Journal of Engineering Physics and Thermophysics, Vol. 67, No. 1-2, 1994

HEAT AND MASS TRANSFER IN ABNORMAL METAL PLASTICITY

G. M. Klyuchnikov and I. G. Klyuchnikov

UDC 536.52:539.214

The authors show the decisive role and special features of heat and mass transfer in the mechanism of abnormal plasticity and in formation of thermomechanical dissipative structures under large plastic strains by the examples of computer modeling of stretching of a specimen, high-pressure torsional shear in a Bridgeman chamber, and shearing strain of a material in the form of flow of a quasiviscous liquid in a channel with local heat removal via a stationary wall.

Abnormally high plasticity is observed in strain and failure of many metals and alloys and is widely used in practice, for example, for so-called superplastic strain and high-speed strain. In the majority of the proposed mechanisms and, correspondingly, theories of abnormal plasticity, for example, [1–3], it is the evolution of defects of a crystal lattice, plastic flow waves and the highly excited state of crystals related to them, and their boundaries that is among the main factors, while thermal processes rank secondary. However, numerous investigations show that under large plastic strains of polycrystalline materials grains are cleared of dislocations, and at sites where the strain if localized (in a "running neck," in "adiabatic bands of shear") temperature bursts and traces of stuctural transformations appear even at cryogenic temperatures of the medium [4–6].

Our proposed mechanism of abnormal plasticity [7, 8] is associated with transitions in materials were disordering of the atomic structure and, under the appropriate loading, facilitated shearing strain and abnormal mass transfer occur. These transitions may include polymorphic and magnetic transformations, recrystallization, carbide formation, etc., which are associated with certain temperatures T_{tr}, which makes it of primary importance to estimate the actual temperature fields in considering processes with abnormal plasticity. Owing to nonuniformity and nonstationarily of the temperature fields at a seat of strain the transitions appear in local regions and the transition front (the geometric boundary of the onset of the transition) moves following an isotherm (T_{tr}), which leads to local abnormal plasticity and slipping of groups of atoms, individual grains, groups of them, or portions of the material relative to each other. Here, slipping in the direction of the maximum tangential stresses and along the surface, on most of which there is abnormal plasticity, is most likely. Slippings can only be pulsed and brief in connection with the fact that the temperature in the slipping zone increases sharply owing to dissipation of mechanical energy and removal of lattice dislocations, and the transition front, together with the abnormal plasticity, leaves this zone. Furthermore, the straining stress decreases sharply (relaxation), and time is needed for its growth to a value sufficient for the next slipping at the site to which the transition front has moved. Replenishment of the supply of elastic strain energy is needed. Abnormal slippings are accompanied by abnormal pulsed mass transfer along the slipping surfaces with filling of the cavities formed (accommodation). This approach enabled us to develop a method for calculating the evolution of thermomechanical dissipative structures at a seat of large plastic strain for different cases of external thermal and force effects. A brief analysis of special features of thermal processes from the results of numerical modeling of the particular cases of abnormal plastic strain is given below.

Stretching of the Specimen. Figure 1 shows a fragment of a polycrystalline specimen of grains represented in the form of tetracandecahedrons with slipping in the zone of the transition front, i.e., the polymorphic transformation $\alpha \rightleftarrows \beta$, which moves under the action of the energy flux J_k, for example, a heat flux, from the previous slipping. The shear of one portion of the specimen relative to the other occurs by grain boundary slippings

Izhevsk Mechanical Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 67, Nos. 1-2, pp. 127-131, July-August, 1994. Original article submitted October 19, 1992.

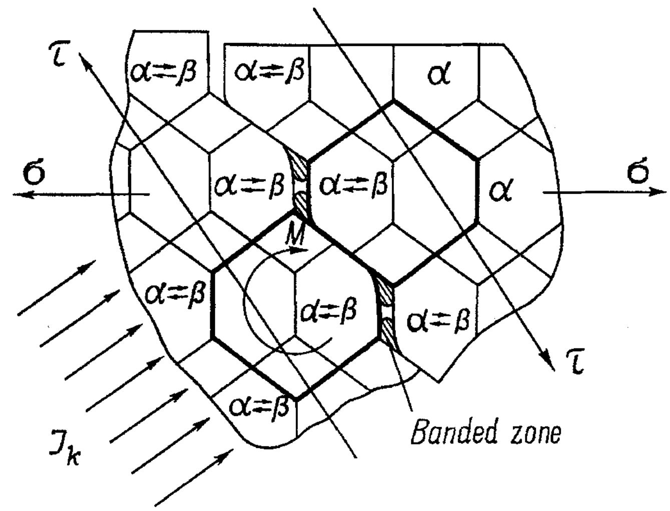

Fig. 1. Fragment of a polycrystal with a surface of slipping.

