The macrolocalization features of plastic deformation on the pre-fracture stage

VLADIMIR I. DANILOV, LEV B. ZUEV
Siberian Branch of Russian Academy of Science
Institute of Strength Physics and Material Science
2/1, Akademichesky ave., Tomsk, 634021
RUSSIA

Abstract: - The behavior exhibited by localized plasticity domains at the final stage of the plastic flow process upon a transition to macroscopic necking and viscous fracture is considered. A series of experiments was conducted on materials differing in crystal lattice type. This enables one to establish the regular features of the process, which are revealed by the concerted motion of the flow domains towards the center of the trajectories bundle in the "co-ordinate-time" space. It is found that the fracture patterns are related to the kinetics of nucleation and motion of localized plasticity fronts. The probable source of the observed effects is considered.

Key-Words: - Deformation, Macrolocalization, Necking, Localized plasticity domains, Pre-fracture patterns

1 Introduction

The earlier theoretical findings [1-5] and the experimental research conducted previously by Zuev *et al.* [6-12] strongly suggest that macro-scale plastic deformation localization will occur at all the stages of plastic flow in metals and alloys. In the course of deformation in the test specimen there emerge wave patterns whose type is determined by the acting law of work hardening. The authors [13, 14] investigated recently the distinctive features exhibited by the behavior of localized plastic deformation domains at the final flow stage for the specimens of single-crystal and polycrystalline alloy Fe-3wt.%Si (siliceous iron). It is an established fact [15] that at the above stage the stress σ and the strain ε are related as $\sigma \sim \varepsilon^n$ (n is the parabola exponent). It is found that at $n < ½$ the localized deformation fronts move along the specimen at a rate V, which is related to n as

$$V(n) = V_0 (n - q)^2 , \qquad (1)$$

Zuev *et al.* [10] determined the form of equation (1) (the constant $q \approx ½$). However, in accordance with the work hardening law $\sigma \sim \sqrt{\varepsilon}$ predicted by Taylor [15], i.e. at $n \approx ½$, the localized deformation domains would be stationary ($V_{n=1/2} = 0$), which was validated experimentally [8]. Relation (1) also encompasses the linear work hardening stage for which the condition $n = 1$ is also satisfied and the quantity $V_{n=1}$ is constant and has the same value for all the plasticity domains observed in the given specimen.

In the course of plastic flow the parabola exponent n gradually decreases, which enabled Zuev *et al.* [10] to distinguish on the flow curve a number of parabolic substages, with the respective values of the exponent n varying discontinuously. The results obtained by Barannikova *et al.* [13] and Danilov *et al.* [14] suggest that at $n < ½$ the localized plasticity domains gain the capacity to move. An important and intriguing feature of their motion at the above flow stage is that they travel in a concerted manner, with their rates being spontaneously correlated.

The significance of such concerted motion of localized plastic deformation domains can be easily deduced from Fig. 1(a), which illustrates the kinetics of domains motion in the case of submicrocrystalline aluminum. As is seen from the figure, the diagrams of domains motion at the final stage of the flow process, which are drawn in the co-ordinates "domain's position X - time t", are rectilinear ones; they form a converging bundle with the common point having co-ordinates X^* and t^*.

2 Experimental finding

The evidence derived by Barannikova *et al* [13] and Danilov *et al.* [14] for the BCC alloy Fe-3wt.%Si in the single-crystal and polycrystalline states is supplemented by the results of recent studies that were made on samples of pure submicrocrystalline FCC aluminum (grain size $D < 0.1$ μm) and alloys on the base of HCP magnesium and BCC vanadium (for the materials compositions see the Table). The method used to define the parabola exponent n values, and those employed for the visualization and quantitative description of the kinetics of motion of localized plastic deformation domains are described in detail elsewhere (see [6, 8-10].

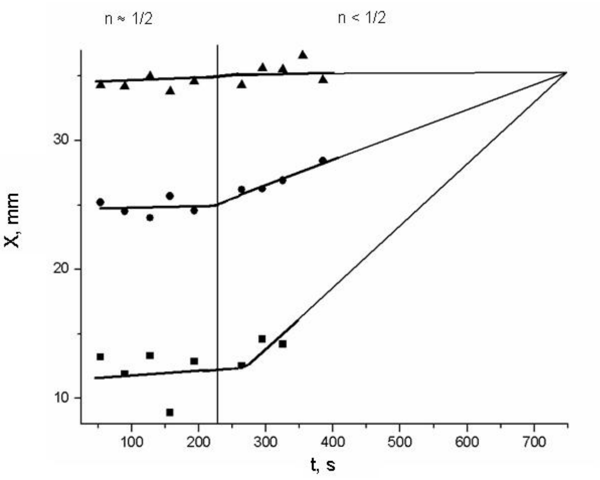
The results obtained for all the investigated alloys are presented in Fig.1(a)-(d). Examination of the *X* - *t* diagrams shown in Fig.1 and an analysis of the profiles of the flow curve $\sigma(\varepsilon)$ and the dependence $d\sigma/d\varepsilon = \theta(\varepsilon)$ has permitted the following deformation hardening stages to be distinguished:

