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Deformation localization and ultrasonic wave propagation rate in tensile Al as a function of grain size

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Abstract

The grain-size dependence of the space period (wavelength) of flow localization observed in the stage of parabolic work hardening of polycrystalline Al has been investigated. The dependence behavior has been defined in the range of grain sizes $8 \times 10^{-3} \leqslant D \leqslant 4.5$ mm and the significance of the relationship has been elucidated. The effect of grain size on the multi-stage behavior of plastic flow curve and on ultrasonic wave propagation rate has been considered.

Keywords: Plastic flow; Ultrasound propagation rate; Deformation localization; Structure

1. Introduction

In the last few years much progress has been achieved toward an understanding of the nature of plastic flow localization by invoking the concept of self-organization of faulted structure. The principal contributions to the comprehension of the problem above were made by Aifantis (1984, 1987, 1995, 1996, 1999, 2001) and also by Estrin and Kubin (1986), Saxlova et al. (1997), Zaiser and Hähner (1997). That the given approach is appreciate and workable is substantiated by the results of the experimental investigations of plastic flow occurring in metals and alloys in a single crystal and a polycrystalline state (Zuev and Danilov, 1997, 1998, 1999; Zuev, 2001). It has been found that in the course of this significant and interesting phenomenon, the arrangement and evolution of plastic flow nuclei exhibit certain regular macroscopic features. Thus it is shown that in the stage of linear work hardening ($\sigma \sim \varepsilon$), the flow nuclei form a running wave propagating along specimen extension axis, while in the stage of parabolic work hardening ($\sigma \sim \sqrt{\varepsilon}$), they are arranged into a stationary pattern.

However, to gain a more penetrating insight into the nature of this phenomenon, it is necessary to obtain sufficiently detailed data on the grain-size dependence of wavelength observed for polycrystalline materials. By virtue of being a natural structural characteristic, the above quantity is assumed to appreciably affect the parameters of strain localization in the polycrystal. Thus we investigated the space period of flow

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localization as a function of material grain size as well as the multi-stage flow behavior and the related variation of the ultrasonic wave rate.

2. Experimental conditions

The study was made using 99.85% purity-grade Al specimens. The specimen grain size was tailored in the range of $8 \times 10^{-3} \leqslant D \leqslant 4.5$ mm due to recrystallization after preliminary plastic deformation. Grain size was determined by the secant method. In so doing, the variance coefficient of the measured value was about 10%. The specimens having work part 50×10 mm were prepared by stamping out of 2-mm-thick Al sheet. These were tested in straining in an "Instron-1185" test machine, the relative straining rate being $\dot{\varepsilon} = 6.7 \times 10^{-5}\ \mathrm{s}^{-1}$. Using the method of speckle interferometry developed by Jones and Wykes (1983), the distribution of plastic distortion tensor components over specimen was determined and the localized strain zones were revealed.

The deforming specimen was photographed in coherent He–Ne laser light. The resulting images of the coherently illuminated specimen surface contained bright spots, the so-called speckles, which were about 3 μm in diameter. The specimen image formed by the photographic lens turned out to be modulated with speckles. When the load was relieved, the specimen was photographed a second time on the same spot of the film, so that another system of speckles shifted with respect to the original one was obtained. The resultant double-exposure speckle interference pattern with two superimposed systems of speckles contained information on the field of the displacement vectors $\boldsymbol{R}(x, y)$ for individual points on the flat specimen. The encoded information was treated by a special optical procedure to reconstruct the $\boldsymbol{R}(x, y)$ field, then the local components of the plastic distortion tensor $\beta = \nabla \boldsymbol{R}(x, y)$, i.e. elongation ε_{xx}, shear ε_{xy} and rotation ω_z, were calculated using numerical differentiation and finally, their distributions over the entire specimen surface or along any specific line, e.g. extension axis, were plotted. Using the above procedure, a set of speckle-modulated images was obtained for the deforming specimen in all the stages of deformation. This permitted step-by-step registration of the variation in the plastic distortion tensor components with growing overall deformation (at a constant straining rate, the total deformation $\varepsilon_{\mathrm{tot}} \sim t$). A typical distribution pattern of localized deformation in a tensile specimen is shown in Fig. 1.