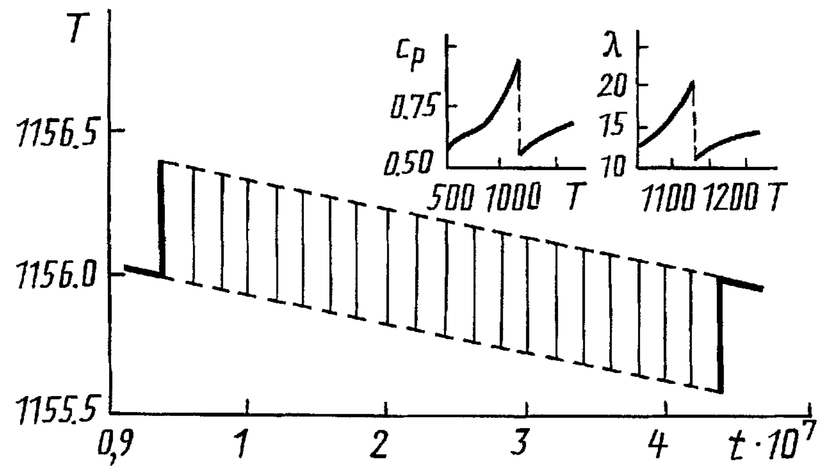

Fig. 2. Temperature oscillation. c_p, kJ/(kg·K); λ, W/(m·K); T, K; t, sec.

over a complex slipping surface with formation of cavities that are instantaneously filled with material by abnormal mass transfer (formation of the "banded zones" observed in practice).

Nonstationary processes on different structural levels are considered.

In numerical modeling of thermal processes in the zone of slipping surfaces we solved nonstationary nonlinear two-dimensional heat conduction problems using Patankar's method [9]. We established the phenomenon of heat localization and temperature oscillation in movement of the transition front relative to the slipping surface and that of considerable temperature nonuniformity along the perimeter of the surface owing to irregularities. Methods and some results of calculations are reported in [8, 10]. Based on the procedure of [11] we developed a program of numerical solution of a hyperbolic heat conduction problem and established with its aid the influence of the finite rate of heat propagation (the time of processes at the grain boundary level is comparable with the relaxation time) on the thickness of the peripheral layer of the grain (the "mantle"), where the above active nonequilibrium processes are concentrated in abnormal slipping.

Because of the article's limited space we will give just one result of the calculation. Figure 2 shows the temperature oscillation on a titanium grain boundary with abnormal changes in the thermophysical properties, indicated in the insets, in the region of the $\alpha \rightleftarrows \beta$ transformation according to experimental data [12]. The oscillation is associated with a cooperative reversible transition of groups of atoms at the surface of slipping from one phase to the other. It occurs when the emerging new phase alters the surface temperature in the direction opposite to the change in it due to the action of an external heat source.

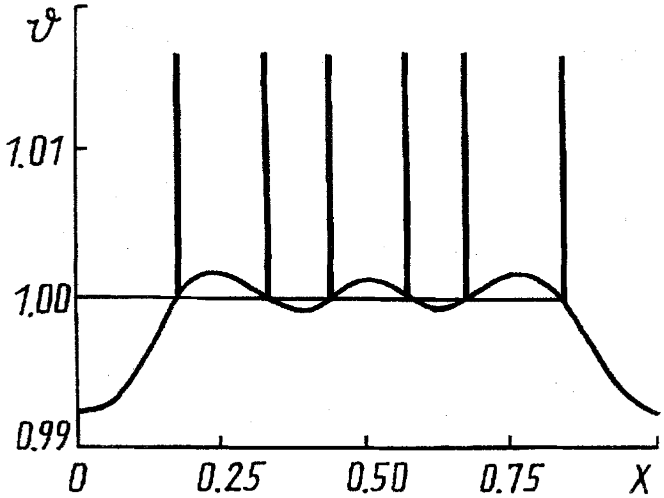

Fig. 3. Temperature distribution along the specimen length at the moment of completion of six simultaneous slippings.

