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SOME PECULIARITIES OF MASS TRANSFER IN THE METALS AND ALLOYS WITH DIFFERENT INITIAL STRUCTURES UNDER HIGH-RATE DEFORMATION CONDITIONS

L. O. Zvorykin, V. M. Fal'chenko, and
A. V. Filatov

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Results of experimental studies of the mass transfer processes in metals and alloys subjected to the action of plane shock waves are reported. The influence of the initial structural state of poly- and monocrystalline materials on atom mobility are established.

The processes of element redistribution in metallic materials under shock compression conditions entail necessarily changes in their initial structure. Even slow quasi-equilibrium diffusion processes are realized through the migration of crystal defects (mainly point defects). Formation, interaction, and displacement of the defects greatly depend on the initial structure of the deformed material. In this connection, investigation of the influence of the initial metal structure on the formation of the mass transfer zone may provide additional information about the physical nature of the phenomenon in question.

Changing the initial structure by the creation of deformation defects to modify mass transfer conditions in the case of various modes of pulsed treatment is investigated in [1-3]. It has been found that the pulsed irradiation of nickel by a laser ($\dot{\varepsilon} \sim 10^3$ sec^{-1}) results in formation of a mass transfer zone whose characteristics depend monotonically on the dislocation density [3]. For uniaxial plastic deformation with rates of 0.2–10^2 sec^{-1} an increase in the dislocation density in the initial structure to the level $\rho_d \sim 10^8$ cm^{-2} moderates mass transfer processes. Further increase of ρ_d to 10^{11} cm^{-2} causes an even greater decrease in the penetration depth of the elements of the covering [1].

Deformation of metals due to a plane shock wave with amplitude $P_{\text{sh.w}} = 40$ GPa ensures a deformation rate of $\dot{\varepsilon} \sim 10^8$ sec^{-1}. Studies of the atom redistribution due to the passage of a shock wave in copper with a different degree of lattice perfection in the initial state will make it possible to extend the results of [1-3] and to understand more clearly the factors responsible for the relationship observed.

To create a different amount of defects, the samples were subjected to three types of processing, namely, isothermal annealing (1273 K; 30 min) and quasistatic and high-rate modes of deformation. The rate of copper predeformation was 1, 10^2, and 10^8 sec^{-1}. The characteristics of the copper lattice distortions caused by different preliminary treatment are shown in Fig. 1. As a result of the quasistatic deformation, the dislocations in copper are distributed in small aggregates which are absent in the annealed copper sample. An increase in the deformation rate gives rise to a cellular dislocation structure. Preliminary detonation treatment ($P_{\text{sh.w}} = 40$ GPa) of copper produces cells with distinct boundaries and sizes that are two to three times smaller than in the case of deformation with $\dot{\varepsilon} = 10^2$ sec^{-1}. Moreover, as shown in [4], the passage of a shock wave causes the formation of a great number of dislocation loops and deformation twins.

Figure 2 shows the influence of the initial state of a metal matrix on the depth of iron and nickel penetration into copper upon the passage of plane shock waves ($P_{\text{sh.w}} = 50$ GPa, $\tau_{\text{sh.w}} = 1$ μsec). The results obtained show that an increase in the lattice microdistortions associated with an increase of the predeformation rate causes a decrease in the penetration depth of the elements of coverage. An analysis of the concentration distribution of these elements with respect to the depth of copper with different initial structures shows that in all cases the concentration profiles

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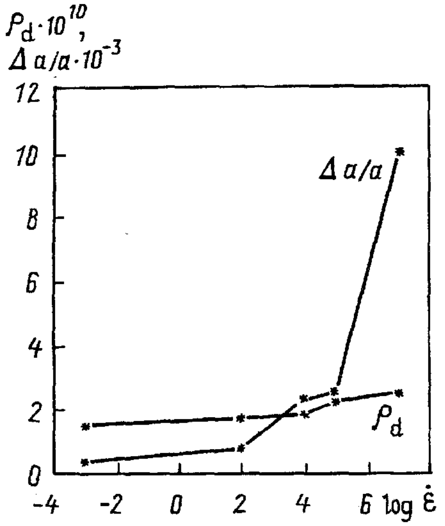


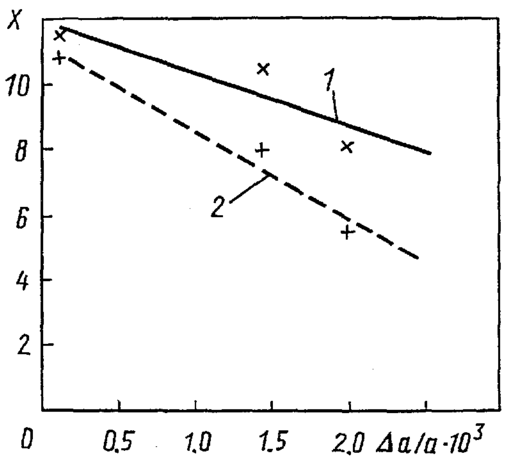


Fig. 1. Dislocation density (cm^{-2}) and microstresses (dimensionless) in copper versus deformation rate (sec^{-1}).

