JMEPEG (2000) 9:170-173 ©ASM International

On the Initial Stage of Plastic Deformation of Metal Alloys

L.B. Zuev, V.I. Danilov, and S. Yu Zavodchikov

(Submitted 3 July 1998, in revised form 26 October 1999)

Plastic deformation has been studied for a range of metal alloys using speckle interferometry. It has been found that, in the initial stage, the process of plastic flow occurs by the propagation of a deformation front, which divides the deforming material into two regions differing with respect to the material's state. The flow exhibits regular features that can be described in terms of a self-excited wave process manifesting itself in an active medium under external mechanical action.

Keywords plastic deformation, speckle interferometry, yield-point plateau, easy-glide stage, localization of strain, self-excited waves of deformation, active medium

1. Introduction

Plastic flow of solids is known to cause changes in the state of the medium under deformation,[1] which are largely associated with the changes occurring in the ensemble of lattice defects, one of the most common manifestations of effects of this kind being dislocation density growth. During plastic deformation, various sets of dislocations are likely to emerge, *e.g.,* planar pileups of dislocations, dislocation walls, unit dislocations, *etc.;*[2] these subsequently evolve in an intricate manner, with one type of dislocation set giving way to another. Numerous attempts have been made to relate the types of ensemble of defects to the strongly pronounced stages on the plastic flow curve. However, different workers had to restrict their consideration to a purely qualitative analysis, with partial success (if any). The complexity of experimentally observable ensembles of defects and the availability of data on their evolution led to a hypothesis of the ensemble of defects undergoing self-organization in the material under deformation.[3] In order to elucidate the process, the concepts of synergetics had to be invoked.[4–6] However, investigations of these types of phenomenon have been generally carried out for a range of chemical and biological systems, while a deformed medium does not appear in the literature (see, for example, Ref 4 to 6). Nevertheless, use of the apparatus of synergetics to address the process of self-organization occurring in an ensemble of lattice defects seems to be a promising line of research.[6] A deforming medium is known to be nonequilibrium and nonlinear,[7] since a deforming system is open to energy supplied from without. It is therefore contended that, at such conditions, the synergetic approach may be applied.[5]

The above problem can hardly be solved using the microscopic strategy, which is common practice in plasticity physics, since, by detailed examination of ensembles of defects evolving in small-bulk specimens, the interrelationships among neighboring zones of the specimen and such as are far removed from one another escape detection. In our opinion, progress can be made possible by using a technique, which (1) has resolution comparable to optical microscopy (<1 mm) and (2) allows the entire specimen or areas comparable in size to the specimen to be examined. The above two requirements are met by different variants of holography.[8,9] A technique of this kind was used to study a range of metal alloys.

2. Experimental Procedure and Specimens

In our work,[10–13] we used speckle interferometry,[9] a version of focused-image holography,[8] which met the above two requirements. Speckle interferometry has an additional advantage in that this can be used in conjunction with routine methods of mechanical testing of materials; moreover, the experimental procedure employed is relatively simple.

The application of speckle interferometry to materials testing is described elsewhere;[14] in what follows, the basic capabilities of the method will be emphasized. Speckle interferometry is used to measure the displacement vector at all the points on a thin flat specimen under active loading, with an increment in the total deformation being 0.1 or 0.2%. A series of measurements were performed from yield point to fracture, and the evolution of the field of the displacement vectors in the course of plastic flow was examined. Then, numerical differentiation of the field of the displacement vectors ***r****(x, y)* yielded the components of the plastic distortion tensor:[15]

$$\beta = \nabla r = \left|\frac{\varepsilon_{xx}\varepsilon_{xy}}{\varepsilon_{yx}\varepsilon_{yy}}\right| + \omega_z \qquad \text{(Eq 1)}$$