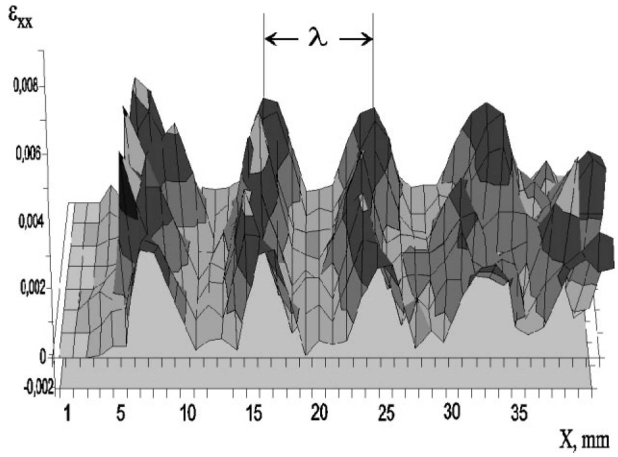

Fig. 1. Strain localization in the polycrystalline Al (distribution of zones with maximal values of the component ε_{xx} of the plastic distortion tensor): $D = 0.54$ mm, $\varepsilon = 3.5\%$.

The rate of ultrasound wave propagation, V, (Reyleigh wave: frequency $\nu = 2.5$ MHz, wavelength $\lambda_R \approx 1.2$ mm) was measured directly for the tensile specimen by the method of self-circulation of ultrasound impulses (Truel et al., 1969). Two piezotransducers fixed in a rigid clamp were pressed to the deforming specimen surface with force providing for acoustic contact. Such means of measuring allowed one to maintain contact spacing between the piezotransducers during specimen tension. For this purpose the equipment developed by Muraviev et al. (1996) was used, and the measured values were good to $\sim 10^{-4}$. All the tests were performed at the same experimental conditions (shape and size of the specimen, straining rate and temperature), grain size being the only variable.

3. Acoustic characteristics and multi-stage behavior of plastic flow in Al polycrystals

The use of Al polycrystals furnishes a unique opportunity of checking the validity of the relationship between local strain pattern type and flow curves' multistage behavior, which was established previously by Zuev and Danilov (1997, 1998, 1999). It was found by Jaoul (1957) that several stages can be distinguished on the flow curves obtained for Al polycrystals. In this instance, however, the nature and salient features of such multi-stage behavior of the flow curves are different from those of FCC single crystals (see, e.g., Nabarro et al., 1964). Thus all $\sigma(\varepsilon)$ plots show a linear portion, to which corresponds $\sigma = \sigma_1 + \theta\varepsilon$ ($\theta = d\sigma/d\varepsilon$ is the coefficient of work hardening; $\sigma_1 =$ const). With growing grain size D, the length of the linear portion becomes less. At $D \geqslant 0.5$ mm, the above portion of the curve degenerates into a transition point between two stages of parabolic work hardening. In so doing, a jumpwise change occurs in the index $m < 1$ from the expression $\sigma = \sigma_2 + A\varepsilon^m$, which described the latter two stages ($\sigma_2 =$ const). This is in conformity with the finding of Jaoul (1957) that at $T > 77$ K during the deformation of coarse-grain Al and single Al crystals, the stage of linear work hardening is virtually indiscernible on the flow curves obtained.

The investigation of deformation localization in polycrystalline Al, which was carried on by the method of speckle interferometry, has revealed that the localization behavior fully corresponds with the previously established regularities. Thus at the stages of parabolic work hardening a set of stationary localized strain nuclei is found to emerge in the deforming specimen, while at the stage of linear work hardening, an ensemble of equidistant nuclei will propagate synchronously along the specimen at a constant rate, thereby generating a wave process. The change-over of local strain patterns is illustrated in Fig. 2. As is seen from

