Journal of Applied Mechanics and Technical Physics, Vol. 39, No. 1, 1998

ANALYSIS OF FRAGMENTATION OF DEFORMATION IN Ni_3Ge SINGLE CRYSTALS

Yu. A. Abzaev, V. A. Starenchenko,
Yu. V. Solov'eva, A. I. Potekaev, and É. V. Kozlov

UDC 539.4.015

The strain distribution on two faces of Ni_3Ge *single crystals compressed to a strain* $\varepsilon = 14.16\%$ *at* $T = 77.673$ K *was studied by the grid method. It is shown that temperature has a significant effect on the strain distribution. Fragmentation of local strain due to shape change in specimens during active loading was established by the method of main components.*

Plastic deformation of single crystals leads to formation of macroscopic regions in which the strains differ considerably from the average values. A characteristic of these regions is that deformation in them is performed by slip systems that differ from slip systems in other regions of the crystal [1]. Therefore, in some cases, distinct fragmentation of crystals occurs, which is most pronounced in rough slippage. This phenomenon was observed in studies of macroscopic plastic deformation of single crystals of Ni, Cu, 88% Cu–12% Al [1–3].

Strain domains in alkali halide single crystals were detected by polarization methods. Deformation domains in LiF single crystals were detected using a cholesteric liquid. In single crystals of metals, fragmented deformation occurs against a background of formation of nonuniform disordered substructures. Characteristically, deformation of Ni_3Ge single crystals leads to formation of a chaotic homogeneous dislocation substructure, which is retained up to very high dislocation densities. In this case, slip turns out to be very thin: the shear in a slip trace is $\sim 1.0\text{–}1.4 \cdot 10^{-8}$ m. The natural question arises as to whether fragmented deformation (formation of macroscopic deformation domains) occurs in the case of thin slip. Direct methods of observation of slip lines have not provided answers to this question, because it is necessary to perform studies on large areas, and this decreases the resolution of slip traces. At the same time, it is possible to analyze the macroscopic distribution of plastic deformation on the surface of a specimen using the grid method. However, use of the grid method alone allows one to judge only the degree of nonuniformity of the plastic-strain distribution over a specimen, and the question of fragmentation of plastic deformation remains to be solved. This difficulty can be surmounted using powerful methods of statistical analysis that establish a correlation between various phenomena and processes.

The objective of the present paper is to study fragmentation of plastic deformation in Ni_3Ge single crystals at various temperatures using the grid method and statistical analysis. The statistical methods include spectral, correlation, and factor analysis.

Experimental Procedure and Results. In the present paper, we study Ni_3Ge single crystals of [111] orientation and dimensions ($3 \times 3 \times 6$) mm grown by the Czochralski method. They were subjected to compression at a rate $\dot{\varepsilon} = 0.002$ sec^{-1} to strains $\varepsilon = 14\%$ (at $T = 77$ K) and $\varepsilon = 16\%$ (at $T = 673$ K). Under these test conditions, the cubic and octahedral slip systems have significantly different Schmidt factors ($\chi = 0.471$ and $\chi = 0.272$, respectively). Either the octahedral ($T = 77$ K) or cubic ($T = 673$ K) system dominates in this case [4]. The faces of the single crystals coincided with the crystallographic planes $(1\bar{1}2)$ and (110). The orientations of the strain axis and the crystal faces were determined from Laue patterns with an error of $\pm 2°$. Our analysis of slip traces showed that slip occurs over the octahedral system (111) at $T = 77$ K

Tomsk State Architecture-Construction Academy, Tomsk 634003. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 39, No. 1, pp. 154–159, January–February, 1998. Original article submitted January 29, 1996; revision submitted May 7, 1996.

0021-8944/98/3901-0135 $20.00 © 1998 Plenum Publishing Corporation

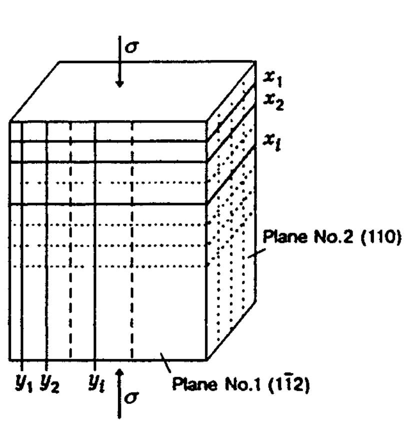

Fig. 1

and the cubic systems (100) [011] and (010) [101] at $T = 673$ K. Traces obtained experimentally (on the end faces) differ from the calculated traces by 3° on plane No. 1 (1$\bar{1}$2) and 0.5° on plane No. 2 (110).

