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Compression wave structure under plane impact deformation of a molybdenum single crystal [100] with different initial density of dislocations

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The features of the evolution of the elastic-plastic compression wave in Mo single crystals along the crystallographic plane [100], having a different initial dislocation structure formed by small deformations of varying degrees of static compression at room temperature, have been studied. The analysis of wave profiles recorded using the VISAR laser interferometer in samples of different thicknesses showed a non-monotonic change in the Hugoniot elastic limit depending on the initial dislocation density pre-strain of a single crystal by compression reduces the Hugoniot elastic limit by 3 times.

Keywords: Single crystal, small deformations, compression wave evolution, wave profile, VISAR interferometer.

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Molybdenum is a typical representative of refractory metals with a volume-centered cubic structure. Plastic strain mechanisms have been well studied under quasi-static loading [1]. Shock-wave tests on polycrystalline specimens have been carried out in paper [2] in the load duration ranges of $10^{-9}-10^{-6}$ s and intensity from 5 to 100 GPa. The authors of [3] focused on measuring elastic-plastic wave profiles as a function of specimen thickness from 0.23 to 2.31 mm using numerical simulations to understand dislocation mechanisms and slip systems activated by shock-wave strain. The Hugoniot elastic limit of molybdenum measured in this paper was 3.6 GPa and varied little depending on the distance traveled (thickness) in the specimens. The effect of initial defectiveness of monocrystals on the value of the elastic limit has not previously been investigated. Such information is necessary to ensure complete description of material properties under extreme conditions, construction of govening ratios and models for predictive calculations of various kinds of impact actions [4–6]. Previous studies on titanium alloy VT1-0 [7] have shown that 0.6% plastic strain and associated increase in dislocation density radically change the strain kinetics and lower the value of Hugoniot elastic limit. The results of wave profile evolution analysis indicate monotonic increase in the density of mobile dislocations with strain at the initial stage, regardless of the acting stress magnitude. The relationship between dynamic strength properties and dislocation density in the structure for austenitic stainless steel 03H17N14M3 and copper M1 has been determined in paper [8]. In materials with a face-centered cubic crystal lattice the dynamic yield strength increases with increasing dislocation density (with constant grain size).

The purpose of the present paper is to obtain new data on the features of elastic-plastic compression wave evolution in monocrystalline molybdenum specimens [100] having various initial dislocation density H_d.

Mo monocrystal [100] was fabricated by float zone melting method. The measured density of monocrystals was $\rho_0 = 10.230\,\mathrm{g/cm^3}$. Specimens for the study with nominal thicknesses of 0.9 and 2.0 mm and transverse dimensions of 15×20 mm were cut from a monocrystal blank on an EDM machine so that the plane of the specimens corresponded to the crystal plane [100]. Deviation from the orientation plane was 11°. Experiments were conducted on single-crystal specimens in the initial state (unstrained), as well as after plastic deformation by precipitation on a laboratory hydraulic press MS-1000. The degree of strain was 0.6 and 5.5%. Estimation of the dislocation density H_d was carried out by the etch hole method. For surface preparation, Murakami etchant was used with the following composition: $3-10$ g $\mathrm{NaOH} + 10-30$ g $\mathrm{K_3Fe(CN)_6} + 100$ ml $\mathrm{H_2O}$. Images were analyzed using an electronic scanning microscope TESCAN MIRA 3. For all specimen states, longitudinal sound speed (c_l) and microhardness HV were measured (average quantity of measurements 10, load of 1000 g, delay of 15 s) with the purpose to determine the properties after changing the defectiveness of the monocrystal structure. The collected data is presented in Table 1.

As can be seen from the table, the results of such measurements demonstrate a noticeable effect of plastic

Table 1. Longitudinal sound speed, hardness and dislocation density measurement results for molybdenum monocrystal as a function of strain degree

Parameter	Deformation		
	0%	0.6%	5.5%
c_l, m/s	6680 ± 5	6650 ± 5	6420 ± 5
HV, kgf/mm^2	159 ± 1	168 ± 1	179 ± 3
H_d, cm^{-2}	$\sim 1.8 \cdot 10^7$	$\sim 2.4 \cdot 10^7$	$\sim 1 \cdot 10^8$

strain on monocrystal characteristics. Increased dislocation density leads to the growth of its hardness, and decrease of longitudinal sound speed can be explained by appearance of stress areas mosaic in the process of strain within the crystal volume, and their distribution and size change along with plastic strain [9]. Longitudinal sound speed at 5.5% strain degree decreases by almost 4% compared to the value for unstrained crystals.