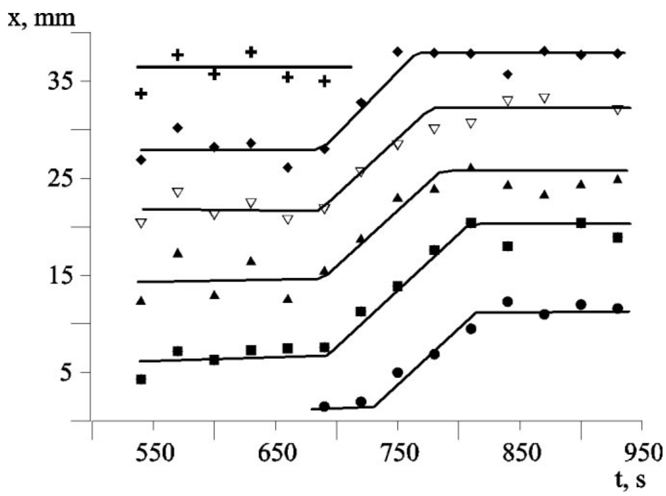

Fig. 2. The kinetics of motion of local strain nuclei during the tensile loading of Al polycrystal ($D = 0.2$ mm).

Fig. 2, the position of the maxima (similar to those in Fig. 1) on the co-ordinates X shift with time. In this case, the inclined portion of the curve corresponds to the stage of linear work hardening (the slope is equal to the rate of propagation of deformation wave) and the horizontal portions to the stages of parabolic work hardening (the rate of propagation is equal to zero).

The rate of ultrasound wave propagation varies non-monotonically during plastic flow. This fact can be used for in situ pinpointing of the exact moment, at which a transition occurs from one stage of flow to the next, especially where this is hard to achieve using the conventional analysis of the strain dependence of the coefficient of work hardening, $\theta(\varepsilon)$. Fig. 3 shows various portions of the plastic flow curves $\sigma(\varepsilon)$ set opposite the dependencies $V(\varepsilon)$ obtained for the Al polycrystals. Apparently, at all the stages of linear work hardening, $V = \text{const}$. Such constancy might be associated with the regular motion of plastic flow nuclei at this stage of flow, with an ever increasing number of non-deformed material slices becoming involved in the process of flow and helps single out the stage of linear work hardening.

The above change-over of flow stages and of local strain patterns is liable to raise the following questions:

1. In what manner is the above periodicity related to such an important structural parameter as grain size?
2. What factor determines the macroscopic distance between flow nuclei?

These questions are tackled in the next section of this paper.

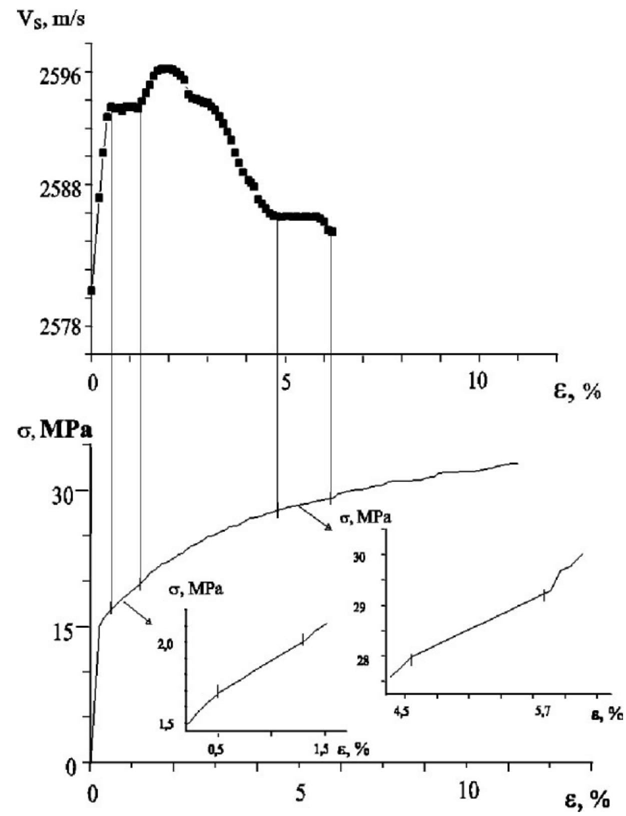

Fig. 3. The constancy of ultrasound propagation rate at the stage of linear work hardening of polycrystalline Al. The insertions show scaled-up stages of linear work hardening.