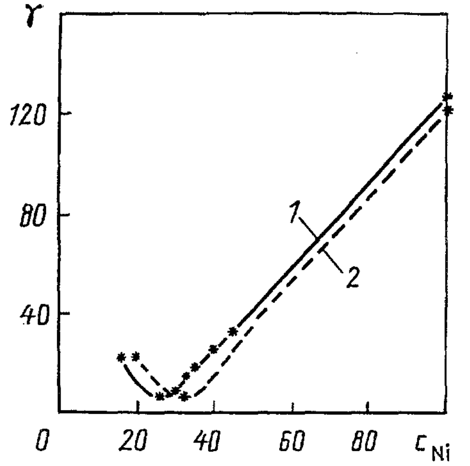
Fig. 2. Penetration depth (μm) of ^{55}Fe (1) and ^{63}Ni (2) in copper versus microstresses (dimensionless) in the initial state.

TABLE 1. Characterization of the Copper Structure in Different Initial States and after Shock Compression, $P_{\text{sh.w}}$ = 50 GPa; $\tau_{\text{sh.w}}$ = 1 μsec

Mode of initial treatment	Deformation rate, $\dot{\varepsilon}$, sec^{-1}	Initial state			Final state	
		$\Delta a/a$, $\times10^3$	ρ_d, cm^{-2}	twin	ρ_d, cm^{-2}	twin
Annealing	0	0	$5\cdot10^7$	No	$1.1\cdot10^{11}$	Yes
Quasistatic deformation	1	1.45	$5\cdot10^{10}$	No	$1.1\cdot10^{11}$	No
Pulsed deformation	10^2	1.9	$2\cdot10^{10}$	No	$1.1\cdot10^{11}$	No
Detonation treatment, $P_{\text{sh.w}}$ = 40 GPa, $\tau_{\text{sh.w}}$ = 1 μsec	10^8	2.1	10^{11}	Yes	$1.5\cdot1011$	Yes

are satisfactorily approximated by the function $C = C_0 \exp(\alpha X)$. The main characteristics of the copper structure in the initial state and after the passage of a plane shock wave, causing mass transfer of the coverage elements, are given in Table 1. In analyzing the reasons for the observed dependence of mass transfer on the density of the structural defects in copper (Fig. 2), particular attention should be given to the small difference in the initial and final states of the copper predeformed by detonation. In practically all cases the passage of a 50 GPa plane shock wave leads to the formation of a structure similar in basic features, i.e., a cellular dislocation structure with a cell size of ~0.1–0.2 μm. In copper predeformed under quasistatic loading conditions, traces of twinning are observed extremely rarely. The repeated detonation treatment yields an increase in the dislocation density in the walls of dislocation cells and the width of these cells; the volume of the twinning regions increases as well. In this case, the increase in the amount of twins is associated with the generation of dislocations at the boundaries of the twins produced after the first deformation [4].

The changes observed in the mass transfer processes in copper with different initial structures may be associated with the fact that an increase in the initial density of structural defects entails a decrease in the increment



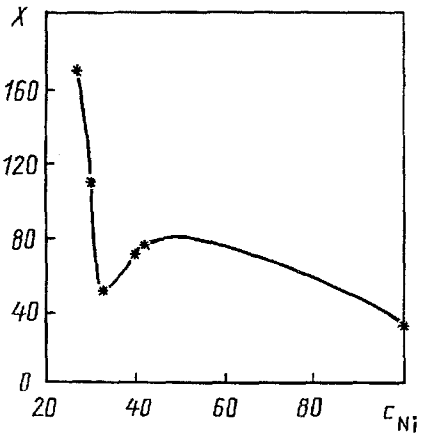


Fig. 3. EPD (mJ/m^2) at 293 K in alloys based on cobalt with different nickel concentrations (1) (wt.%) and at a high pressure (2).