- linear stage ($V = const$, $n = 1$),
- Taylor's hardening stage ($V = 0$, $n \approx ½$),
- stage preceding fracture ($V \neq 0$, $n < ½$).

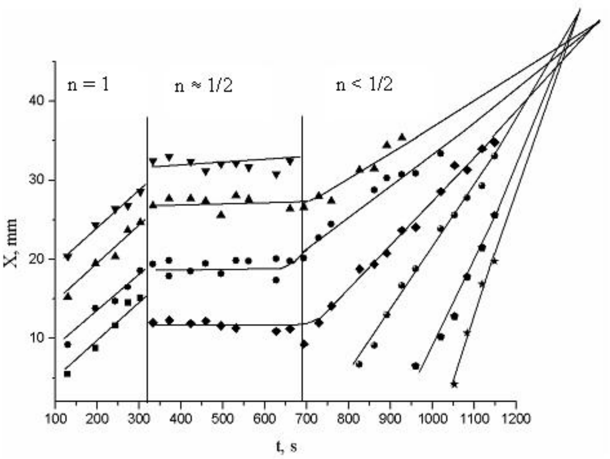
Table

The constants of equation, which has determined of the motion rate of localized plastic deformation domains; the co-ordinates of place and time of fracture

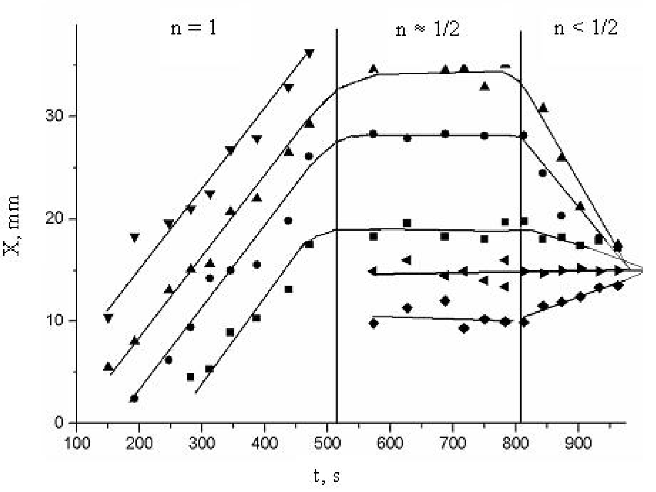
Characteristic	Materials			
	Al	Mg-2.0 wt.% Mn-0.25 wt.% Ce	V-2.3 wt.% Zr-0.4 wt.% C	Fe-3 wt.% Si
α, s^{-1}	$1.13·10^{-3}$	$4.64·10^{-3}$	$7.24·10^{-3}$	$1.32·10^{-3}$
α_0, $m·s^{-1}$	$6.7·10^{-3}$	$1.7·10^{-2}$	$-6.1·10^{-4}$	$-1.27·10^{-3}$
$X^* = -\alpha_0/\alpha$, m	6.2	3.7	–0.008	1.0
$t^* = t_0 - 1/\alpha$, s	1174	1265	980	2560



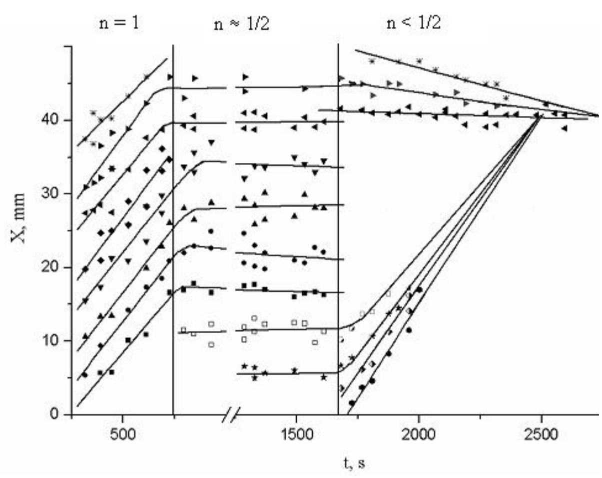
a



b



c



d

Fig.1. The motion of localized plastic deformation domains in submicrocrystalline aluminum *(a)*, magnesium alloy *(b)*, vanadium alloy *(c)* and siliceous iron *(d)*