Impact compression pulses in Mo crystals were generated by flat copper impactors accelerated with a 50mm caliber gas gun. The impact compression pressure did not exceed 8 GPa. Impactor throwing was 350 ± 10 m/s. 0.193 or 0.474 mm thick impactors were glued to a 5 mm thick organic glass (PMMA) substrate on the end of a hollow duralumin (D16T) projectile. Impactor velocity was measured by the electrocontact sensor method. Experiments were carried out in vacuum $\leqslant 1$ Torr. $u_{fs}(t)$ velocity profiles of specimen free surface were recorded in the loading process using a VISAR laser interferometer [10]. Fig. 1, 2 shows the measured free surface velocity profiles of specimens with nominal thicknesses of 0.9 and 2 mm. Precise value of thickness and preliminary plastic strain value ε are specified for the corresponding profiles. As a result of collision, compression waves are generated in an impactor and a specimen, and their duration is proportionate to impactor thickness, and the peak value of compression stress $P_{\max} = \rho_0 U_S u_p$ is proportionate to impact velocity [11]. Here u_p — maximum particle velocity value determined from wave profiles, and U_S — impact wave velocity calculated on the basis of Hugoniot adiabat of molybdenum in the form of $U_S = 5.14 + 1.22 u_p$ [12]. Exit of elastic and the following plastic compression waves on the free surface of the specimen was recorded in wave profiles. Minor variations of maximum velocity of surface $u_{fs}(\max)$ from an experiment to an experiment are evidently related to a difference in Hugoniot impedances (ρc_l) of source material and material exposed to various plastic strains. The compression wave is followed on the surface by the unloading part of the compression pulse — rarefaction shock wave, which causes decrease in velocity of specimen spike surge in the elastic precursor front u_{HEL} is proportionate to Hugoniot elastic limit of material [12]. It can be seen from fig. 1, 2 that Hugoniot elastic limit of molybdenum monocrystal as a result of 0.6% prior plastic strain drops more than threefold, but then increases slightly when the prior strain increases to 5.5%. The obtained result agrees qualitatively with dependence of yield strength on dislocation density

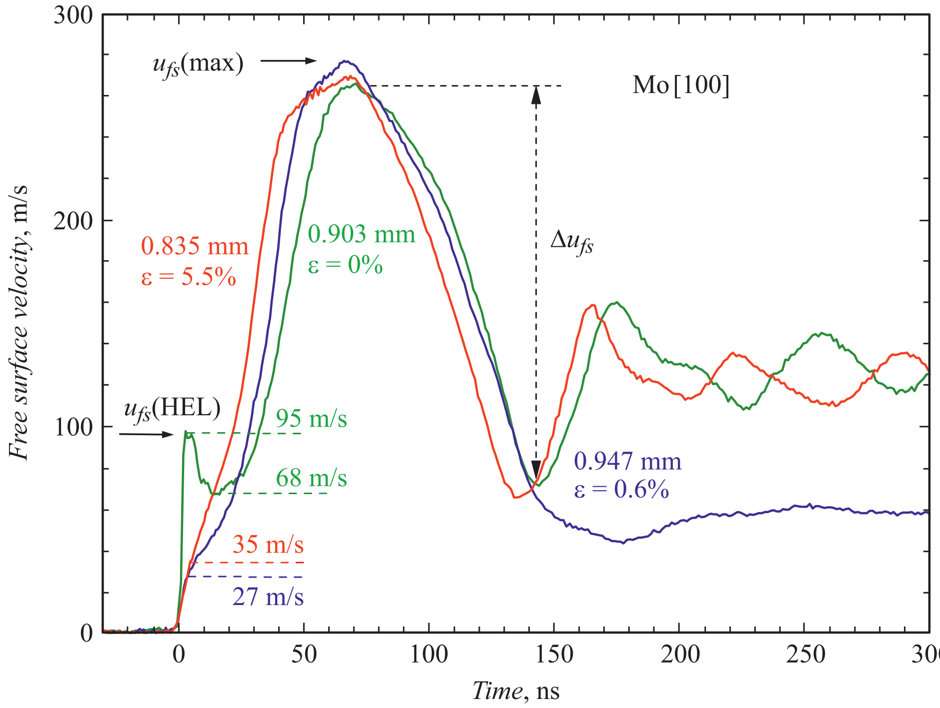

Figure 1. Free surface velocity profiles of monocrystalline specimens with nominal thickness of 0.9 mm (real thicknesses are indicated near each profile). Copper impactor thickness is 0.193 mm.

