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Criteria of Instability and Kinetics of Jumps under Unstable Low Temperature Plastic Flow

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A review of the modern state of the low temperature ($T \leqq 10$ K) jump-like deformation is presented. Two aspects of the problem are pointed out: 1) investigation of the physical mechanism of instability and finding of its criteria and 2) study of the kinetics of the processes occuring in crystals after loss of stability. The physical causes and the criteria of instability are considered. Much attention is given to experimental data on the kinetics of changes of the flow stress, the strain rate, and the temperature during the jumps.

1. Introduction

Low temperature jump-like deformation (JD) is one of the most striking manifestations of plastic flow instability and is similar to the well-known high temperature Portevin - Le Chatelier effect in some features. During the thirty years that have passed since the discovery of this phenomenon, a lot of experimental data have been obtained on various metals and alloys. However, this relates mainly to the macroscopic faetures of JD: the temperature – strain rate range of its existence, the influence of the crystal parameters and experimental conditions on the jump onset stress and the jump amplitude. However, only a few works have attempted to study the phenomenon at the "micro-level", i.e. to investigate the processes occurring in the crystal after loss of stability with high time resolution and to influence the sample in order to induce a deformation jump. As a result, there is no complete theory of the phenomenon, or even clear understanding of the nature of low temperature JD. The main macroscopic features of JD are described, for example, in reviews [1, 2]. This paper is intended to provide a short review of the modern state of the JD problem and experimental data on the kinetics of processes occurring in the crystal during a jump, which is the worst known aspect of the phenomenon.

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2. General description of the problem

The essence of the JD phenomenon is that during active deformation of the sample with a relatively small rate $q \sim 10^{-5} - 10^{-3}\ s^{-1}$ provided by the rod of the deformation machine steep load drops are seen in the stress-strain curve which result from plastic flow with a strain rate $\dot{\varepsilon}$, considerably higher than q. The relation $\dot{\varepsilon} > q$ is typical also for other manifestations of plastic flow instability, such as stress drop after the yield point, formation of a "neck", the Portevin - Le Chatelier effect, deformation twinning, etc. A distinctive feature of low temperature JD is that it occurs when the temperature falls below some critical $T_{cr} \lesssim 10$ K and is typical for a wide class of solids, which retain plasticity at helium temperatures: pure metals and alloys with various crystall lattice types, etc. Deformation curves of the FCC

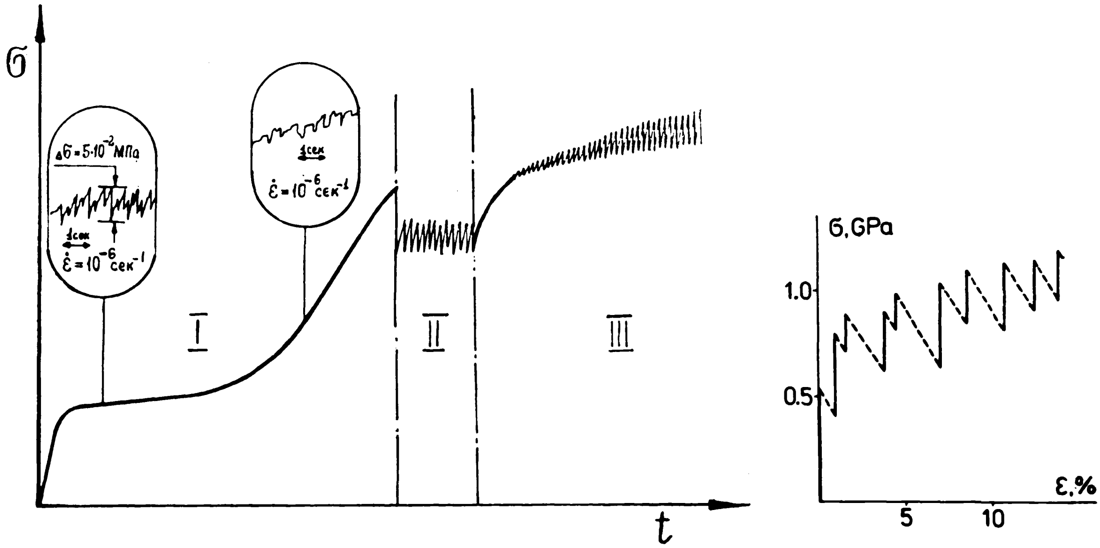

Fig. 1. Typical stress-strain curves of single crystals at 4.2 K for a) FCC alloy Cu + 14 at. % Al [3] and b) BCC metal Nb [4].