4. Wavelength of localized deformation

The experimentally obtained grain-size dependence of the space period of strain localization is illustrated in Fig. 4a and b. From the experimental data it follows that at $D < 0.6$ mm, $\lambda \sim e^D$ (i.e. $\ln \lambda \sim D$, Fig. 4a), at $0.6 < D < 7$ mm $\lambda \sim \ln D$ (Fig. 4b) while at $D \geqslant 10$ mm, λ tends to the limit $\lambda_0 \approx 16$ mm; after the limit is achieved, λ remains virtually the same.

Consider the probable nature of the above shape of dependence $\lambda(D)$. It is contended that the relative growth of wavelength $(d\lambda/dD) \sim \lambda$. However, under the condition that λ becomes commensurable with the specimen size, the relative growth of λ would fall. This is easily taken into account by writing

$$\frac{d\lambda}{dD} = a\lambda - a^*\lambda^2, \tag{1}$$

where a and a^* are positive dimensional constants and the square-law term $a^*\lambda^2$ in the right-hand side of (1) accounts for the reduction in the rate of growth of λ in the range of large D values. Integration of (1) yields the familiar equation of logistic curve (see, e.g., Menzel, 1955)

$$\lambda = \frac{\lambda_0}{1 + C\exp(-aD)}, \tag{2}$$

where $\lambda_0 = a/a^*$ and C is the dimensionless integration constant. In order to construct the plot of (2), the co-ordinates $\ln((\lambda_0/\lambda) - 1) - D$ can be conveniently used for straightening of the above curve. The experimental data subjected to the above treatment are presented in Fig. 5. As is seen from Fig. 5, Eq. (2) describes adequately the set of experimental data, which was obtained for the relation $\lambda(D)$ in a reasonably wide interval of D values.

Numerical treatment of the experimental data with the aid of Eq. (2) yields the following values of the constants: $a = 1.37$ mm^{-1} and $a^* = 8.8 \times 10^{-2}$ mm^{-2}. Correspondingly, $\lambda_0 = 15.6$ mm. Zhu et al. (1997) and Carsley et al. (1997) also investigated the grain-size dependence of deformation localization. However, these authors examined alloy in the ultrafine grain range, which hampers comparison of their results with the data presented herein.

In the interval of grain sizes $D \leqslant 0.6$ mm, the term $a^*\lambda^2$ in (1) can be ignored due to it being negligibly small. Then the solution derived from (1) yields the relation $\lambda \sim \exp(aD)$ observed for the above range of D values. On the contrary, in the region of macroscopic D values ($D \geqslant 1$ mm), over which the rate of growth

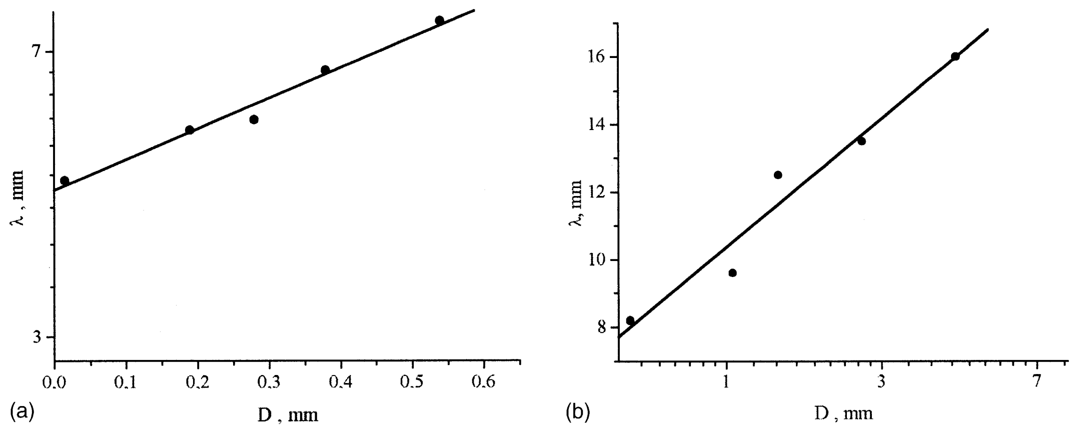

Fig. 4. The grain size D dependence of wavelength λ of localized deformation: (a) region of fine grain, $\lambda \sim e^D$ and (b) region of coarse grain, $\lambda \sim \ln D$.