Fig. 4. Penetration depth of ^{63}Ni atom coatings in cobalt-nickel alloys as a function of increasing nickel concentration.

of their amount during passage of a shock wave. This is shown, in particular, by the minimum increment of microstresses $\Delta a/a$ in the case of detonation pretreatment of the copper (see Fig. 1). This agrees with the concepts [5] in accordance with which on shock loading the dislocations are homogeneously generated in the front of the shock wave. As a result of the preliminary deformation, some stress deviators in the front of the shock wave may be neutralized by the existing dislocations. This causes a decrease in the number of dislocations generated in the front of the shock wave. In this case, the formation of lattice defects under shock compression conditions seems to exert a positive influence on the mass transfer processes. A decrease in the increment of the structural defect density on preliminary deformation of the metal matrix causes a decrease in the depth of nickel and iron penetration (Fig. 2). Furthermore, the structural defects in the initial state may be an obstacle to mass transfer events, as is speculated for mass transfer involving deformation at a rate of $\dot{\varepsilon} = 0.2-10^2$ sec^{-1} with initial dislocation density $\rho_d \sim 10^8-10^{11}$ cm^{-2} [1].

The regularities of the mass transfer in metals under high-rate deformation conditions [1-3, 6] point to the structural sensitivity of this process. The influence of the crystal lattice type on mass transfer is shown in [6]. This process has been observed both in the case of parent atoms and interstitial and substitutional species as well. It is established that mass transfer involving passage of shock waves occurs only when plastic deformation develops. One of the important characteristics specifying the formation of a deformation structure is the energy of packing defects (EPD) [4, 5]. Therefore it is especially interesting to study the redistribution of the elements of coverage in the cobalt-nickel systems, a distinctive feature of which is the EPD variation at high dynamic pressures with the nickel content (Fig. 3) [7]. The dependence EPD $\gamma = f(C_{Ni})$ is a minimum in alloys that contain approximately 30–33% Ni. A change in the concentration of one of the alloy components exerts an influence, as a rule, on the mobility of atoms in the alloy under isothermal annealing. However, in the case of mass transfer caused by pulsed action such an influence, especially on changing the concentration of substitution atoms, is not substantial for the processes of atom migration [6]. It should be noted that the proximity of shock adiabats of cobalt and nickel leads to a weak dependence of the characteristics of shock waves, generated in the cobalt-nickel alloys under the same conditions, on the nickel concentration. This provides reason enough to think that a direct change in the content of nickel and cobalt from 27/73 to 42/58 does not exert a substantial influence on the mass transfer due to shock compression. At the same time, on passage of shock waves in alloys with different nickel content, a change in the EPD exerts a pronounced influence on the $\alpha \to \varepsilon'$ transition [8]. An increase in the nickel contents causes a decrease in the amount of the high-pressure ε'-phase. At a nickel concentration of $\sim 40-42\%$ only traces of the ε'-phase are observed. This suggests that the $\alpha \to \varepsilon'$ transition does not occur in such alloys at the mentioned loading conditions.

In the mass transfer investigations we used alloys with 27, 29, 33, 40, and 42 wt.% nickel. The thickness of the initial ^{63}Ni coverage was $\delta_c = 0.3$ μm. Detonation treatment was accomplished by generating plane shock

TABLE 2. Penetration Depth of ^{63}Ni in Single Crystals of Molybdenum and of ^{14}C in Those of Aluminum of Different Orientation

Orientation of single crystals	Penetration depth, μm
100 Mo	5.9–6.4
110 Mo	3.2–4.2
111 Mo	8.0–11.5
110 Al	140
111 Al	80

waves with $P_{sh.w} = 40$ GPa, $\tau_{sh.w} = 1$ μsec. The variation of the depth of ^{63}Ni penetration in the mentioned alloys is shown in Fig. 4. A comparison of the dependences $\gamma = f(C_{Ni})$ and $X_{max} = f(C_{Ni})$ reveals a correlation between them. Thus, with decreasing the EPD by approximately a factor of 5, the maximum penetration depth undergoes a threefold decrease. Both dependences are characterized by the presence of minima at a nickel concentration of ~33%. Analyzing the reasons for the established dependence, it is pertinent to note that the magnitude of the EPD specifies to a great extent the plastic deformation in metals and alloys. With EPD greater than 60 mJ/m^2, in ffc metals under shock compression a cellular dislocation structure is formed and a greater number of slip systems is involved than in quasiplastic deformation [4, 5]. Fcc metals with EPD less than 40 mJ/m^2 are characterized by the formation of plane aggregates of split dislocations and other plane defects of the crystal lattice. In the range of 40–60 mJ/m^2 fcc metals exhibit transition microstructures [4, 5]. This dependence also holds for the cobalt-nickel alloys. The structure of the investigated alloys with $\gamma < 40$ mJ/m^2 (Fig. 3) shows, in accordance with the mentioned regularities due to shock compression, plane packing defects and deformation twins. Therefore we may think that the changes in the mass transfer zone in this case are determined by the change in the deformation mechanism. It is pertinent to note that in ^{63}Ni redistribution in nickel (the Co–Ni alloy) caused by passage of a shock wave with analogous characteristics ($P_{sh.w} = 40$ GPa, $\tau_{sh.w} = 1$ μsec) the penetration depth is 35 μm, which is considerably smaller than in the other investigated cobalt-nickel alloys. The energy of packing defects in the nickel is significantly higher, equal to 128 mJ/m^2, and the prevailing mechanism of deformation is slip. The general regularity of the influence of the deformation mechanism on mass transfer involving passage of shock waves is the same as at considerably smaller deformation rates $\dot{\varepsilon} \sim 10^2$ sec^{-1}; for mass transfer to proceed, deformation mechanisms producing plane defects, twins, are preferred. Since with increase in nickel concentration in cobalt-nickel alloys within the limits 27–42 wt.% Ni does not cause any changes in the deformation mechanism, it seems that the influence of the specificity of the $\alpha \rightarrow \varepsilon'$ transition on X_{max} is more substantial. In accordance with [6] the pronounced mobility of the coverage elements is observed in a denser phase, i.e., the ε'-phase in our case. Therefore, the observed decrease in the amount of this phase with increase in nickel concentration to 33% may be responsible for the decrease in X_{max}. With further increase in nickel concentration, the phase transition in a shock wave ceases. In this case, the front of the shock wave acquires the single-wave configuration which, as known [9], leads to an increase in the penetration depth X_{max}.