alloy Cu-Al and the BCC metal Nb are shown in Fig. 1. As a rule, JD in FCC metals takes place on later stages of work hardening and the typical amplitude of jumps is about 1–10 % of the flow stress. In BCC metals jumps often occur after the yield point and their amplitude is up to 30–70 %. JD takes place in a certain area on the temperature – strain rate diagramm (see Fig. 2). Jumps often are accompanied by an acoustic effects and a temperature rise to 50 K.

Both from the theoretical and the experimental point of view, the problem of JD can be divided into two aspects. First, we have to find a physical cause of instability, to determine of its criterion on the basis of some model, i.e. to derive the inequality relating the crystal characteristics to the experimental conditions and defining the range of parameters in which the deformation process deviates essentially from stability. This problem, as a rule, has been considered in linear approximation since the stability has been analysed against small deviations of the variables from their quasi-stationary and homogeneous values. The second and more complicated aspect of the problem consists in analysis of the essentially nonlinear processes occurring in the crystal after loss of stability: determination of the factors which stabilize the deformation and investigation of the time evolution of the processes

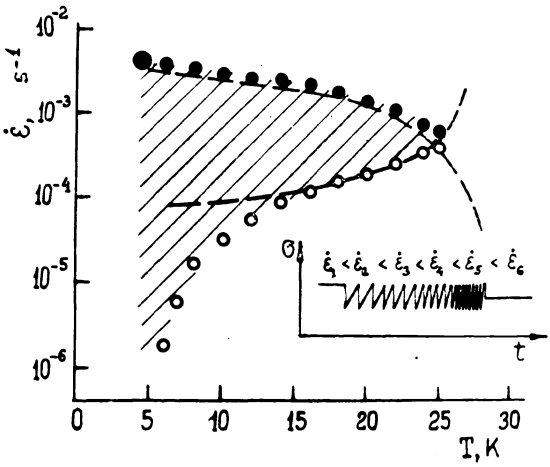

Fig. 2. Temperature- strain rate diagram of jump-like deformation in Cu + 14 at. % Al [11], area of its existence is shaded.

taking place within one jump. Generally, without such an analysis it is impossible to formulate unambiguously the criterion of instability of JD. Thus, if the criterion is obtained by linear analysis of stability of the set of nonlinear equation, then it is not clear if its validity will lead to periodically reproducible jumps of deformation or to other manifestations of instability (yield drop, formation of a „neck" and failure of the sample) or, on the contrary, to microdeformation due to stabilization of the system resulting from small variations of the variables.

Although in some features low temperature JD is similar to the Portevin - Le Chatelier effect, its physical mechanisms are considerably complicated. In the early sixties, Davidenkov [5] suggested that from the phenomenological point of view deformation jumps (both in the case of low temperature JD and in the case of the Portevin- - Le Chatelier effect) are associated with the range of the negative strain rate sensitivity of the flow stress. This quite a clear idea which refferring to a wide range of physical processes reduces, however, one question to another, what the cause of the negative strain rate sensitivity is and if the latter is the case at the level of a single dislocation, or it is due to inconstancy of other parameters of the system, some cooperative processes.

As regards low temperature JD, there can be three main types (or causes) of plastic flow instability: Thermal (thermomechanical), geometric, and dislocation (athermal).