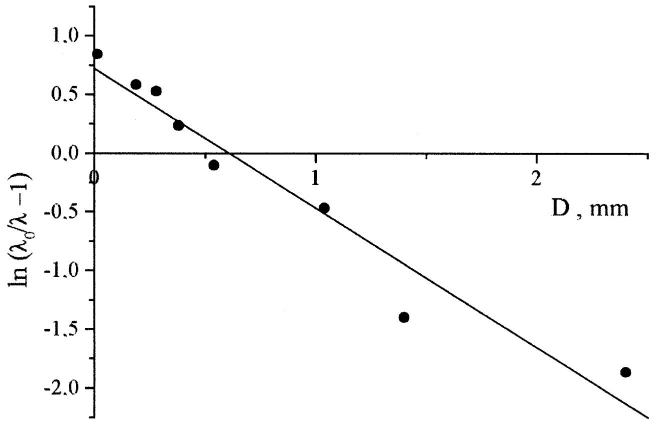

Fig. 5. The reconstruction of the data in Fig. 4 in the co-ordinates $\ln((\lambda_0/\lambda)-1)-D$.

of λ is found to fall, a relative increase in λ is assumed to be proportional to the number of grains on the specimen work part L_S, i.e.

$$\frac{d\lambda}{dD} \sim L_S/D. \tag{3}$$

Hence $\lambda \sim \ln D$, as it has been established earlier by Danilov et al. (1991) experimentally.

It should be noted that the scale effect (logarithmic dependence of λ on the macroscopic parameter L_S) has been recently established by Zuev (2001) during the investigation of deformation localization in Zr + 2.5% Nb alloy specimens having different length and similar grain size $D \approx 5$ μm. It is found that in the interval $25 \leqslant L_S \leqslant 125$ mm, $\lambda = \lambda^* + \alpha \ln L_S$ (α and λ^* being constants), i.e. in the range of macroscopic values of D and L_S, the logarithmic type of the dependence between λ and the above variables turns out to be universal enough.

The variation in the acoustic parameters of the plastically deforming medium may be related to one of the most complicated problems concerned with elucidation of the specific features of deformation localization. It is shown that the plastic waves generated in the various stages of flow have a characteristic macroscopic scale $\lambda \approx 5$–10 mm (Zuev and Danilov, 1998, 1999; Zuev, 2001), whereas the underlying processes responsible for the material's plasticity occur on the macroscopic scale of order of dislocation ensemble ($\sim 10^{-2}$ mm) (Friedel, 1964).

In order to relate the above two scales, one can use a model based on the following assumptions. Consider the propagation of acoustic impulses emitted, according to, e.g., Gillis and Hamstad (1974), during every elementary plasticity act. As the impulses propagate in the non-uniformly deforming medium, they are likely to be focused at a certain distance from the plastic nucleus acting at the given stage of flow. To do this, the dislocation structure's heterogeneities should be able to act as acoustic lenses. This is quite possible, since the velocity of sound propagation in a medium is found to depend on medium straining (Zuev et al., 2000). Let ξ be the characteristic size (curvature radius) of non-uniformity, then according to Bergman (1954), the focal distance f of such an acoustic lens is given by

$$f \approx \frac{\xi}{n-1}, \tag{4}$$

where $n = V_0/V$ is the refraction index of acoustic waves (V_0 and V being the rates of ultrasound wave propagation in a deformed and a non-deformed medium, respectively). It is known that by the deformation of Al $n \approx 1.002$ (Zuev et al., 2000) and $\xi \approx 0.01$ mm (for example, Ball, 1957). Then it follows from (4)

$f \approx 5$ mm $\approx \lambda$. It is at this distance that the probability of occurrence of the next shear becomes high. The quantities n and ξ are determined by the material structure; their evolution in the course of plastic flow involves the respective changes in the wave pattern of strain localization.