(x is the tension axis). In Eq 1,

$$\varepsilon_{xx} = \frac{\partial_{r_x}}{\partial_x}; \varepsilon_{yy} = \frac{\partial_{r_y}}{\partial_y} \qquad \text{(Eq 2)}$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial_{r_y}}{\partial_x} + \frac{\partial_{r_x}}{\partial_y}\right) \qquad \text{(Eq 3)}$$

$$\omega_z = \frac{1}{2}\left(\frac{\partial_{r_y}}{\partial_x} - \frac{\partial_{r_x}}{\partial_y}\right) \qquad \text{(Eq 4)}$$

The calculated values of the components could be represented in different forms, in particular, as functions of the coordinates x and y for a specified instant of time or as time functions for a specified point on the specimen. The components from Eq 1 can be measured to an accuracy of $<10^{-4}$ and the displacement vector to an accuracy of <0.1 mm.

L.B. Zuev, V.I. Danilov, and **S. Yu Zavodchikov,** Institute of Strength Physics & Materials Science, Russian Academy, Sciences (Siberian Branch), 634021, Tomsk, Russia.

The study was made using the following materials:

- low-carbon steel (<0.1% Ñ by weight);
- single Cu-Ni-Sn alloy crystals (10% Ni and 6% Sn by weight);
- Ni_3Mn alloy in an ordered polycrystalline state; and
- single TiNi alloy crystals.

All the materials investigated have a feature in common: at the outset of deformation, the value of the coefficient of work hardening $d\sigma/d\varepsilon$ is close to zero or an easy-glide stage is observable (Cu-Ni-Sn in a tempered state). The deformation of the above materials (with the exception of TiNi) involves dislocations motion,[1] while in the latter case, martensitic transformation-related deformation takes place in the material.[16]

Thin flat specimens with a gauge section having dimensions $50 \cdot 10 \cdot 1$ or $30 \cdot 5 \cdot 1$ mm^3 were subjected to tension along the longitudinal axis x in an Instron-1185 testing machine (Instron Ltd., England) at a rate of $<5 \cdot 10^{-5}$ s^{-1}. At the yield plateau, five to ten speckle photographs were obtained and the components of the plastic distortion tensor were calculated for the different moments of the deformation.

3. Main Experimental Results

The microscopic features of the plastic deformation occurring in the above materials are well known. The above technique was used to examine the strain distribution in the deforming material volume. In the yield-plateau stage of flow, the Lüders band visible to the unaided eye is known to emerge in low-carbon steel under deformation;[17] in the vicinity of the Lüders band, strain localization is observed, with the band front separating the deformed from the undeformed material volume. Speckle interferometry reveals a number of significant peculiarities in this seemingly thoroughly studied phenomenon.[11] The region of localized rotations and the extreme values of the other components of the plastic distortion tensor (see, for example, ε_{xx} in Fig. 1) are evidently similar to the Lüders band front observable in steel. Allegedly, this phenomenon was not observable in other materials. However, the use of speckle interferometry helped ascertain that this picture is common enough, and in the yield-plateau stage, the above peculiarities were found to reveal themselves in Ni_3Mn, Cu-Ni-Sn, and TiNi as well. The motion velocities of plastic deformation fronts were measured for the materials investigated; the data obtained are listed in Table 1. The distributions of plastic deformation nuclei obtained for the specimens examined are illustrated in Fig. 2 to 4. Comparison of the above distribution patterns obtained for different materials reveals close similarity of the main features, *i.e.*, front width and motion velocity, the rate of propagation of the deformation front being determined by the straining rate of the specimen in a testing machine.

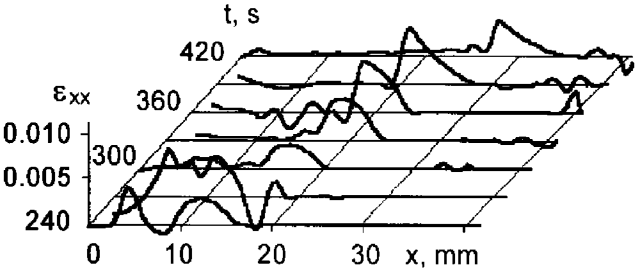

Fig. 1 The deformation front moving in the yield-plateau stage of the loading curve obtained for the low carbon steel

