Space-time self-organization of plastic deformation of fcc single crystals

L. B. Zuev, V. I. Danilov, and N. V. Kartashova
Institute of the Physics of Strength and Materials Science, Siberian Branch of the Russian Academy of Sciences, 634048 Tomsk, Russia

(Submitted 24 August 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 7, 538–540 (10 October 1994)

Fundamentally new information on the nature of the plastic deformation of fcc single crystals has been found by speckle interferometry. The distinct stages on the curve of the plastic flow stem from differences in the nature of the propagation of plasticity fronts along the extension axis in the different stages of the flow. The evolution of local elongations during the deformation of single crystals has been studied.

The description of plastic deformation in crystalline solids is based on information extracted from analysis of the shape of the flow curve and study of the defect structure by optical and electron microscopy.[1] Certain difficulties usually arise in attempts to construct a reasonably rigorous description of the process of plastic flow, even for the simplest situations. These difficulties have prevented a convincing reconciliation of the data obtained by standard research methods. These difficulties were seen in the very first studies using dislocation theory, e.g., in efforts to explain the dynamics of the plastic flow of fcc single crystals[2] which have a three-stage flow curve, with very different strain-hardening coefficients $\Theta = d\sigma/d\epsilon$ in the different stages.

In this letter we are reporting some new results found in a study of plastic deformation of fcc single crystals by a method of speckle interferometry.[3] These results indicate some distinctive features of the process, which have not previously been considered. The validity of this method for studying plastic deformation was described and analyzed in Ref. 1; here we will simply mention that this method can be used to measure displacement vectors at any point on a plane surface during loading, and that the components of the strain tensor and the rotation can be calculated within an error $\lesssim 10^{-4}$. Analysis of these results can add substantially to our understanding of the kinetics of plastic deformation.[4,5] As the test samples we used single crystals of the alloy Cu+10% Ni +6% Sn grown by the Bridgman method. These crystals have a three-stage flow curve which is completely similar to the curves for the single crystals of Ref. 2, but with a higher yield point. This higher yield point makes it easier to manipulate the samples, and it improves the reproducibility of the results. Samples with a working region with dimensions of $25\times5\times1$ mm, cut by an electric-arc method, had a growth axis in the [111] orientation and a (111) $[\bar{1}01]$ acting glide system. The extension was carried out at a rate of 6.7×10^{-5} s^{-1}.

The data found under these experimental conditions are shown in Fig. 1. This is a distribution of the longitudinal strain component ϵ_{xx} along the axis of the sample during extension of the sample in the stages of easy glide and linear hardening. The behavior of

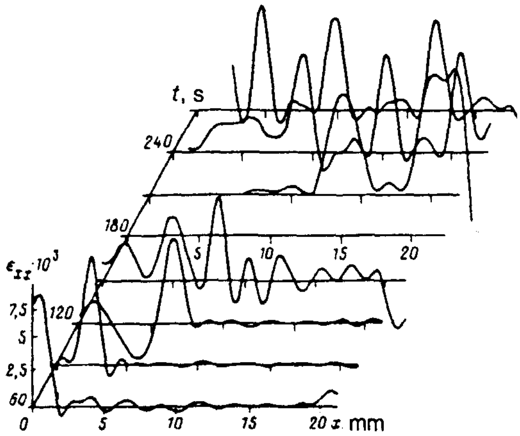

FIG. 1. Evolution of ϵ_{xx} during deformation of a single crystal.

the other components of the distortion tensor is similar. The primary result is that the patterns for these two stages are quite different. In the stage of easy glide (the lower part of the figure), a solitary seat of plastic flow ~6–8 mm in size propagates along the axis, at a velocity of $(6.5\pm 0.3)\times 10^{-5}$ m/s. Ahead of its front, and also behind it, the material is undeformed. When a seat of strain of this sort traverses the entire length of the sample, the stage of easy glide ends, as can easily be detected on the basis of the change in the strain-hardening coefficient.

In the picture observed in the stage of the linear hardening, in which Θ is larger by a factor of about 30, seats of plastic flow move along the axis, one behind another, at a velocity of $(7.5\pm 0.4)\times 10^{-5}$ m/s (Fig. 1). They are separated by an interval ~8 mm. Comparing the nature of the motion of the seats of plastic flow for each of the stages under consideration, we should point out two more important details. First, the directions in which the seats move are opposite: away from the fixed clamp of the testing engine toward the moving one in the stage of easy glide and away from the moving clamp toward the fixed one in the stage of strain hardening. Second, a correlation analysis[6] shows that the difference between the values of the propagation velocity given above is statistically significant.

The transition from one stage of the flow to another occurs through a stage of a random distribution of ϵ_{xx} along the extension axis, as can also be seen clearly in Fig. 1. The end of the stage of linear hardening and the transition to a parabolic stage, in which Θ falls off as the strain increases,[2] is again accompanied by the onset of a random distribution of ϵ_{xx}. Fixed zones of a localization of strain subsequently form from this distribution. We obtained corresponding results in a study of the deformation of Cu single crystals, also oriented for easy glide.

These results thus show that a space–time periodicity arises in the distribution of the components of the plastic-distortion tensor in the zone of plastic flow of fcc single crystals. A similar behavior seen previously in other materials[1,4,5] led to the idea that the plastic deformation is of an autowave nature.

It would seem a bit premature at this point to offer any definite arguments regarding the nature of the observed effects. Nevertheless, the close analogy with phenomena which occur in open systems far from equilibrium looks valid. A deformable medium falls in this class, since energy is continuously supplied to the sample from the loading device, and defects are created in the material itself. These defects substantially alter the properties of the material. We know that dissipative structures[7] can grow in systems of this type, in particular, in the form of autowave processes.[8] Interestingly, structures analogous to those observed during plastic flow are seen in experimental and theoretical research on some chemical and biological systems which have been studied quite extensively.[8]

The particular form of the autowaves which arise depends on the nature of the interaction between the dislocation displacements in the medium being deformed. We know[2] that the hardening in the easy-glide stage is governed by a dislocation interaction inside a planar pileup, and in the linear-hardening stage these pileups begin to interact with each other. This circumstance is apparently pertinent to the difference in the space–time distributions of the components of the plastic-deformation tensor observed experimentally.

The features of plastic flow observed here may play an important role in deformation and must not be ignored in a description of deformation and in the construction of any version of plasticity theory.

[1] *Structural Levels of Plastic Deformation and Fracture* [in Russian], ed. by V. E. Panin (Nauka, Novosibirsk, 1990).
[2] A. Seeger, in: *Dislocations and Mechanical Properties of Crystals* (New York, 1957), p. 243.
[3] C. Vest, *Holographic Interferometry* (Wiley, New York, 1979).
[4] V. E. Panin *et al.* Dokl. Akad. Nauk SSSR **308**, 1375 (1989) [Sov. Phys. Dokl. **34**, 940 (1989)].
[5] L. B. Zuev *et al.*, Dokl. Akad. Nauk SSSR **317**, 1386 (1991).
[6] D. Hudson, *Statistics* (CERN, Geneva, 1964).
[7] G. Nicolis and I. Prigogine, *Self-Organisation in Nonequilibrium Sistems* (Wiley, New York, 1977).
[8] V. A. Vasil'ev *et al.*, *Autowave Processes* [in Russian] (Nauka, Moscow, 1987).

Translated by D. Parsons