5. The ultrasound propagation rate viewed as a structure sensitive characteristic

According to Papadakis (1968), the rate of ultrasound wave propagation in non-deformed polycrystalline media is sensitive to grain size. Thus it is possible to keep track of the mechanical behavior of loaded materials using the variation in the rate of ultrasonic wave propagation. This demonstrates that one should have a clear knowledge of the nature and quantitative parameters of the relationship between the above quantity and grain size of metals.

From the experimental data in Fig. 6 it follows that the rate V of ultrasound wave propagation in Al polycrystals grows with specimen grain size, with $\Delta V \sim 1/\sqrt{D}$. Hence the same relationship may be written in the following form:

$$V = V_0 - \frac{\kappa}{\sqrt{D}} \tag{5}$$

with the correlation coefficient ρ for V and $1/\sqrt{D}$ being $\sim$0.69. The level of statistical significance, ψ, was assessed for ρ using the procedure described by Menzel (1955). It was found that the above value of ρ was not accidental, with the probability $\psi > 0.999$. The scatter of points is most likely due to the unavoidable grain-size dispersion in the specimens.

Consider the nature of the above relationship. It would be reasonable to relate such variation in the rate of ultrasonic wave propagation to the dispersion of ultrasound wave from grain boundaries. In the range of grain sizes considered, $\lambda_R \approx D$, which corresponds to the region of diffraction dispersion of ultrasound wave. Assume that relation (5) is determined by the accidental fluctuations of the rate of ultrasound wave propagation. Let the rate of ultrasound propagation as measured for a single crystal $V_0 = \Lambda/t$, where $\Lambda = 30$ mm is the distance between the piezoelectric transducers (unit's base) and t is the time of passage of

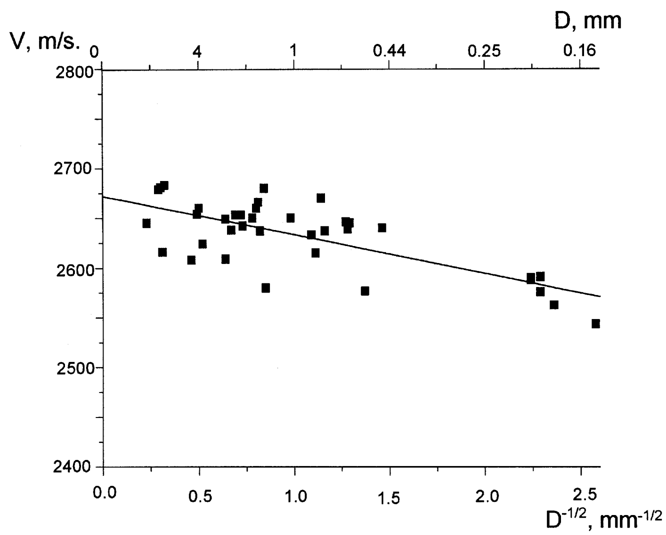

Fig. 6. The variation in the rate of ultrasound wave propagation V with grain size D.

the ultrasonic signal between the transducers. Let $\pm\delta t$ is the fluctuation of the time of passage of ultrasound wave for individual grains and n the number of grains that can be placed in a row over the unit's base. According to Menzel (1955), an increment in quantity due to n accidental fluctuations of opposite sign is proportional to $\sqrt{n}$, then $\Delta t \approx \delta t\sqrt{n}$. Hence

$$V = \frac{\Lambda}{t + \Delta t} = \frac{\Lambda}{t + \delta t\sqrt{n}}. \tag{6}$$

Under the condition $|\delta t| \ll t$, simple manipulation yields

$$V = \frac{\Lambda}{t}\frac{1}{1 + \frac{\delta t}{t}\sqrt{n}} \approx \frac{\Lambda}{t}\left(1 - \frac{\delta t}{t}\sqrt{n}\right). \tag{7}$$