3. Thermal instability

This idea first suggested by Basinski [6] is the best developed today. It is that under certain conditions the feedback between the rate of heat generation during plastic deformation and the temperature is positive because of thermoactivated dislocation motion. As a result, the temperature and strain rate increase in a avalanche fashion which leads to a drop of flow stress. An important advantage of this conception is that it explains the main features of low temperature JD: its existence at $T < T_{cr}$ and the general character. First, low values (and, as a rule, monotonically decreasing with temperature) of the heat capacity C and thermal conductivity χ at helium temperature can lead to significant warming of sample at relatively small strain rates. Second, low temperatures lead to a sharp increase of the rate of termoactivated deformation $\dot{\varepsilon} \infty e^{-H/kT}$ at small temperature changes. Both these factors which are favorable to instability are common to all solids irrespective of the dislocation structure.

The concept of thermal instability has been subsequently developed in a number of papers (see, for example [7 ÷ 10]). Their central idea is in linear analysis of stability of the set of equations containing the thermal conductivity equation, the equation of plastic deformation (the relation between the strain rate $\dot{\varepsilon}$, the stress σ, and the temperature T), and the "machine" equation, which describes the conditions of sample loading. Here are, as an example, two expressions for the critical stress of loss of stability:

$$\sigma_{cr} = - \frac{C(M + \Theta)}{\partial\sigma/\partial T}; \tag{1}$$

$$\sigma_{cr} \frac{\partial\dot{\varepsilon}}{\partial T} = \frac{\chi}{d^2} \eta(hd/\chi) - C \frac{\partial\dot{\varepsilon}}{\partial\varepsilon}; \tag{2}$$

where Θ is the work hardening coefficient, M is the effective modulus of the system, d is the sample size, h is the heat transfer coefficient, and η (hd/χ) is the function of nondimensional parameter of heat emission. The criterion (1) [7] was obtained in the adiabatic approximation using the quasi-static "machine" equation which is true for quite slow changes in σ and $\dot{\varepsilon}$. The criterion (2) [9] takes into account the heat transfer. It was obtained using the dynamic equation for total deformation.

Quantitative comparison of the theoretical results with experimental ones is faced, however, with some difficulties. First, the form of criterion and the parameters it contains essentialy depend on the assumption of the factors which restrict the heat transfer, the form of the plastic deformation equation, the "machine" equation, the character of the deformation localization, etc. This can be illustrated by the comparison of the criteria (1) and (2). In most experimental situations not all the factors are known. Secondly, there have been only a few works in which the parameters entering into the criterion were varied. As a result, only in a few cases it is possible to reach quantitative coincidence of the theory with the experiment.

As an example, we shall mention the explanation of the temperature – strain rate diagram of JD obtained in Cu-Al [11]. At the same time, most effects can be explained qualitatively: besides those mentioned above, these are localization of slip, the dimensional effect, the influence of the N-S transition in superconductors, the transient processes at strain rate cycling, etc.

An important evidence of the thermal nature of instability is given by the experiments in which deformation jumps were initiated by heat pulses. In the alloy Cu + 14 at. % Al heating was induced by passing current pulses through samples. In superconducting polycrystalline Nb [13], at 4.2 K, pulsed heating of about 50 μs up to 12–13 K took place during magnetic flux jumps. In both the cases it was possible to initiate the process which was equivalent completely to a deformation jump. In the case of Nb, the experimental value of the stress invertal $\Delta\sigma$ in which a jump can be induced coincides well with the theoretical one obtained on the basis of the criterion (2). It should be noted that heating of the sample during a jump is not in itself an evidence of the thermal origin of instability, but it is only a consequence of energy dissipation during plastic deformation.