Thus, analyzing the specific features of the mass transfer in metallic materials, one should account for the peculiarities of plastic deformation and phase transitions caused by loading conditions. For mass transfer under the conditions of passage of shock waves, formation of plane defects of the crystal lattice is preferred, which is typical for materials with low EPD. But on shock compression of binary alloys it should be taken into consideration that a decrease in the EPD favors $\alpha \rightarrow \varepsilon'$ transitions that exert a negative influence on the mass transfer process. An important factor characterizing the physical origin of mass transfer in metallic materials under shock compression is the absence of an experimentally detectable zone of ^{63}Ni mass transfer in the amorphous $Co_{58}Ni_{10}Fe_5Si$ alloy after the passage of a plane shock wave with $P_{sh.w} = 12$ GPa ($X_{max} < 3$ μm). This means that intense mass transfer in metallic materials is typical mainly for crystalline materials.

Previously mass transfer has been studied in cubic single-crystal systems at a deformation rate of 50–120 sec^{-1}. The authors of [1] have shown that when single crystals of different orientation are deformed at the same rate, the mobility of atoms remains unchanged. However, no literature data are known for rates higher than 10^2 $\sec^{-1}$. The mobility of atoms has been studied in single crystals of molybdenum of three orientations, namely, [100], [110], and [111], as well as in single [110], [111] crystals of aluminum under pulsed high-speed loading. High-rate deformation (with a deformation rate higher than 10^6 $\sec^{-1}$) was accomplished by the method of throwing a plate accelerated by explosion products. The amplitude of the shock wave was 50 GPa for molybdenum and 25 GPa for aluminum loading.

Table 2 shows experimentall results for the orientation effect on substance transfer. As is seen, the largest penetration depth is observed for molybdenum [111] crystals and the smallest – for the [110] crystals. It should be noted that fcc molybdenum and bcc aluminum structures exhibit the general regularity, i.e., a minimum depth of penetration is achieved when the mass transfer zone is formed in the direction perpendicular to the plane of slip. The results obtained show that the mass transfer events implemented in a shock wave are associated with displacement of lattice defects whose dynamics is characterized by the anisotropy in cubic crystals.

The regularities of mass transfer on the passage of plane shock waves in metals and alloys in combination with different properties of the metal matrix make it possible to state that this process depends strongly on specific features of the crystalline structure. An increase in the amount of its defects leads to a decrease in the depth of penetration of tracer atoms until mass transfer in the amorphous alloy is suppressed almostcompletely. The occurrence of phase transitions in the alloys, which cause the failure of a loading wave, reduces the influence of shock waves on element redistribution in metallic materials. At the same time an increase, due to the change of the elemental composition, in the amount of a denser martensite phase, formed in the metal matrix upon shock compression, is accompanied by mass transfer enhancement. The mass transfer in metals with a cubic structure on passage of shock waves is characterized by the anisotropy usually observed upon development of plastic deformation processes.

The regularities revealed indicate that mass transfer and plastic deformation processes are similar under shock compression conditions. Apparently, the development of such concepts may provide a deeper insight into the mechanism of mass transfer processes in metals under pulsed loading.

NOTATION

$\dot{\varepsilon}$, deformation rate; ρ_d, dislocation density; $P_{sh.w}$, $\tau_{sh.w}$, amplitude and compression pulse duration of the shock wave; C, substance concentration at the depth X; C_0, initial concentration; $\Delta a/a$, microstresses in the lattice; γ, energy of the defects of packing in the material; α, ε'; phases; X_{max}, maximum depth of mass transfer.

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