At the final (pre-fracture) stage each localized plasticity domain will move at a rate of its own which is maintained constant during the lifetime of the domain. Extrapolation of the portions of $X(t)$ plots for which n < ½ to the intersection point reveals that these form bundles in all the cases; the X^* and t^* co-ordinates can be defined within comparatively small areas in the $X-t$ plane for all the test materials. In some cases extrapolation of $X(t)$ to large times is required in order to define X^* and t^* (see Fig.1a, c). Clearly, at the very beginning of the final flow stage the localized deformation domains will move in a concerted manner, which enables them to arrive all together in the center X^* at the time t^*, with the location of the center and the time of arrival being close, respectively, to the place and time of specimen failure.

The complex pattern of domains motion has a significant feature: at the pre-fracture stage each individual localized flow domains will move at one and the same rate, which depends on the place of nucleation (the closer to the zone of future fracture, the lower the motion rate). It should be noted also that the mobile domains observed at the above stage would come to a standstill at a certain moment of time with a resultant disappearance of all the domains but one. The only domain that is likely to "survive" is that nucleated in the location of macroscopic neck where viscous fracture is bound to occur. Upon its nucleation at the stage of Taylor's deformation hardening at $n \approx$ ½ the domain remains almost stationary till the onset of fracture as can be seen from Fig.1*b*, *d*. The localized plasticity domains that move in a concerted manner at the pre-fracture stage are likely to start traveling on either one or both sides of the stationary domain (Fig.1*a*, *c* and Fig.1*b*, *d*, respectively).

3 Discussion

Consider the conditions at which the straight lines $X(t)$ in Fig.1 will form bundles. This is only possible when the linear law of motion rate distribution at the moment of time t_0 is satisfied, i.e. $V(\xi) = \alpha\xi + \alpha_0$. Here ξ is the initial co-ordinate for the moment of time $t = t_0$; α and α_0 are empirical constants. As is seen from Fig.1 *a*, the co-ordinate ξ can be conveniently measured from the position of the stationary localization domain. The plots $V(\xi)$ obtained for all the investigated materials are shown in Fig.2; the estimated values of the constants α and α_0 for the above dependencies are listed in the Table. The domain's motion rates as a function of their original positions are determined for the test materials from the inclination of the plots in Fig.1. In all the cases the dependence $V(\xi)$ is evidently a linear one. At the parabolic deformation hardening stage the coefficient of work hardening $\theta = d\sigma/d\varepsilon \sim n\varepsilon^{n-1}$ decreases with the parabola exponent n. In accordance with the relationship established by Zuev [8], the motion rate of localized deformation front depends on θ as $V \sim 1/\theta$; hence with decreasing n, the above value will grow due to decreasing θ. A similar increase in the value V at n < ½ is predicted from (1).

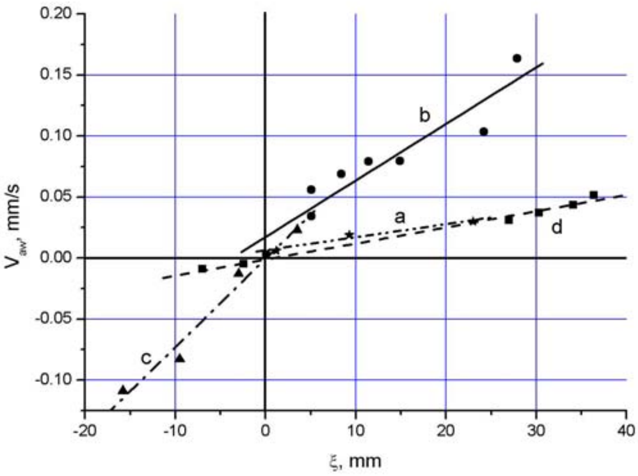


Fig.2. The dependences $V(\xi)$ in submicrocrystalline aluminum *(a)*, magnesium alloy *(b)*, vanadium alloy *(c)* and siliceous iron *(d)*

It can be easily shown that the co-ordinates of the bundle center (place and time of fracture)

$$X^* = \alpha_0/\alpha\,, \tag{2a}$$

$$t^* = t_0 + 1/\alpha\,. \tag{2b}$$

The values of the above quantities are also listed in the Table. Thus, the convergence of the lines in the co-ordinates $X-t$ might be attributed to the fact that at the pre-fracture stage at n < ½ the motion rates of the localized plasticity domains emergent in the tensile sample satisfy the condition $V(\xi) = \alpha\xi + \alpha_0$.