4. Geometrical instability

Even if the process of plastic deformation is stable in the sample bulk, instability can arise from changes in the crystal shape during deformation. Thus, for example, the cross-section area S of a whole sample or a part of it decreases under tention and, therefore, the flow stress $\sigma = P/S$ (P is the load) increases. Under certain conditions, this increase of σ leads to a strain rate rise and subsequent decrease of S, and the whole process will increase in avalanche manner. In the paper [14] the condition of geometrical softening has been formulated on the basis of simple phenomenological reasons. This condition is that in some cross-section of the sample the inequality $\sigma > d\sigma/d\varepsilon$ should be valid, where ε and σ are the average (over the cross-section) strain and flow stress respectively. More rigorously, the problem of geometric instability was considered in [15]. It reported a linear analysis of the stability of the set of equations describing the development of local deformation of the rod. The set of equations takes into account a possible dependance of the rod cross-section area S on time and the coordinate along the rod axis. The criterion of instability obtained requires that some of the two inequalities should be fulfilled:

$$d\dot{\varepsilon}/d\sigma < 0; \quad (3) \qquad \sigma > \Theta + 8l_0K/\pi^2S_0(2n+1)^2 ; \quad (4)$$

where l_0 and S_0 are the initial length and the cross-section area, K is the system stiffness, n is the number of harmonic which defines the wavelength of deviations along the rod axis. Only the values of $n_{max} \sim l_0/S_0$ for which the wavelength is of the order of the diameter have a real physical meaning. Inequality (3) is the phenomenological criterion of the bulk instability, that is negative strain rate sensitivity of the flow stress. Inequality (4) is the criterion of geometrical instability associated with local contraction of the cross-section. The criterion shows that geometrical instability is determined by two factors, namely, the work hardening and the stiffness of the system which characterizes the decrease of the stress after increase of the sample strain. In experiments, as a rule, the second factor is essentialy less important than the first one, i.e. the critical stress is $\sigma_{cr} \approx \Theta$.

An experimental indication of geometric instability according to [15], is the appearance of local contractions the number of which correlates with the number of jumps and a correlation between σ and Θ which was observed for some materials. However, these facts cannot prove the realization of such a mechanism because the contractions can be explained naturally in terms of different mechanisms, in particular, by thermal instability for which localization of deformation is typical, too. On the other hand, the work hardening coefficient is one of the most important parameters of a material (in terms of stability of the deformation) and must be included in any criterion (see expressions (1) and (2)). Obviously, geometrical instability can take place in some cases, but there are no reasons to ascribe the phenomenon of low temperature JD entirely to this mechanism.

5. Dislocation (athermal) instability

By this mechanism we mean the instability on a scale of dislocation groups which is not related directly to a temperature rise (although thermal fluctuations can play a certain role). Seeger [16] suggested that the preliminary deformation forms strong dislocation pile-up which cannot overcome barriers by thermoactivated cross slip since the temperature is low, but overcome them by the force due to the stress concentration in the head of pile-up. According to other authors [17, 18], high flow stresses at low temperatures can promote avalanche multiplication of mobile dislocations, and action of surface or bulk sources. These hypotheses are qualitative and have not been developed into models. In particular, they do not answer the main question: what is responsible for the cooperative character of individual dislocation acts which leads to macroscopis deformation jumps? Nevertheless, we cannot reject the dislocation mechanisms of instability for the following reason.

Probably, there can be a combination of two or three mechanisms of instability. For example, localized deformation arising from thermal instability can be intensified by the geometric factor or conversely. Thus, in Ref. [18] in which Nb single crystals were deformed by tension at 4.2 K, a descreae of sample cross-section area more than by three times was observed in the region of shear after some deformation jumps. At the same time, the temperature of the slip band reaches 200 – 250 K during such a jump, which will be discussed below. It is obvious that it is impossible to describe this process in terms of any one concept. In another situation some dislocation act (break-through of pile-ups or action of sources) will lead to local heating which can develop into macrojumps due to thermal instability. Such a situation was considered in Ref. [19] which found an anomalous temperature dependence of the flow stress of Nb single crystals compressed at $T < T_{cr} = 12-15$ K in which the deformation becomes jump-like and observed asymmetry of the jump onset stress under tension and compression. It has been shown there that such features cannot be explained entirely in terms of the concept of thermal instability. These results can be explained on the assumption that there are some regions in the crystal (mainly near the suface) with a higher level of the interlan stress σ_i. Plastic deformation under the action of the local stress $\sigma_e = \sigma_i + \sigma$ begins in such regions before the macroscopic plastic flow takes place. In the absence of instability this will lead only to microplastic deformation (an evidence of its existence in Nb was given in Ref. [13]). In the presence of thermal instability, microdeformation accompanied with local heat generation can develop into a macroscopic slip band which passes through the bulk of the sample at higher temperatures and, consequently, at stresses $\sigma < \sigma_e$. Thus, althouth deformation jumps are associated with thermal instability, still the jump onset stress is due also to other factors, space distribution of the internal stress in particular.