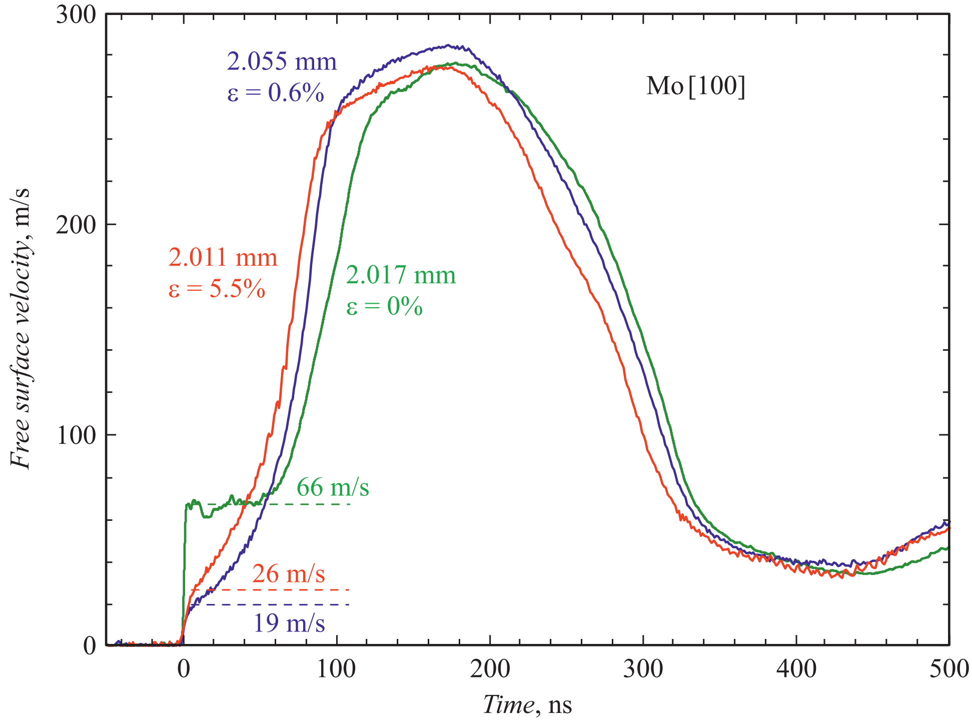

Figure 2. The results of experiments with specimens of nominal thickness about 2 mm (the real thicknesses are indicated near each profile). Thickness of a copper impactor is 0.474 mm.

Table 2. Calculated and summed parameters from experimental wave profiles for monocrystal molybdenum

Parameter	$h = 0.9$ mm			$h = 2$ mm		
	Strain			Strain		
	0%	0.6%	5.5%	0%	0.6%	5.5%
σ^*_{HEL}, GPa	3.24/2.32	0.92	1.15	2.25	0.65	0.85
$\dot{\varepsilon}_{\mathrm{HEL}}$, $10^4\,\mathrm{s}^{-1}$	12	2.4	2.4	12	1.6	1.6
$\dot{\varepsilon}_x$, $10^4\,\mathrm{s}^{-1}$	1.8	2.4	2.4	1	1.5	1.5

* Measurement confidence interval σ_{HEL} does not exceed 1%.

suggested by Oding and Bochvar [13]. With appearance of mobile dislocations in the Mo crystal after plastic strain ($\varepsilon \sim 0.6\%$), flow stress rapidly decreases to a minimum, apparently at some critical dislocation density. Further increase in dislocation density at $\varepsilon \sim 5.5\%$ strain causes dislocations to start blocking each other, causing the flow stress to increase. Difference in the time of plastic shock wave exit to the surface relative to the elastic precursor front is partly due to different values of the longitudinal sound speed, and partly — to different laws of hardening or softening during dynamic compression of the initial and pre-strained material.

