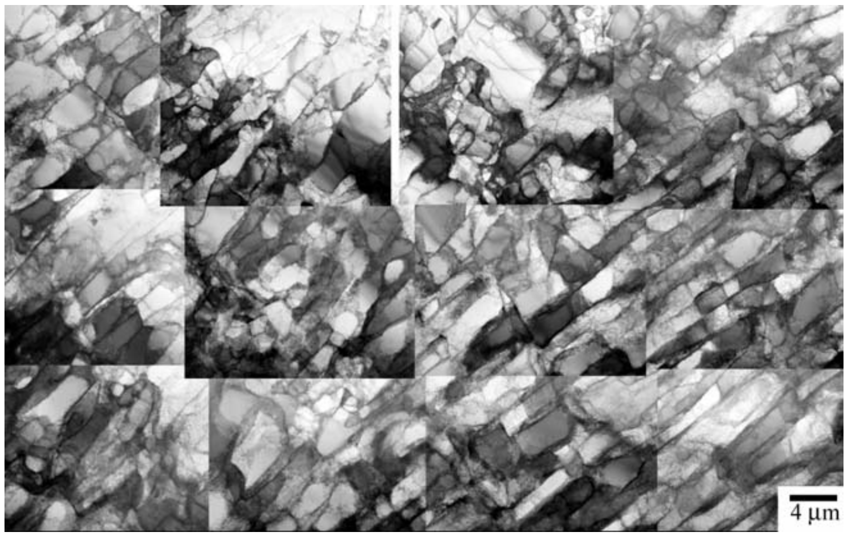

Fig. 1: TEM image of dislocation cells in an Al single crystal deformed 15 % in tension near a <111> orientation.

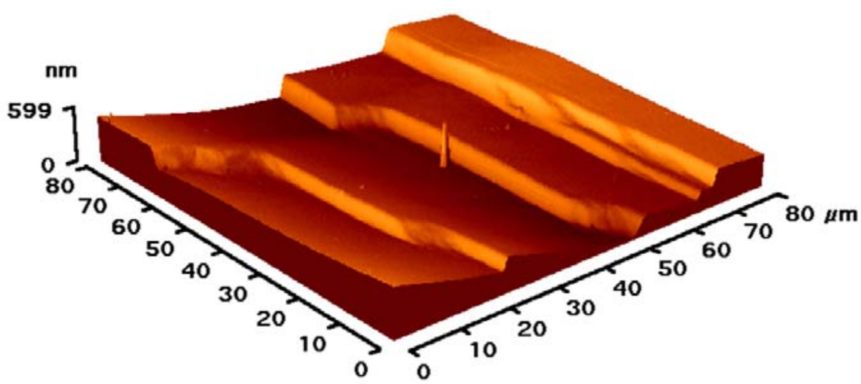

Fig. 2: AFM image of surface slip structure (slip bands) on an Al single crystal deformed 4 % in tension near a <100> orientation.

The heterogeneous nature of both the evolving dislocation structures and the slip distribution means that spatially and temporally localized data, obtained *in situ*, is needed. For pure single crystals, information is required on the spatial distribution of the cells and cell walls, the dislocation density and character of the walls, the local crystallographic orientations and the local stresses. For commercial polycrystalline materials, additional information is required on the grain orientations and the composition and distribution of precipitates.

[1]*Dislocations 2000: An International Conference on the Fundamentals of Plastic Deformation*, Ed. by L. Levine, L. Kubin and R. Becker, Mat. Sci. & Eng. **A**309-310, 2001