This example shows the restricted applicability of linear analysis of stability which considers the stability against infinitesimal fluctuations. In reality the acts of plastic deformation making finite contributions to the sample deformation can work as fluctuations. An other example is the pulsed heating of the crystal. In such conditions, the range of instability can be much broader and this is what takes place in Nb.

6. The kinetics of deformation jumps

Even in one of the early investigations of low temperature JD it was found that the duration of jumps was very small: $\Delta t_j \lesssim 1$ ms. And this proved to be quite typical: almost all works in which time resolution of the apparatus was sufficient to measure Δt_j obtained values of the same order of magnitude: in Cu-Al [20], Ta [21], Nb [4]. These values are comparable with the time Δt_s of sound propagation through the sample-machine system and it has been proved today [4, 20] that the dynamic effect plays a significant role and the quasi-static "machine" equation cannot be used to describe the kinetics of such jumps, and, possibly, even to formulate the criterion of stability. Thus, for example, Demirski and Komnik [20] investigated the dependences of jump parameters in Cu-Al on the stiffness and the mass of loading system and showed that the jump duration Δt_j is governed by the mechanical properties of the system and the stress during the jump is not the same in different parts of the system.The same result was obtained also for Nb (see below). Very few theoretical papers have attempted to analyze the jump kinetics [8, 10]. However, they used the quasi-static ,,machine" equation. Therefore, their results cannot be used to describe such experiments.

Thus, the small jump duration imposes special requirements on experimental techniques, and this might be one of the main causes of the lack of information on the jump kinetics. Taking into account these requirements, we developed a method of synchronous recording of the high-velocity process kinetics during low temperature plastic deformation. It includes recording of the time dependences of the flow stress σ measured near the sample, the sample strain rate $\dot{\varepsilon}$ and the stress σ_1 measured by a remote dynamometer with a time resolution of about 1 μs; recording of the sample-average temperature and the state (superconducting S or normal N) with a time resolution of about 10 μs (the method is based on measuring the penetration depth of the magnetic field (200 kHz) in the region of the skin effect). Using this technique, an investigation of the jump kinetics in Nb signle crystals deformed by compression at 4,2 K has been performed. The typical stress-strain curve is shown in Fig. 1b.

Synchronous oscillograms of $\sigma(t)$, $\sigma_1(t)$, and $\dot{\varepsilon}(t)$ during a jump are shown in

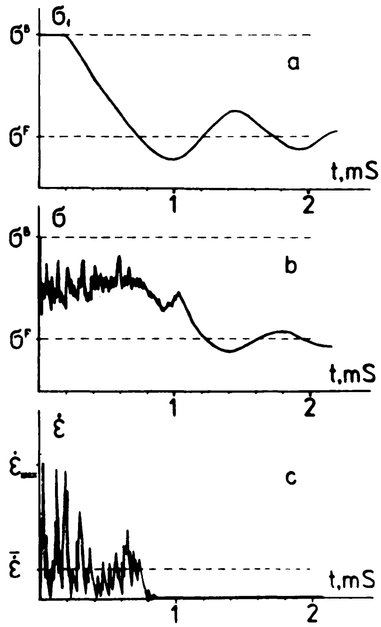

Fig. 3. Synchronous oscillograms of the flow stress measured a) by a remote dynamometer, b) near the sample and c) those of the strain rate during a deformation jump in a Nb single crystal at 4.2 K. σ^B and σ^F are the stresses of the jump onset and end, respectively.