As is noted above, localized deformation domains may originate on one side of the place of future failure (magnesium alloy and aluminum) or on both sides of the same place (vanadium alloy, Fe-3%Si alloy). In the latter case, the inclinations of two sets of domains are opposite in sign, which probably determines the character of viscous fracture in materials, which have relatively high plasticity (FCC and HCP) or low plasticity (BCC). Thus a typical fracture zone observed for magnesium alloy and aluminum is that of viscous shearing, while vanadium and Fe-3%Si alloy specimens undergo mostly brittle fracture as is noted by Danilov *et al* [14].

Then normalization of the quadratic dependence $V(n)$ using experimental values of $V_{n=1}$ and $V_{n=1/2} = 0$, which correspond to the stages of linear and Taylor's deformation hardening (n = 1 and $n \approx ½$ respectively), allows one to estimate n values from relation (1) for the individual mobile domains of localized plasticity observed in all the investigated materials (with the exception of submicrocrystalline aluminum whose flow curve shows no linear work hardening stage). The results obtained by the above data treatment are presented in Fig.3. Of particular significance are the negative values of the parabola exponent ($n < 0$), which are known to correspond to the descending branch of the stress-strain dependence on the conventional deformation diagram (McClintock, Argon, 1966), with the n value observed at the same stage for the entire specimen being positive in sign. It is noteworthy that the localized plastic flow domains observed at $n < 0$ belong to a set of domains that originates spontaneously at the pre-fracture stage; these are in no way related to the localization zones, which erge at the stage of Taylor's work hardening and remain stationary at $n \approx ½$.

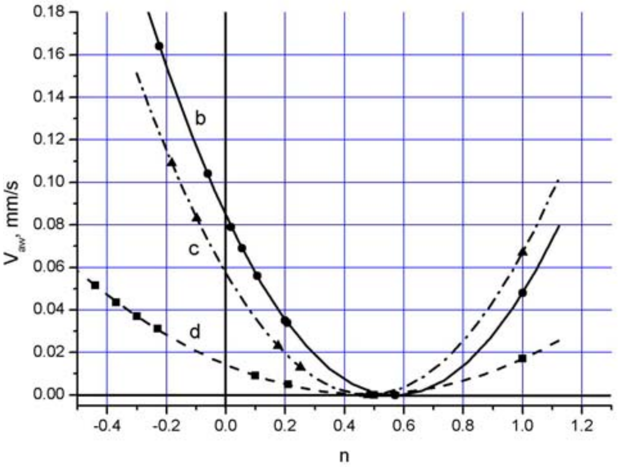


Fig.3. The dependences $V(n)$ in magnesium alloy *(b)*, vanadium alloy *(c)* and siliceous iron *(d)*

The above regularities can be accounted for by assuming that the parabola exponent n may have different values, both positive and negative in sign, for every mobile localized plasticity domain emergent at the pre-fracture stage. It is, therefore, concluded that the material volumes may exhibit different deformation behaviors in the course of plastic flow and, consequently, different capabilities for work hardening. The above contention is supported by the dislocation structure investigations conducted by Zuev *et al.* [10]; thus it is found that the evolution of material dislocation structure within the domains at the various flow stages occurs at a higher rate relative to the regions in between the domains.

4 Conclusion

On the base of the results presented herein, the deforming material behavior is found to exhibit the following distinctive features at the pre-fracture stage before a macroscopic neck forms in the specimen.