We performed numerical modeling of the evolution of slippings (the "running neck") and formation of thermomechanical structures at a seat of plastic strain for different combinations of thermal and force effects.

In one of the cases a titanium specimen length of the working portion of the specimen is $3 \cdot 10^{-3}$ m and the diameter is $6 \cdot 10^{-2}$) with initial temperature equal to 1146 K, which is 10 K lower than the $\alpha \gtrless \beta$ transformation temperature, is subjected to stretching with a constant velocity of the clamp that corresponds to the initial rate of relative strain $\dot{\varepsilon} = 10^{-3}$ sec^{-3}. A decrease in the temperatures to a value lower than the transition temperature ($\vartheta < 1$) is realized through heat removal to the clamps and convection to the environment or by the value supplied for heating the specimen by energy. Figure 3 gives one of the intermediate moments of evolution of the temperature field, i.e., the distribution of the relative temperatures $\vartheta = T/T_{tr}$ along the specimen axis with six simultaneous slippings. In the calculation we fixed the site of each slipping and their number, which enabled us to explain the reason for the formation of slipping bands, a neck or necks, and superplastic strain.

By calculating variants we established the influence of the following factors on local strains: the specimen's geometry, the sites of the first slipping, the rate of deformation, the temperature of the medium, and the methods of heating and loading.

Shearing Strain in a Bridgeman Chamber. We performed a series of calculations of plastic strain for materials that were placed in a Bridgeman chamber with layer variation within $(1-5) \cdot 10^{-4}$ m for a diameter of $6 \cdot 10^{-3}$ m and were subjected to torsional shear with strong compression. It is established that the heat released under strain is removed rapidly by heat condition to the massive walls and, via the lateral surface, to the environment, producing a considerable temperature gradient across the thickness of the material. As in the previous example a "running neck" emerges in the strained volume not only with respect to the thickness but also with respect to the radius. Analyzing the thermomechanical dissipative structures that emerge under the "pressure plus shear" conditions enabled us to explain phenomena established in well known Bridgeman experiments [13], in particular, different sounds that emerge in the strain of materials: hissing, creaking, rattling, clicking, and sometimes an explosive discharge of material. The association of abnormal plasticity with transitions is confirmed by Bridgeman's use of plastic strain in a chamber to reveal previously unknown polymorphic transformations in materials.

Shear Flow of a Quasiliquid in a Channel. In accordance with the proposed mechanism of abnormal plastic strain a solid will act as a liquid (a quasiliquid) when, under a uniform shearing strain, abnormal plasticity accompanies all mechanical interactions of the structure of the elements of the strained material. This will be the case when the material is in the state of an active kinetic medium [14] and the temperature, which increases in a pulsed manner in the interaction zone of these elements, attains periodically the transition temperature T_{tr}. This state is very unstable since with an excessive deviation of the material temperature from T_{tr} abnormal plasticity will not appear, slippings of the structural elements relative to one another will cease, and the quasiliquid "will

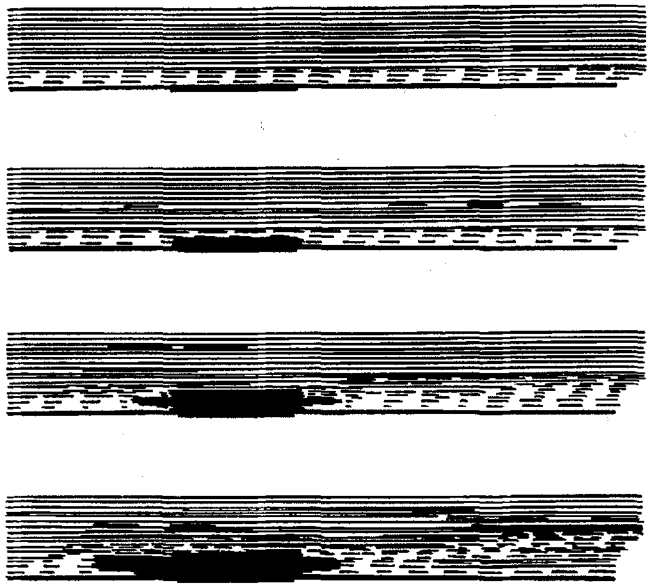

Fig. 4. Four moments of the evolution of shear flow of a quasiliquid with local heat removal via a stationary wall.

harden." In this connection the flow of the quasiliquid acquires an unusual character since the temperature may change along the path of its motion, for example, owing to local heat removal via the channel walls, warmup inside vortices that arise, warmup in stagnation of the flow, etc.