Fig. 3. In all the cases the curve of $\sigma(t)$ starts with a steep load drop by about a half of the jump amplitude. The drop takes $5-10$ μs, then $\sigma(t)$ becomes nonmonotonic. Within 1 ms, $\sigma(t)$ transforms into attenuating oscilation near the stress of the jump end. The frequency f_1 of the oscillations is equal to that the first harmonic of oscillations of the sample-machine system. As can be seen from curve of $\sigma_1(t)$, the components of signal spectrum having frequencies higher than f_1 do not reach the remote dynamometer. The $\dot{\varepsilon}$ peak corresponds to the steep load drop in the curve of $\sigma(t)$. The time of shear development may be determined exactly from $\dot{\varepsilon}(t)$ oscillo-

grams: for all the cases, $\Delta t_j = 0.8$ ms, which is close to the doubled time of sound propagation along the system.

An important feature of the $\sigma(t)$ and $\dot{\varepsilon}(t)$ curves are the high-frequency oscillations. They are particularly pronounced in the $\dot{\varepsilon}(t)$ curve. Its maximum values, ε_{max}, can increase the average one $\bar{\dot{\varepsilon}}$ by a factor of 5–10 that correspond to the shear rate $\dot{\gamma}_{max} = (1 - 2) \times 10^4 \text{ s}^{-1}$. It is known that so high strain rates correspond to viscous rather than thermoactivated dislocation motion.

We analysed the dynamical properties of the sample-machine system on the basis of the model which represents it as an elastic rod. One end of the rod is moved by the reductor of deformation machine and the sample is fixed at the other end. We obtain the equation relating σ and $\dot{\varepsilon}$, which is in this sense an analogue of the „machine" equation for the dynamical case:

$$\sigma(t) = \sigma^B - \alpha\dot{\varepsilon}(t), \quad \text{at} \quad t < 2\Delta t_s, \tag{5}$$

where σ^B is the jump onset stress, α is the constant depending on the effective modulus of the system. As it is shown by comparison with experiment, equation (5) precisely describes the correlation between the $\sigma(t)$ and $\dot{\varepsilon}(t)$ curves within the first 20–30 μs, while at the later stage of the jump it is correct only for the average values of σ and $\dot{\varepsilon}$, owing to reflections of elastic waves from various parts of the system. Nevertheless, it provides understanding of the main dynamical properties.

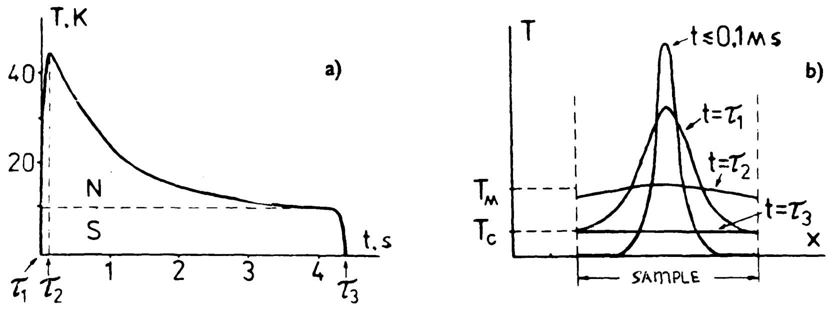

Fig. 4. Dependence of the average crystal temperature on the time since the jump onset (a) and approximate curves illustrating the temperature distribution along the sample length at various moment of time (b).