Since $n = \Lambda/D$, from (7) it follows Eq. (5), if $\kappa = (\sqrt{\Lambda^3}/t^2)\delta t$. From the data in Fig. 7 it follows that the rate of propagation of Reyleigh waves in Al single crystals is $V_0 = \Lambda/t \approx V_R = 2590$ m/s. Assume that $V_0 \approx 0.9V_t$ (Truel et al., 1969); then the propagation rate of transverse acoustic waves $V_t = 2877$ m/s, which is close to the data reported by Truel et al. (1969). After t is eliminated, $\kappa = (V_0^2/\sqrt{\Lambda})$, then (7) can be conveniently reduced to the form

$$\frac{1}{V_0^2}\sqrt{\Lambda}(V_0 - V) \equiv \phi(V) = \frac{|\delta t|}{\sqrt{D}}. \tag{8}$$

From the inclination of the approximation curve in the plot constructed in the co-ordinates $\phi(V) - 1/\sqrt{D}$ (Fig. 7) one can assess the average value of time fluctuation during the passage of ultrasound wave through the grain boundaries in the polycrystal. In the above instance, $\delta t \approx \pm 2 \times 10^{-8}$ s, i.e. for $D \approx 1$ mm, the above condition $|\delta t| \ll t \approx D/V \approx 0.5 \times 10^{-6}$ s is satisfied.

It remains to be elucidated what is the physical nature of reduction in the rate of ultrasonic wave propagation due to the specimen's grain boundaries; however, this is beyond the scope of the present investigation. Nevertheless, it is contended that the above effect is associated with the intergranular microslip

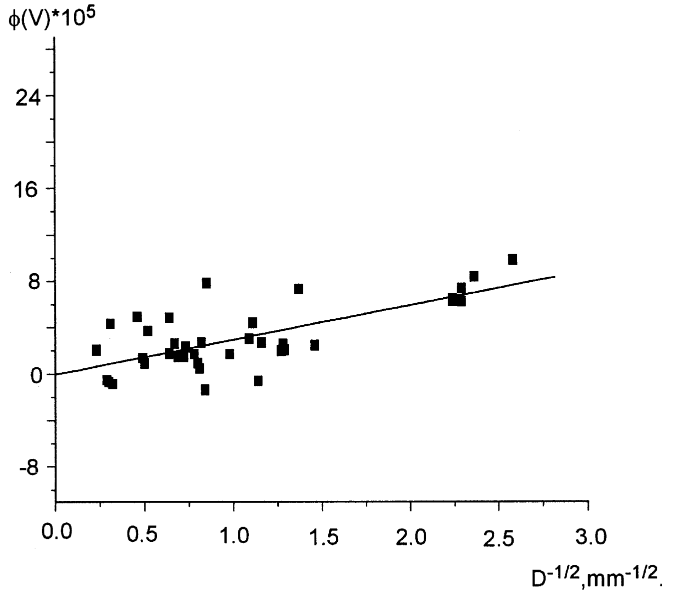

Fig. 7. The assessment of time fluctuation observed by the propagation of ultrasound wave through the grain boundary.

in the elastic field of ultrasound wave. According to Nowick and Berry (1972), it is this phenomenon that causes internal friction spikes to appear in the investigated specimen, Al polycrystals included.

6. Conclusion

It has been shown, in particular, that at stage of linear work hardening, the rate of ultrasonic wave propagation in the deforming Al polycrystal is independent of the extent of deformation. The constant magnitude of the above quantity is an indication of the beginning of the above stage of flow.

The experiments conducted and the interpretation of the results obtained offered a clearer view of the significance of the macroscopic scale of plastic flow nuclei distribution. In the framework of the proposed model, this scale is connected with acoustic emission impulses being focused by regions with non-uniformly distributed strains.

The data on grain-size dependence of ultrasound wave rate permit evaluation of this important characteristic of metals; these are also a course of information about events occurring on grain boundaries in polycrystalline media.

References

Aifantis, E.C., 1984. On the microstructural origin of certain inelastic models. Journal of Engineering Materials and Technology 106, 326–330.

Aifantis, E.C., 1987. The physics of plastic deformation. International Journal of Plasticity 3, 211–247.

Aifantis, E.C., 1995. Pattern formation in plasticity. International Journal of Engineering Science 33, 2161–2178.

Aifantis, E.C., 1996. Nonlinearly, periodicity and patterning in plasticity and fracture. International Journal of Non-Linear Mechanics 31, 797–809.