Table 1 The motion velocities of plastic deformation fronts

Materials	$\nu \cdot 10^5$, m/s	$D \cdot 10^7$, m^2/s
Cu-Ni-Sn	6	27
Low carbon steel	4.5	22.5
Ni_3Mn	10	30
TiNi	1	2.3

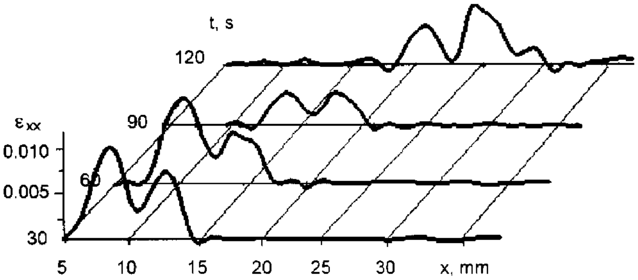

Fig. 2 The deformation front moving in the yield-plateau stage of the loading curve obtained for the alloy Ni_3Mn

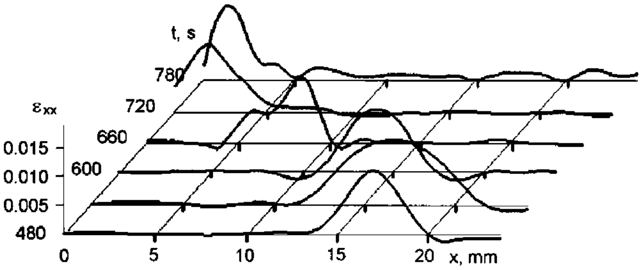

Fig. 3 The distributions of local strains ε_{xx} observed in the yield-plateau stage of flow for the tensile TiNi alloy specimen

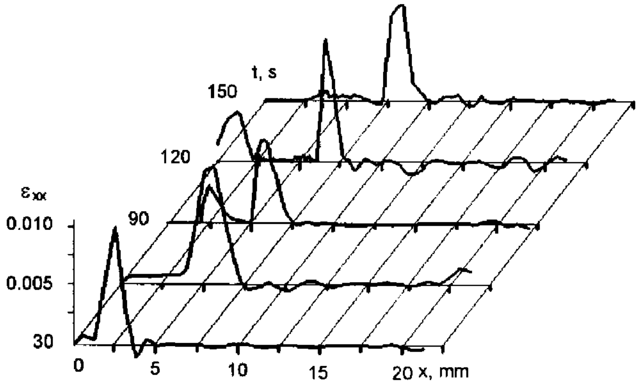

Fig. 4 The distribution of local strains ε_{xx} observed in the easy-glide stage of flow for the Cu-Ni Sn alloy specimen under deformation

During transition from the yield-point plateau ($d\sigma/d\varepsilon = 0$) to the work-hardening stage ($d\sigma/d\varepsilon > 0$), the former pattern breaks and, in the material under deformation, emerge chaotically distributed components of the plastic distortion tensor. Later on, a localized strain pattern forms out of chaos, which is different from the ones illustrated in Fig. 1 to 4. Thus, a pronounced difference between the localized strains patterns observed in the deforming material in the linear and the parabolic work-hardening stage suggests that the same patterns depend critically on work hardening type.

Thus, examination of a range of plastically deforming materials at the stage of yield-point plateau allowed one to establish the peculiarities of the process common to all the materials investigated. In the yield-plateau stage, a localized strain zone moves at a constant rate along the specimen; in the case of low-carbon steel, the same zone is similar to the Lüders band. The material structure before the moving zone remains virtually intact. After the yield-plateau stage is over, the pattern observed changes crucially.

4. Interpretation of the Experimental Results

In our discussion, attention will be directed to the regular features of plastic flow instabilities common to all the materials investigated. The main feature is as follows. In the yield-point plateau (steel, TiNi, and Ni_3Mn) or easy glide stage (Cu-Ni-Sn), a plastic flow front propagates along the specimen, thereby dividing it into two regions. Strain localization takes place in the vicinity of such a front.