Fig. 4 shows the dependence of the average sample temperature T on the time since the jump onset and several approximate curves which illustrates the development and relaxation of thermal perturbations. At the initial moments of time ($t \lesssim 0.1$ ms), all heat generated is localized near the acting slip band and the rest of the sample remains in the S state. Because of the smearing of the heat distribution the normal zone extends to whole sample ($T > T_c = 9.2$ K) within the time $\tau_1 = 0.6$ ms. At $t = \Delta t_j = 0.8$ ms, the plastic deformation stops, but the heat distribution remains ėssentialy inhomogeneous in the crystal. During its equalization, the measured value of T increases, since the averaging is nonlinear (see the dashed line in Fig. 4a). At the moment $\tau_2 = 50-100$ ms, which corresponds to the maximum of $T(t)$, the heat is distributed uniformly along the sample. From this moment on, the true crystal temperature is measured. Within $\tau_3 = 4.5$ s, the sample recovers the S state ($T < 9.2$ K). Thus, the conditions of the deformation processes during the jumps are adiabatic and, as the relationship between the times shows, it is not only on the scale of the sample but also on the scale of a slip band. This enables estimation of the local temperature in the acting slip band: $T_1 = 200-250$ K.

Let us summarize the main conclusions which follow from the results presented:
1. A nonzero strain rate $\dot{\varepsilon}$ causes radiation of a load-relief wave into the sample--machine system (the initial load drop in the $\sigma(t)$ curve). This wave, reflected from the other end of the rod within the time $2\Delta t_s$, comes back to the sample and stops the deformation process. Thus, the jump duration Δt_j and, consequently, the whole jump strain $\varepsilon = \bar{\dot{\varepsilon}} \, . \, \Delta t_j$ totally depend on the time of sound propagation through the system: $\Delta t_j = 2\Delta t_s$. It can be pointed out that, according to eq. (5), the stress during the jumps can rise if $\dot{\varepsilon}$ decreases. This important property, which does not characterize the quasi-static case, can be responsible for the periodic reproducibility of individual dislocation acts.
2. The high shear strain and local temperature in slip bands suggest a change of the character of the dislocation motion during the jump. Before the jump onset and within the first few microseconds of the jump, the dislocation motion has the thermo-activaed character. This provides thermal instability, i.e. increase in $\dot{\varepsilon}$ and T. As it was shown by estimation which was based on experimental values of $\dot{\varepsilon}$, a slip band with a width of $0.01-0.1$ mm can be heated up to $200-250$ K within about 10 μs. This heating causes transition to viscous dislocation motion: the level of the flow stress is more than an order higher than the yield stress of Nb at such temperatures, i.e. the situation during the jumps is similar to that in shock loading experiments. The change of the charactre of the dislocation motion with increasing temperature can be due to the fact that the fluctuation waiting time τ_w becomes smaller than the time of the passage between obstacles, τ_p, and the dislocation velocity will be determined by the mechanisms of dynamic breaking. As follows from the estimation for Nb at 250 K, the ratio τ_w/τ_p is of order of the ratio of dislocation velocity to the sound velocity which is much smaller than 1.
3. The oscillations of $\dot{\varepsilon}$ during a jump, in contrast to the other features, cannot be explained in terms of the above concept. Indeed, during adiabatic heating, T and consequently the dislocation velocity must be a monotonically increasing function of time. The oscillations of σ cannot be the cause either since, according to (5). they are in antiphase to $\dot{\varepsilon}$. Therefore, the most probable cause of oscillations of $\dot{\varepsilon}$ are changes in the mobile dislocation density ϱ, which can be related to inhomogeneity of the space distribution of the shear. Thus, structural investigations of the slip band in Nb which were made in Ref. [23] show that at 4.2 K they are formed by successive origination of shears in slip lines and transmission of the shears from

one slip line to another. Periodic reproducibility of this prpcess, as was mentioned above, may be provided by the dynamical properties of the system.

An analysis of the relation of the mobile dislocation density ϱ to σ and $\dot{\varepsilon}$ [19] showed that in the dynamic case (high-rate deformation) the experimentally observed oscillations of $\dot{\varepsilon}$ and σ could be explained by oscillations of ϱ if their values $\Delta\varrho$ were comparable with their average value ϱ_0. At the same time, in the quasi-static case (slow deformation), at the same value of $\Delta\varrho/\varrho_0$ the amplitude of oscillations of σ is a few order of magnitude lower than in the dynamic case. Thus, the space inhomogeneity which is inherent in the deformation process cannot affected the $\sigma(t)$ curve.