To study local deformation, a grid of mutually perpendicular lines with a step of ~0.14 mm was applied on polished faces by means of a rigidly fixed "'Neva" blade using of a goniometer head. The minimum grid size, in accordance with the goniometer calibration, was 0.04 mm. The width of a grid line was ~0.01 mm. Strain values for the sides of a grid cell were obtained both along the direction of applied load (compressive strain) and perpendicular to it (tensile strain) using a PMT-3M microhardness gauge fitted with a computer with an FOM-2 micrometer. The discrete variables of the numerical sequences of compressive and tensile strains are denoted by x_i and y_i, respectively (Fig. 1). The grid origin on all faces coincides with the left upper corner of the specimen face (σ is external applied stress).

The order of the numerical sequences of compressive–tensile strains made it possible to study multidimensional correlations using known matrices of correlations by pairs and the method of main components [5]. It should be noted that for analysis of fragmentation, we used lines x_i and y_i (Fig.1) that crossed the entire specimen. Obviously, the dimensions of the domain in this case correspond to the dimensions x_i and y_i. Distinguishing partial numerical sequences of the variables x_i and y_i aimed at establishing small-scale domains (without changing the grid size) would not have led to success, because the sample of grid sizes would be small (the maximum size for x_i and y_i is about 40 elements). For a sufficient sample (in our case grids of much smaller size), this method allows one to detect all deformation domains.

Spectral analysis of all sequences by the EVRISTA method showed that, in the studied scale of 0.14–6 mm, smoothed spectra and power spectra do not show peaks, i.e., no structuring of local strain is observed. Figures 2 and 3 show examples of surfaces of compressive strain ε_c and tensile strain ε_t on plane No. 1 (a and b) and plane No. 2 (c and d) (Fig. 2 for $T = 77$ K and Fig. 3 for $T = 673$ K). Detailed analysis of the local strain showed that it develops nonuniformly. Regions having close strain values are distinguished. The local compressive strains vary over a wide range: from nearly zero values to 30–35%, differing significantly from average values. Negative-strain regions are observed. At low temperatures, the deformation is more uniform over the crystal, and at $T = 673$ K, it is more localized. On plane No. 1, the local strain is more chaotic at $T = 77$ K than at $T = 673$ K, because the dispersion of the compressive strain is higher. The local tensile strain ε_t is much more chaotic. At some sites, both strongly extended ($\varepsilon \approx +10\%$) and strongly compressed regions ($\varepsilon \approx -10\%$) occur. On plane No. 1, these series are primarily stationary, but higher irregularity is observed at sites where the compressive strain ε_c is relatively small.

On plane No. 2 the deformation is nonuniform at $T = 77$ and 673 K. At the center of the plane, the local strain is twice the strain near the edges. At the beginning and the end of the face, this difference is smaller. The strain is generally more chaotic at $T = 77$ K. For all planes and test temperatures, the local strain is highly stochastic: $\sigma_i/\langle x_i\rangle$ and $\sigma_i/\langle y_i\rangle \approx 0.2$–1.0, where $\langle x_i\rangle$ and $\langle y_i\rangle$ are the average values for compression and tension, and σ_i is the variance, i.e., the variances for the variables are comparable with the