1. The examination of the evolution of localized deformation zones observed before macroscopic neck formation reveals that the location of future fracture can be determined at early flow stages. There is a transition between the stage of Taylor's parabolic deformation hardening ($n \approx ½$) and macroscopic necking followed by viscous fracture at $n < ½$. It is believed that the above change in the value of n corresponds with the moment of time at which a changeover in the plastic deformation regimes takes place, i.e. steady-state plastic flow gives way to an unsteady state one [1-3, 5, 16,17].
2. The observation of localization patterns at the stage of pre-fracture reveals that the active macroscopic zone of plastic deformation becomes shorter, which brings about inhibition of the plastic flow process in a greater portion of the sample volume. From this viewpoint, macroscopic neck formation, which is a forerunner of fracture, occurs as a result of gradual damping out of localized deformation wavelength with increasing level of total deformation.
3. On the base of the results obtained, it is contended that at the pre-fracture stage the deforming specimen volume becomes layered into individual material regions that behave independently in terms of deformation hardening: regions in which the material undergoes work hardening ($n > 0$) alternate with regions in which material softening takes place ($n < 0$) (see, e.g. Stanford *et al.* [18]).

Clearly, the process of necking and fracture zone nucleation results from the complicated concerted motion of localized plasticity domains, which causes the domains to concentrate in the zone of viscous fracture, with each domain moving at a constant rate.

References

[1] E.C. Aifantis, The physics of plastic deformation, *International Journal of Plasticity*, Vol.3,

1996, pp. 211-247.

[2] E.C. Aifantis, Nonlinearly, periodicity and patterning in plasticity and fracture, *International Journal of Non-Linear Mechanics*, Vol.31, 1996, pp. 797-809.

[3] E.C. Aifantis, Gradient deformation model at nano, micro, and macro scales, *Journal of Engineering Materials and Technology*, Vol.121, 1999, pp. 189-202.

[4] L.P. Evers, W.A.M. Brekelmans and M.G.D. Geers, Scale dependent crystal plasticity framework with dislocation density and grain boundary effect, *International Journal of Solids Structures*, Vol.41, 2004, pp. 5209-5230.

[5] M. Zaiser, E.C. Aifantis, Randomness and slip avalanches in gradient plasticity, *International Journal of Plasticity*, Vol.22, 2006, pp. 1433-14.

[6] L.B. Zuev, and V.I. Danilov, A self-excited wave model of plastic deformation in solids, *Philosophical Magazine A*, Vol.79, 1999, pp. 43-57.

[7] V.I. Danilov, G.N. Narimanova and L.B. Zuev, On evolution of plasticity zone in the vicinity of crack tip, *International Journal of Fracture*, Vol. 101, 2000, pp. L35-L40.

[8] L.B. Zuev, Wave phenomena in low-rate plastic flow of solids, *Annalen der Physik*, Vol.10, 2001, pp. 965-984.

[9] L.B. Zuev, T.M. Poletika, S.Yu. Zavodchikov *et al.*, The self-excited waves of deformation localization and limiting state criterion for Zr-Nb alloys, *Materials Processing Technology*, Vol.125-126, 2002, pp. 287-294.

[10] L.B. Zuev, T.M. Poletika and G.N. Narimanova, The relationship between plastic flow macrolocalization and a dislocation structure, *Technical Physics Letters*, Vol.29, 2003, pp. 519-520.

[11] L.B. Zuev, V.I. Danilov, T.M. Poletika, and S.A. Barannikova, Plastic deformation localization in commercial Zr-base alloys, *International Journal of Plasticity*, Vol.20, 2004, pp. 1227-1249.

[12] L.B. Zuev. On the waves of plastic flow localization in pure metals and alloys. *Annalen der Physik*, Vol.16, 2007, pp. 286-310.

[13] S.A. Barannikova, V.I. Danilov and L.B. Zuev, Plastic strain localization in Fe-3%Si single crystals and polycrystals under tension, *Technical Physics*, Vol.49, 2004, pp. 1296-1300.

[14] V.I. Danilov, G.V. Shlyakhova, L.B. Zuev, M.A. Kunavina and Yu.V. Ruzanova, Multistage character of plastic flow and macrolocalization of deformation in the Fe-3%Si polycrystals, *The Physics of Metals and Metallography*, Vol.98, 2004, pp. 333-337.

[15] J. Friedel, *Dislocations*, Pergamon Press, Oxford, 1964.

[16] L.P. Kubin, Yu.Z. Estrin, E.C. Aifantis, Viewpoint set on propagative plastic instabilities, *Scripta Metall. Mater.*, Vol.29, 1993, pp. 1147-1150.

[17] H.M. Zbib, and T.D. de la Rubia, A multiscale model of plasticity, *International Journal of Plasticity*, Vol.18, 2002, pp. 1133-1163.

[18] N. Stanford, D. Dunne and M. Ferry, Deformation and annealing of $(011)[01\bar{1}]$ oriented Al single crystals, *Acta Materialia*, Vol.51, 2003, pp. 665-676.