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Low-Melting Metal Resistance to Plastic Strain in Shock-Compressed State

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Abstract: The measuremental results are presented for the main stresses, σ_x and σ_y , behind the plane stationary shock wave front in the low-melting metals (Mg, Cd, Sn, Zn, Bi). In every test the piezoresistive gauges were employed for the measurements, placed in two mutually perpendicular planes of a sample. The gauge measuring element is a linear piece of the manganine wire of 0.05 mm in diameter and 10 mm long. The total gauge thickness with polymer insulation was 0.23 mm at low stresses and 0.53 mm at high ones behind the shock wave front. Stationary shock waves of duration about $\sim 1 \mu\text{s}$ entered into the sample from the screen where the shock wave propagates being generated by a detonation wave incident along the normal.

The measured values correctness for the main stresses, σ_x and σ_y , is supported by the special tests with paraffin, steel (elastic and plastic deformation regions), ceramics (elastic deformation regions) and vanadium.

For the low-melting metals investigation in the normal stresses range, $\sigma_x=4-25 \text{ GPa}$, the strong strengthening was recorded at the high-speed deformation by the shock waves. The dependence of dynamic ultimate yield, $Y_g=\sigma_x - \sigma_y$ on σ_x approaches a linear one the range investigation.

Resume: Les résultats des mesures des contraintes principales σ_x et σ_y ayant lieu derrière le front de l'onde de choc plate stationnaire dans les métaux fusibles (Mg, Cd, Sn, Zn, Bi) sont présentés. Les mesures ont été réalisées par les capteurs piezorésistants disposés dans deux plans d'échantillon réciproquement perpendiculaires. Les ondes de choc stationnaires de durée $\sim 1 \mu\text{s}$ ont été introduites dans l'échantillon de l'écran dans lequel l'onde de choc produite par l'onde de détonation normale se propagait.

Le durcissement fort a été enregistré pour les métaux fusibles examinés dans la gamme des contraintes normales $\sigma_x=4-25 \text{ GPa}$ à la déformation ultra-rapide dans les ondes de choc. Dans la gamme examinée la relation entre la limite élastique dynamique $Y_g=\sigma_x - \sigma_y$ et σ_x ressemblait beaucoup à la relation linéaire.

Investigations of resistance of materials, compressed by stationary shock wave, reveal a complicated character of manifestation of reological properties. Different methods, such as the method of overtaking unloading [1], "self-consistent" method [2], measurement of unloading elastic wave amplitude [3], etc. are employed to obtain experimental data on reological properties of shock-compressed substances. The special place is given to the method of direct measurement of the primary stresses (σ_x , σ_y) in one experiment in two mutually perpendicular sections of the sample under study, where shock wave (SW) propagates in the x axis direction [4,5].

Measurements of σ_x and σ_y allow to determine the value $Y_g=\sigma_x - \sigma_y$ without any additional assumptions and calculations of the medium flow, if assuming that according to [6,7] the model of hardened elasto-plastic medium with effective dynamic yield strength Y_g (DYS) is true for metals behind the front of SW with amplitude more than $\sim 1 \text{ GPa}$ and, correspondingly, strains rates higher than 10^5 s^{-1} .

In this work the DYS value of low-melting metals (Mg, Bi, Cd, Zn, Sn) is determined in the range of primary stress change $\sigma_x=2.5...20 \text{ GPa}$ by primary stresses method (PSM). Scheme of the experiments is described in detail in [8,9,10]. The piezoresistive Π -shaped gauges, which had been

manufactured from manganin wire with diameter of 0.05 mm and placed in thin isolating medium (lavan, fluoroplastic), were located in cuts in a sample of the metal under study. Total thickness of the gauge, including layers of additional isolation, was 0.25...0.53 mm, and length of the gauge sensor was 10 mm. Characteristic oscillograms of recorded signals, caused by sensors (fig.1) show change for the stationary regime.

Fig.1

Amplitude values of σ_x and σ_y stresses were calculated using unified calibration dependence of σ_1 on relative change of $\Delta R/R$ resistance of gauges

$$\sigma_1 = 34.5 (\Delta R/R) + 7.5 (\Delta R/R)^2 \text{ GPa}$$

Plane shock waves were generated in samples by explosive devices with known parameters of shock waves in screens. Duration of stationary flow behind the SW front (duration of rectangular profile σ_x) was equal to (1-3) μs . This is sufficient for reliable measurement of σ_x and σ_y in the stationary regime of flow. Values of σ_x , obtained by experiments, in the limits of measurement error comply with σ_x values, calculated when solving the task on disintegration of arbitrary break. Results of the experiments are tabulated in Table 1. Accuracy of σ_x and σ_y measurements in one experiment was $\pm 8\%$ or better. Correctness of σ_y measurements was confirmed by results of special experiments carried out employing the same scheme with the same gauge design using paraffin, steel, vanadium and ceramics [8].