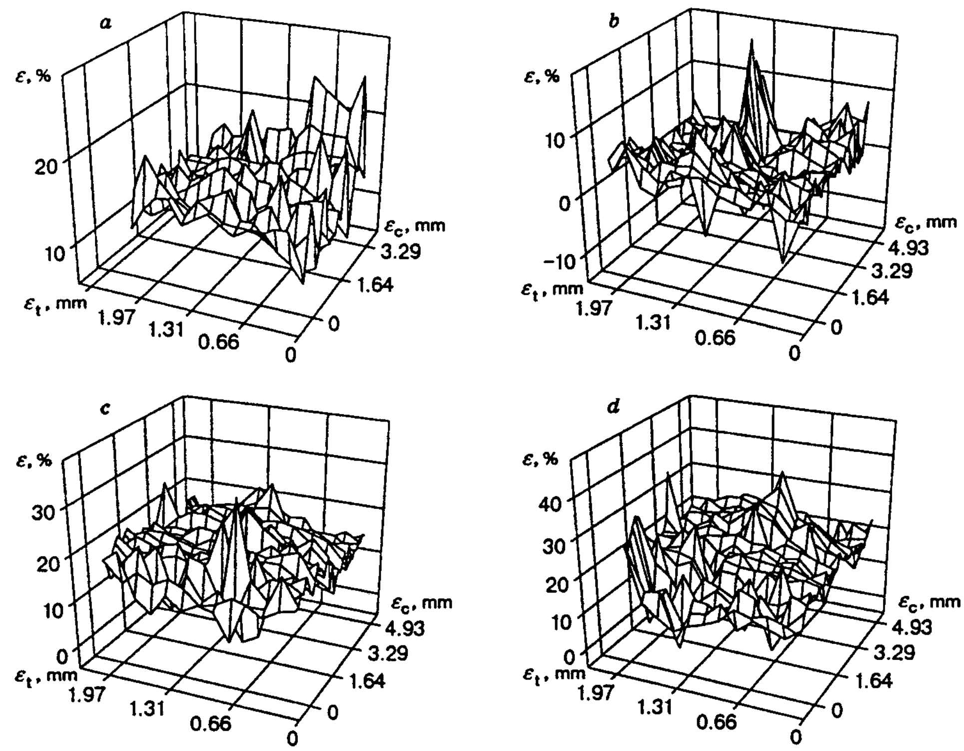

Fig. 2

average values.

Factor-analysis results for joint ordered numerical sequences of compressive and tensile strains are given in Table 1, which gives the values of the factor loads F after rotation in factor space that make the greatest contribution to the "explained variance" [5]. Table 1 gives only those load factors that are representative in the number of variables and have the largest values. The variable numbers N on different faces are also given.

Analysis of Table 1 shows that strong clustering of the local strain variables occurs in factor space. The variables of the compressive and tensile strains form independent clusters (or strain domains in real space) at $T = 77$ K, and at $T = 673$ K (especially on plane No. 2) superposition of these strain types in two clusters is observed. On plane No. 1, upon activation of the octahedra, the compressive strain is divided into two clusters, which are characterized by independent behavior at the edges of the plane: the first is formed by the variables y_1–y_5, and the second by the variables y_{10}–y_{14}. In addition, a single strain domain is formed by tension (x_1, x_6, x_{11}, x_{12}) at the edges of the plane.

For slip over cubic systems ($T = 673$ K), the character of the fragmentation changes: the behavior of the compressive strains became the same at the edges of the specimen, and they formed a common domain. A second domain is formed by the central region of the crystal. At $T = 77$ K, the central part deformed chaotically. On plane No. 2 at $T = 673$ K, clusters of variable compressive and tensile strains are most representative. In this case, the same compressive and tensile strains are observed at the edges of the specimen (the 7th and 8th columns) and in the central region (the 9th and 10th columns). The occurrence of the aforementioned clusters is apparently caused by the shape change of the specimen during deformation, i.e., by division of the crystal into uniformly and nonuniformly deformed regions [6]. The fragmentation is determined by the location of the deformed region of the crystal rather than by the strain characteristics.

In conclusion, the following should be noted. The method of main components is suitable for a search for any small-scale strain domains. This procedure is restricted only by the resolution of the goniometer head, the sample size, and the fact that the detected domains turn out to be unrelated [5]. The latter is not necessarily the case.

Thus, it is established that the deformation in Ni_3Ge single crystals proceeds nonuniformly over the