Figure 4 shows an example of calculating the shear flow of a quasiliquid in a channel in which heat is removed on a short portion of the stationary wall. The problem was solved within the framework of continuum mechanics by a pseudospectral numerical method using the algorithm of a fast Fourier transform. For outgrowth formation a through problem was solved. The figure shows four moments in the evolution of processes in the channel, whose consideration can give an idea of how difficult the formation of the outgrowth in the heat removal zone is. Similar formation of outgrowths in the form of overflows, so-called "white layers," is observed in practice at high shear stresses [15].

The work was reported in its entirety at the 2nd Minsk International Forum on Heat and Mass Transfer, May 21, 1992.

Summary. Abnormal plasticity, abnormal mass transfer, and abnormal plastic strain are closely associated with thermal processes due primarily to transitions that proceed at certain temperatures (over a certain temperature range) and pulsed heat removal in the zone of local strains with dissipation of the energy of elastic strain of the material and the straining device.

It is established that under large plastic strains in accordance with the type of material, the geometry of the seat of strain, and external effects on it thermomechanical dissipation structures with evolution of pulsed abnormal slippings form. Mathematical models and programms for calculating the formation and development of thermomechanical structures under large strains are worked out for the particular cases of stretching of a specimen, high-pressure shearing strain in a Bridgeman chamber, and shear flow of a quasiliquid in a channel with local heat removal.

Some results of numerical experiments are given that show the important role and special features of thermal processes in the action of abnormal plasticity.

NOTATION

T, current temperature; T_{tr}, temperature of the onset of a transition; $\vartheta = T/T_{\text{tr}}$, relative temperature; $X = x/l$, relative coordinate along the specimen length l; J_k, external energy with respect to the surface of slipping; c_p, isobaric specific heat; λ, thermal conductivity; σ, normal stress; τ, tangential stress; M, torque; $\dot{\varepsilon} = d\varepsilon/dt$, rate of deformation; t, time; α, β, phases of the material.

REFERENCES

1. O. A. Kaibyshev, Superplasticity of Industrial Alloys [in Russian], Moscow (1984).
2. V. E. Panin, Yu. V. Grinyaev, V. I. Danilov, et al., Structural Levels of Plastic Strain and Failure [in Russian], Novosibirsk (1990).
3. Yu. I. Krasnoshchyokov, L. K. Kuznetsov, V. N. Perevezentsev, et al., Dokl. Akad. Nauk SSSR, **312**, No. 4, 872-875 (1990).
4. A. A. Presnyakov, Seat of Strain in Plastic Working of Metals [in Russian], Alma Ata (1988).
5. M. A. Meyers and L. E. Moorr (eds.), Shock Waves and High-Speed Metal Deformation Phenomena [Russian translation], Moscow (1984).
6. V. A. Strizhalo, V. Yu. Bugaev, and N. I. Medved', Probl. Prochn., No. 9, 26-30 (1990).
7. G. M. Klyuchnikov, in: Abstracts of Papers of the 3d All-Union Conference "Superplasticity of Metals," Tula (1986), pp. 35-36.
8. G. M. Klyuchnikov and I. G. Klyuchnikov, in: High-Temperature Cooled Gas Turbines of Aircraft Engines [in Russian], Kazan' (1986), pp. 91-96.
9. S. Patankar, Numerical Methods of Solving Problems of Heat Transfer and Fluid Dynamics [Russian translation), Moscow (1984).
10. G. M. Klyuchnikov, in: Thermal State of Cooled GTE Parts [in Russian], Kazan' (1985), pp. 25-29.
11. Wick and Erishil, Teploperedacha, **105**, No. 4, 224-230 (1983).
12. V. E. Zinoviev, A. D. Ivliev, I. G. Korshunov, et al., in: Reviews of Thermophysical Properties of Materials [in Russian], Moscow (1982), No. 5.
13. P. Bridgeman, Investigation of Large Plastic Breaking Strains [Russian translation], Moscow (1955).
14. V. Ebeling, Structure Formation in Irreversible Processes. Introduction to the Theory of Dissipative Structures [Russian translation], Moscow (1979).
15. K. Khebda and A. V. Chichinadze (eds.), Handbook on Triboengineering [in Russian], Vol. 1, Moscow (1989).