The following σ_x and σ_y values were obtained for paraffin: $\sigma_x=0.69$ GPa, $\sigma_y=0.67$ GPa, and $\sigma_x=2.31$ GPa, $\sigma_y=2.24$ GPa, i.e., the stressed state corresponds to the hydrodynamic state. In the elastic area of deformation of St.3 and 30KhGSA steels [9] the values of Poisson's ratio $\nu=\sigma_y/(\sigma_x+\sigma_y)$, calculated basing on measured values of σ_x and σ_y , agree with the literature values, namely, $\nu=0.28$ for St.3 and $\nu=0.30$ for 30 KhGSA. In the elasto-plastic area the experimental data are well described by theoretical dependence

$$\sigma_\theta = \frac{\sigma_x + \sigma_y}{2} \pm \frac{\sigma_x - \sigma_y}{2} \cos 2\theta,$$

where σ_θ - normal stress on a plane oriented at an angle of θ to the plane of the wave front [9]. Dependence of Y_g on σ_x , obtained by the interference method in [11], was reproduced for vanadium by the method of primary stresses. Measurements on cast ceramics (where aluminium oxide is the basis) [12] are in agreement with general regularities of ceramics behaviour: high value of the elastic Hugoniot limit and constancy of Y_g in the plastic area. In the elastic area the value of ν , as for steels, is equal to the value of it under normal conditions.

It follows from data presented in Table 1 that strong hardening of low-melting metals takes place in shock waves in the investigated range of stresses, where they are in the solid phase. Reasons of this require additional study. One of possible reasons is good compressability of investigated metals: the bulk modulus for them is $K \approx (36-70)$ GPa opposite to $K \approx (100-280)$ GPa for such typical metals as copper, iron, titanium, molybdenum.

Table 1
Results of σ_x and σ_y measurements in low-melting metals.

Metal	Stresses, GPa		
	σ_x	σ_y	Y_g
Magnesium $\rho_0 = 1.74 \text{ g/cm}^3$	2.35	2.0	0.35
	5.45	4.65	0.80
	6.30	5.55	0.75
	8.98	7.82	1.16
	9.30	7.95	1.35
	15.30	13.85	1.45
	21.30	19.60	1.70
Cadmium $\rho_0 = 8.64 \text{ g/cm}^3$	4.83	2.80	2.03
	10.15	6.00	4.15
	14.35	9.0	5.35
	18.70	13.75	4.95
Bismuth $\rho_0 = 9.81 \text{ g/cm}^3$	4.13	1.64	2.47
	10.55	7.25	3.30
	14.30	7.30	7.0
Zinc $\rho_0 = 7.14 \text{ g/cm}^3$	4.60	3.15	1.45
	16.30	10.60	5.70
Tin $\rho_0 = 7.28 \text{ g/cm}^3$	5.53	2.57	2.96
	10.80	6.25	4.55

$Y_g(\sigma_x)$ dependence for magnesium along shock adiabat, proposed in [13], is the following:

$$Y_g = Y_0 \left[(1 + \beta e_p)^m + \alpha P \right] \cdot \left[1 - \frac{\varepsilon_T}{\varepsilon_T^{nn}} \right] \quad (1)$$

where Y_0 , β , m , α - are constant, e_p - intensity of plastic strains, ε_T - present thermal energy, ε_T^{nn} - thermal energy needed for homogenous heating up to the melting temperature, when density is specified. ε_T^{nn} describes experimental data on the ascending branch, where they exist (fig.3). Value of ε_T^{nn} from (1) is calculated using Lindeman's law with function of Gruneisen's coefficient.

$$\gamma_p = \gamma_\infty + \frac{\gamma_0 - \gamma_\infty}{\delta^M}$$

$$\varepsilon_T^{nn} = \varepsilon_{T_0}^{nn} (\delta_{nn} / \delta_{0nn})^{2(\gamma_\infty - 1/3)}, \exp \left[\frac{2(\gamma_0 - \gamma_\infty)}{M(\delta_{0nn})^M} - \frac{2(\gamma_0 - \gamma_\infty)}{M(\delta_{nn})^M} \right] \quad (2)$$

Term $Y_0(1 + \beta e_p)^m$ is limited by $Y_{\max}$ value.

Parameters of determining magnesium equation are presented in Table 2.

Table 2

Parameters of determining magnesium equation

Parameters	γ_0	γ_∞	M	Y_0, GPa	$Y_{\max}, \text{GPa}$	β	m
Value	1.6	0.7	2.3	0.19	0.48	317	0.50

	α, GPa^{-1}	$\rho_0^{n, \lambda}, \text{g} / \text{cm}^3$	$T_0^{n, \lambda}, ^\circ \text{K}$	$\varepsilon_0^{n, \lambda}, \text{J} / \text{g}$	
	0.60	1.62	922	963	

Results of performed investigations and analysis of the problem state in the review work [4] show that investigations of shear strengths of low-melting metals were carried out on the ascending branch of $Y_g(\sigma_x)$ dependence. That is why it is interesting from practical and scientific points of view to expand investigations in the area close to the melting state on shock wave. It can be realized in practice for low-melting metals.

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