Aifantis, E.C., 1999. Gradient deformation models at nano, micro, and macro scales. Journal of Engineering Materials and Technology 121, 189–202.

Aifantis, E.C., 2001. Gradient plasticity. In: Lemaitre, J. (Ed.), Handbook of Materials Behavior Models. Academic Press, New York.

Ball, C.J., 1957. On the nature of substructure effect in the polycrystalline aluminum. In: Dislocations and Mechanical Properties of Crystals. J. Wiley and Sons, New York.

Bergman, L., 1954. Der Ultraschall und seine Anwendung in Wissenschaft und Technik. Hirzel, Stuttgart (in German).

Carsley, J.E., Milligan, W.W., Zhu, X.H., Aifantis, E.C., 1997. On the failure of pressure-sensitive materials. Part II: comparisons with experiments on ultra fine grained Fe-10% Cu alloys. Scripta Materialia 36, 727–732.

Danilov, V.I., Zuev, L.B., Mnikh, N.M., Panin, V.E., Shershova, L.V., 1991. Wave effects during plastic flow of polycrystalline Al. Physics of Metals and Metal Science 71, 187–193.

Estrin, Y.Z., Kubin, L.P., 1986. Local strain hardening and nonuniformity of plastic deformation. Acta Metallurgica 34, 2455–2464.

Friedel, J., 1964. Dislocations. Pergamon Press, London.

Gillis, P.P., Hamstad, M.A., 1974. Some fundamental aspects of the theory of acoustic emission. Material Science and Engineering 14, 103–108.

Jaoul, B., 1957. Etude de la forme des courbes de deformation plastique. Journal of Mechanics and Physics of Solids 5, 95–114 (in French).

Jones, R., Wykes, C., 1983. Holographic and Speckle Interferometry. Cambridge University Press, Cambridge.

Menzel, D. (Ed.), 1955. Fundamental Formulas of Physics. Prentice-Hall, New York.

Muraviev, V.V., Zuev, L.B., Komarov, K.L., 1996. The Ultrasound Velocity and Structure of Steels and Alloys. Nauka, Novosibirsk (in Russian).

Nabarro, F.R.N., Basinski, Z.S., Holt, D.B., 1964. The Plasticity of Single Crystals. Taylor and Francis, London.

Nowick, A.S., Berry, B.S., 1972. Anelastic Relaxation in Crystalline Solids. Academic Press, New York.

Papadakis, E.P., 1968. Ultrasonic attenuation caused by scattering in polycrystalline media. In: Applications to Quantum and Solid State Physics. In: Physical Acoustics. Principles and Methods, vol. IVB. Academic Press, New York.

Saxlova, M., Kratochvil, J., Zatlonkal, J., 1997. The model of formation and disintegration of vein dislocation structure. Material Science and Engineering A 234–236, 205–208.

Truel, R., Elbaum, Ch., Chik, B., 1969. Ultrasonic Methods in Solid State Physics. Academic Press, New York.

Zaiser, V., Hähner, P., 1997. Oscillatory modes of plastic deformation: theoretical concept. Physica Status Solidi (b) 199, 267–330.
Zhu, X.H., Carsley, J.E., Milligan, W.W., Aifantis, E.C., 1997. On the failure of pressure-sensitive materials. Part I: Models of yield shear band behavior. Scripta Materialia 36, 721–726.
Zuev, L.B., 2001. Wave phenomena in low-rate plastic flow of solids. Annalen der Physik 10, 961–984.
Zuev, L.B., Danilov, V.I., 1997. Plastic deformation viewed as evolution of an active medium. International Journal of Solids and Structures 34, 3795–3805.
Zuev, L.B., Danilov, V.I., 1998. Plastic deformation modelled as a self-excited wave process at the meso- and macro-level. Theoretical and Applied Fracture Mechanics 30, 175–184.
Zuev, L.B., Danilov, V.I., 1999. A self-excited wave model of plastic deformation. Philosophical Magazine A 79, 43–57.
Zuev, L.B., Semukhin, B.S., Bushmeliova, K.I., Zarikovskaya, N.V., 2000. On the acoustic properties and plastic flow stages of deforming Al polycrystals. Materials Letters 42, 97–101.