7. Conclusions

The results presented are an evidence of a complicated and varied character of the low temperature JD processes, which cannot be described in terms of some simple models. In spite of this and the significant role which is played by alternative mechaniems of instability, all information we have today allows us to believe that the thermal instability plays the most important role in low temperature JD. It is obvious that further investigations of the kinetics of the jumps requires to reveal the common features of the phenomenon (which may be associated with the high-rate character of the processes and the role of the dynamic, wave effects) and its specific features in various materials. On the other hand, such investigations are needed for theoretical models describing adequately the experimental situations.

References

[1] Startsev, V. I., Ilichev, V. Y., and Pustovalov, V. V., Plastichnost i prochnost metallov i splavov pri nizkih temperaturah, Metallurgiya, Moskva, 1975, p. 328 (in Russian).

[2] Klyavin, O. V., in Phizicheskie protsessi plasticheskoy deformatsii pri nizkich temperaturah, Naukova Dumka, Kiev, 1974, p. 5 (in Russian).

[3] Demirski, V. V. Komnik, S. N., and Startsev, V. I., Physica Metallov i Metalloved., 46 (1978) 853 (in Russian).

[4] Dolgin, A. M. and Bengus, V. Z., Phys. Stat. Sol. A, 94 (1986) 529.

[5] Davidenkov, N. N., Phys. Tverd. Tela, 3 (1961) 2459 (in Russian).

[6] Basinski, Z. S., Proc. Roy. Soc., 240 (1957) 229.

[7] Malygin, G. A., Phys. Met. i Metalloved., 40 (1975) 21 (in Russian).

[8] Gitomirski, I. S. and Nechiporenko, I. N., Phys. Niz. Temp., 4 (1978) 1053 (in Russian).

[9] Mints, R. G. and Petuhov, B. V., Phys. Tverd. Tela, 22 (1980) 1085. (in Russian).

[10] Kubin, L. P., Spiesser, Ph., and Estrin, Yu., Acta Met., 30 (1982) 385.

[11] Komnik, S. N., Demirski, V. V., Crystal Res. Technol. 19 (1984) 863.

[12] Komnik, S. N., Demirski, V. V. and Startsev, V. I., Czech. Phys. J. B-35 (1985) 230.

[13] Dolgin, A. M., Phys. Niz. Temp., 14 (1988) 905 (in Russian).

[14] Trefilov, V. I., Milman, Yu. V. and Firstov, S. A., Phyzicheskie osnovi prochnosti tugoplavkih metallov, Naukova Dumka, Kiev, p. 315 (in Russian). 1975.

[15] Eremin, V. I. and Natsik, V. D., Problemi prochnosti, in the press (1990) (in Russian).

[16] SEEGER, A., in Dislokatsii i mechanicheskie svoystva kristalolv, Inostr. Lit., Moskva, p. 179 (in Russian).
[17] WESSEL, E. T., Trans. ASM, 49 (1957) 149.
[18] TABACHNIKOVA, E. D., DOLGIN, A. M., BENGUS, V. Z. and EFIMOV, YU. V., Phys. Metal i Metalloved., 58 (1984) 573 (in Russian).
[19] DOLGIN, A. M., Dissert. kand. Phys.-Mat. Nauk, Kharkov, 1988, p. 199. (in Russian).
[20] DEMIRSKI, V. V. and KOMNIK, S. N., Acta Met., 30 (1982) 2227.
[21] KURAMOTO, E., TAKEUCHI, S., SUZUKI, T., J. Phys. Soc. Japan, 34 (1973) 1217.
[22] DOLGIN, A. M. and BENGUS, V. Z., Phys. Niz. Temp., 16 (1990) 254 (in Russian).
[23] BARAZ, A. R., Dissert. kand. Phys.-Mat. Nauk, Moskva, 1979 (in Russian).