It can be stated with reasonable confidence that the material volumes behind the front and ahead of it are in different states. Consider the situation for each of the above materials. The front traveling in the tensile TiNi specimen destabilizes the intact structure ahead if it and enables the instability to spread, so that the material before the front is in an austenitic (B2) phase,[16] while that behind the front is in a martensitic (B19′) phase, with different mechanisms of plastic flow and of work hardening operating in each of the above material volumes. As the Lüders band front propagates in the low carbon steel under deformation, dislocation motion in the region before the front is impeded by interstitial atom clouds,[17] while the dislocations behind the front are unimpeded by any obstacle and can move easily, which accounts for the difference between the higher and the lower yield points. By the plastic flow of the ordered Ni_3Mn alloy, the long-range order is impaired[18] with a resultant change in the mechanical properties of the deformed material. And last, in the easy-glide stage of flow, dislocation shear lines form in the single Cu-Ni-Sn alloy crystals in a single-phase state;[2,17] this differs from stochastically distributed dislocations in the original material.

Consequently, in the initial stage of plastic flow, the deforming material passes irreversibly to a state different from that of the original material. This finding is sustained by the fact that, after the load is relieved and the same specimen is loaded once again, the plastic flow curve σ-ε never regains its former aspect.

Similar situations are frequently observed when dealing with chemical and biological systems.[4–6,19] In such instances, the traveling front is regarded as a switching self-excited wave of a kind[19,20] that is capable of propagating in an active bistable medium, *i.e.*, such as is in either of the two stable states.[19] The latter is described by a differential equation of the following type:[19,20]

$$\varepsilon = f(\varepsilon)\ D\varepsilon'' \qquad \text{(Eq 5)}$$

where ε is the function describing the system's state; $f(\varepsilon)$ is the nonlinear function, *i.e.*, the rate of the process occurring in a local material volume; and D is a coefficient having the units of the diffusion coefficient ($m^2\ s^{-1}$). In the given case, ε is taken to denote deformation proper. For a self-excited wave to be generated, it is essential that the function $f(\varepsilon)$ should be N shaped. When dealing with plastic deformation, this can be interpreted qualitatively. It has been proven experimentally that plastic deformation has a jumplike character.[17] This is illustrated schematically in Fig. 5, where the elastic deformation rate ε_e is plotted against total deformation $\varepsilon f(\varepsilon)$; the dependence is N shaped when the value of ε is equal to zero. It follows from the above that the emergence and propagation of a switching self-excited wave in the systems studied is a probability.[21] As based on the experimental data listed in Table 1, the values of the coefficient D and of the motion velocity of a self-excited wave, ν, could be assessed. The two sets of values are found to be related;[19] *i.e.*,

$$\nu \approx \left(\frac{D}{\tau}\right)^{1/2} \qquad \text{(Eq 6)}$$

where τ is the time of relaxation of the process. From Eq. 6, we obtain $\tau > 10^3$ s. The same value is obtained from measurements of the time required for the deformation front to traverse the entire specimen length or from the calculated ratio of yield plateau length to macroscopic deformation rate.