Fig. 3 compares the frontal parts of all measured wave profiles. It can be seen that for all material states there is attenuation of the elastic precursor as it propagates in the monocrystal. The precursor shape also changes in unstrained crystal along with propagation. The peak on the precursor front means acceleration of the stress relaxation. Compression stress on the precursor front $\sigma_{\mathrm{HEL}} = 0.5u_{\mathrm{HEL}}\rho_0 c_l$, corresponding to Hugoniot elastic limit of the material, at the exit from the specimen with thickness of 0.9 mm drops from 3.24 to 2.32 GPa. For strained crystals with thickness of around 0.9 mm the value σ_{HEL} is 0.92 GPa at $\varepsilon = 0.6\%$ and 1.15 GPa at $\varepsilon = 5.5\%$. At the distance 2 mm the value of Hugoniot elastic limit is 2.25, 0.65 and 0.85 GPa at prior strain 0, 0.6 and 5.5% respectively. Parameter rising time in the plastic shock wave is proportionate to material viscosity, which in this case is proportionate to density of mobile dislocations. When you compare wave profiles, you can see that prior plastic strain increases compression velocity in plastic stationary wave $\dot{\varepsilon}_x$, which is determined quite easily — by differentiation of the corresponding area in wave profile $u_{fs}(t)$ and division by wave propagation velocity U_S: $\dot{\varepsilon}_x = \dot{u}_{fs}/2U_S$, while the compression velocity in the elastic wave $\dot{\varepsilon}_{\mathrm{HEL}}$ drops substantially. Table 2 provides data collected in shock-wave experiments for Mo monocrystal specimens.

Therefore, shock-wave experiments conducted on molybdenum monocrystal specimens [100] with various start density of dislocations unambiguously demonstrated the effect of the dislocation structure of the material at evolution of compression waves. It was demonstrated that prior cold strain of 0.6 and 5.5% substantially changes strain kinetics and reduces elastic limit by formation of mobile dislocations

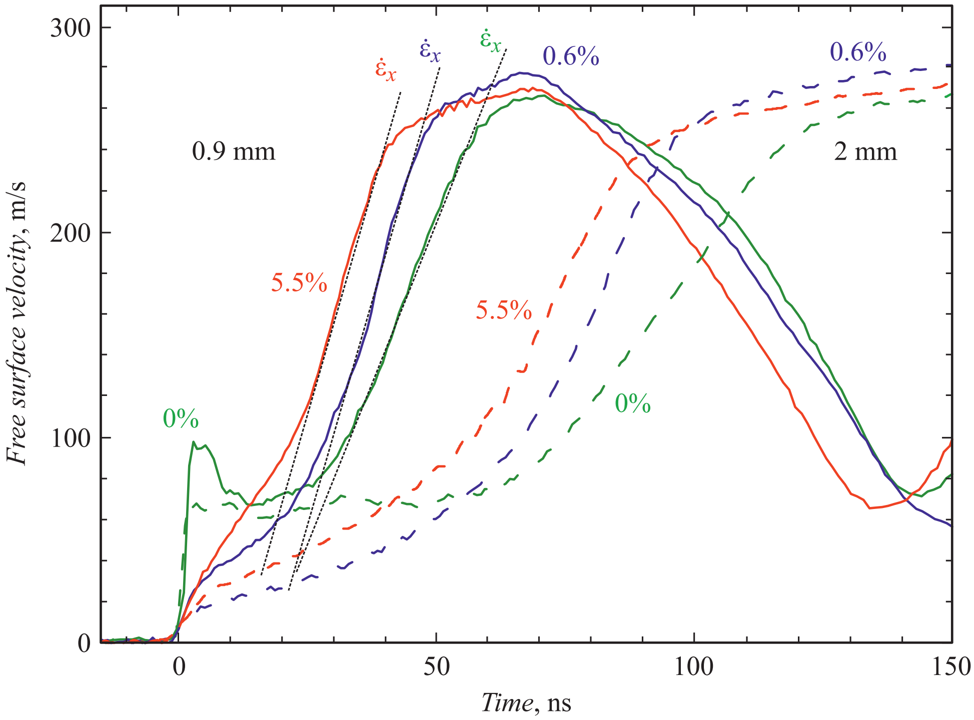

Figure 3. Comparison of the compression wave evolution as it propagates in molybdenum monocrystals in the initial state and the state after prior plastic strain. Dotted lines show the slope of the plastic wave front, which was used in calculating the strain rate $\dot{\varepsilon}_x$ in the plastic compression wave.

and stressed areas of the crystal lattice compared to a case of unstrained crystal. Compression rate in a plastic shock wave increases compared to such for unstrained crystals. Research results may be used to build calculation models and to predict behavior of such materials under plane impact stress.

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Conflict of interest

The authors declare that they have no conflict of interest.

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