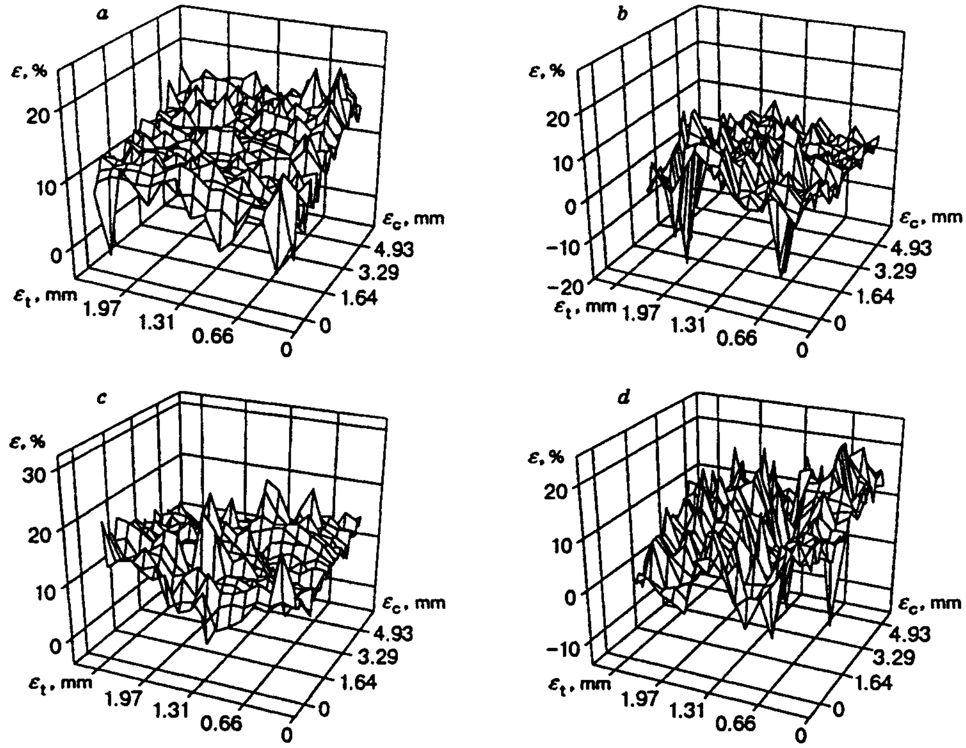

Fig. 3

TABLE 1

Plane No. 1 (T = 77 K)						Plane No. 1 (T = 673 K)							
N	F	N	F	N	F	N	F	N	F	N	F	N	F
1	2	3	4	5	6	7	8	9	10	11	12	13	14
x_7	0.45	x_6	0.56	x_1	0.91	y_5	0.41	x_6	0.79	x_{10}	0.45	x_8	0.53
x_9	0.62	x_{12}	0.53	x_6	0.72	y_7	0.49	x_7	0.57	y_1	0.51	x_{10}	0.41
y_{10}	0.55	y_1	0.90	x_{11}	0.59	y_9	0.47	x_8	0.64	y_2	0.79	x_{11}	0.80
y_{11}	0.58	y_2	0.89	x_{12}	0.45	y_{10}	0.45	x_{10}	0.58	y_3	0.54	x_{14}	0.80
y_{12}	0.83	y_3	0.85			y_{11}	0.88	x_{12}	0.72	y_4	0.45		
y_{13}	0.94	y_4	0.64			y_{12}	0.79	x_{13}	0.92	y_5	0.62		
y_{14}	0.83	y_5	0.60			y_{13}	0.44	y_1	0.45	y_6	0.87		
										y_7	0.53		
										y_8	0.78		
										y_{14}	0.86		
										y_{15}	0.50		
Plane No. 2 (T = 77 K)						Plane No. 2 (T = 673 K)							
N	F	N	F	N	F	N	F	N	F	N	F	N	F
1	2	3	4	5	6	7	8	9	10	11	12	13	14
x_2	0.41	y_5	0.51	y_1	0.57	x_1	0.85	x_3	0.57	x_2	0.65	x_8	0.67
x_3	0.81	y_6	0.66	y_2	0.93	x_2	0.65	x_4	0.70	x_9	0.88	y_7	0.88
x_4	0.84	y_7	0.75	y_3	0.84	x_3	0.51	x_5	0.89				
x_5	0.85	y_8	0.78			x_{10}	0.65	x_6	0.85				
x_6	0.85	y_9	0.73			x_{11}	0.78	x_7	0.71				
x_7	0.86	y_{10}	0.93			x_{12}	0.73	y_3	0.78				
x_8	0.84	y_{11}	0.83			x_{14}	0.83	y_4	0.77				

volume of the crystal. Regions in which the local strain is much higher or lower than the average strain are distinguished. In octahedral slip (T = 77 K), the strain is more uniform but is much more chaotic than the strain over cubic systems (T = 673 K). In Ni_3Ge single crystals that are characterized by a stable chaotic distribution of dislocations, fragmentation of the deformation of the specimen as a whole is observed. Three main fragmentation regions are established: a central region and the edges of the planes. The occurrence of a strain domain is affected by the slip characteristics, deformation, and test temperature. No structuring of local strain was observed on all the planes studied.

REFERENCES

1. N. Yu. Ivanova and V. A. Starenchenko, "Regularities of development of the deformation relief and a dislocation structure in highly deformed single crystals of Ni and alloys based on it," in: *Physics of Strength and Plasticity* [in Russian], Kuibyshev (1986), pp. 82–83.
2. V. A. Starenchenko, L. G. Chernykh, and N. Yu. Ivanova, "Features of the deformation relief in highly deformed Cu and Ni single crystals," *Izv. Vyssh. Uchebn. Zaved., Fiz.*, No. 8, 116–118 (1989).
3. T. S. Kunitsyna, V. A. Starenchenko, and N. A. Koneva, "Regularities of development of the dislocation structure in highly deformed single crystals of Cu–12 at.% Al," in: *Structure of Dislocations and Mechanical Properties of Metals and Alloys* [in Russian], Sverdlovsk (1990).
4. H.-r. Pak, T. Saburi, and S. Nenno, "The effect on the temperature dependences of yield stress in Ni_3Ge single crystals," *Trans. JIM*, 19, No. 1, 35–42 (1978).
5. K. Iberla, *Factor Analysis* [Russian translation], Statistika, Moscow (1980).
6. Yu. A. Abzaev, Yu. V. Solov'eva, and É. V. Kozlov, "On the calculation of shear stresses in Ni_3Ge single crystals," *Izv. Vyssh. Uchebn. Zaved., Fiz.*, No. 6, 45–53 (1995).