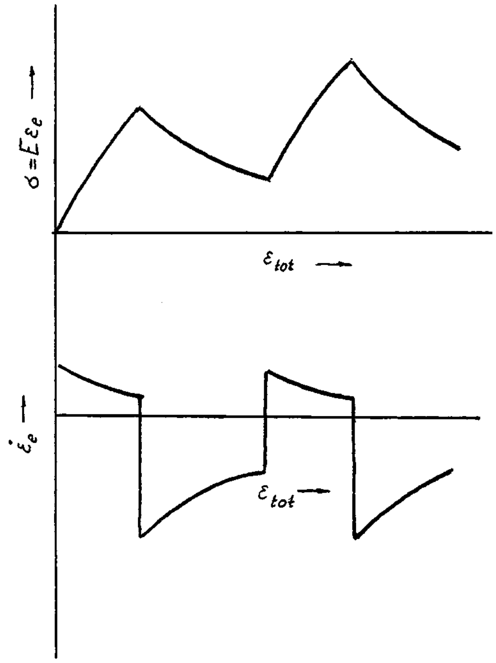

Fig. 5 The jumplike regime of deformation

5. Conclusions

- In the initial stage of flow, the instabilities are found to spread by the propagation of a plastic flow front in a range of metals and alloys having a yield-plateau or an easy-glide stage.
- Such a traveling front is regarded as a switching self-excited wave generating in the bistable active medium of the deforming material.
- At the end of the initial stage of flow, the material under deformation passes to a different state (different type of active medium), which favors generation of other types of self-excited wave.

References

1. J.W. Christian: *The Theory of Transformations in Metals and Alloys,* Pergamon Press, Oxford, United Kingdom, 1975, p. 1.
2. *Electron Microscopy and Strength of Crystals,* Interscience Publ., New York, NY, 1963.
3. *Cooperative Processes of Deformation and Strain Localization,* V.E. Panin, ed., Naukova Dumka, Kiev, 1989 (in Russian).
4. H. Haken: *Advanced Synergetics,* Springer-Verlag, Berlin, 1983.
5. H. Haken: *Information and Self-Organisation,* Springer-Verlag, Berlin, 1988.
6. G. Nicolis and I. Prigogine: *Exploring Complexity,* W.H. Freeman and Co., New York, NY, 1989.
7. *Non-Linear Phenomena in Material Science. Solid State Phenomena,* Proc. Int. CNRS Meeting, Aussois, France, L.P. Cubin and G. Martin, eds., 1988, vol. B3-B4.
8. C. West: *Holographic Interferometry,* John Wiley & Sons, New York, NY, 1979.
9. R. Jones and C. Wykes: *Holographic and Speckle Interferometry,* Cambridge University Press, Cambridge, United Kingdom, 1983.
10. V.E. Panin, L.B. Zuev, and V.I. Danilov: *Dokl. Akad. Nauk USSR,* 1989, vol. 308(6), pp. 1375-79 (in Russian).
11. L.B. Zuev, V.E. Panin, N.M. Mnikh, and V.I. Danilov: *Dokl. Akad. Nauk USSR,* 1991, vol. 317 (6), pp. 1386-89 (in Russian).
12. V.I. Danilov, N.V, Kartashova, and L.B. Zuev: *Fiz. Metall. Metallvd.,* 1994, vol. 78 (1), pp. 141-46.
13. L.B. Zuev, V.I. Danilov, and N.V. Kartashova: *JETP Lett.,* 1994, vol. 60, pp. 553-55.
14. S. Yoshida, Y. Hida, V.E. Panin, and L.B. Zuev: in *Strength of Materials,* H. Oikawa, ed., The Japan Institute of Metals, Tokyo, 1994, p. 295.
15. R. de Wit: in *Fundamental Aspects of Dislocation,* J.A. Simmons, R. de Wit, and R. Bullough, eds., National Bureau of Standards, Washington, DC, Special Publication, 1970.
16. V.S. Boiko, R.I. Garber, and A.M. Kosevich: *The Reversible Plasticity of Crystals,* Nauka, Moscow, 1991 (in Russian).
17. D. McLean: *Mechanical Properties of Metals,* John Wiley & Sons, New York, NY, 1963.
18. N.S. Stoloff and R.G. Davies: *The Mechanical Properties of Ordered Alloys,* Pergamon Press, Oxford, United Kingdom, 1966.
19. A. Yu. Loskutov and A.S. Mikhailov: *Introduction to Synergetics,* Nauka, Moscow, 1990 (in Russian).
20. V.A. Vasiliev, Yu. M. Romanovsky, and V.G. Yakhno: *Self-Excited Wave Processes* Nauka, Moscow, 1987 (in Russian).
21. S. Kyriakides: in *Advances in Applied Mechanics,* J.W. Hutchinson and T.Y. Wu, eds., Academic Press, Boston, MA, 1994.