The spall strength and Hugoniot elastic limit of mono-crystalline and polycrystalline copper near melting temperature

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Abstract. In present work, the Hugoniot elastic limit (HEL) and spall strength of polycrystalline commercial grade copper and single crystal copper of <100> and <111> orientations were determined for sample temperatures varying from 20 to 1081^0C. The differently preheated samples whose thickness varied between 0.5 and 2 mm were shock-loaded by copper plates of 1-mm thickness accelerated up to 300-400 m/s velocity in the 58-mm smooth bore gas gun, or by aluminium plates of 0.4 mm in thickness (~660 m/s), accelerated with explosive facilities. The velocity histories of the free rear surface of the loaded samples were recorded with VISAR laser velocimeter. The velocity histories of the samples of polycrystalline copper demonstrate 9-fold growth of the stress at HEL between room and melting temperatures. Unlike other metals commercial grade copper maintains very high spall strength near the melting point T_m; it is only twice as low as that of the copper at 0.85 T_m. The copper single crystals of both orientations also demonstrate substantial spall strength at 0.94 T_m (1000^0C). At the same time, the increase of the stress at HEL with temperature in these samples is much weaker than that found for polycrystalline samples of copper.

1. Introduction

The detection of the anomalous increasing of the dynamic yield strength of fusible metals under the increasing of temperature in shock wave experiments [1-5] stimulates the more detailed study of this phenomenon. The changing of the sign of temperature dependence of flow stress was explained by the change-over of the basic mechanism of dislocation drag. Under high strain rates, the basic mechanism of it must become a phonon friction [6], and the value of it increases with the temperature growth. However, this hypothesis demands a confirmation and examination. First of all, the question should be answered, how common is this anomalous metal behavior?

The earlier obtained data on temperature dependence of metal dynamic tensile strength (spall strength) near the melting point did not show up any unified patters of relationship: while the strength of the commercial grade aluminum AD1 and cast magnesium tends to zero when approaching to the melting temperature [1], tin [7] and high purity silver [8] retain high values of spall strength even in

immediate vicinity of the melting point. At the same time, single crystals of aluminum and zinc retain high enough values of the resistance to spall fracture near the melting temperature, what is connected with realizing of the overheat crystal states of metals in submicrosecond range of the loading [9]. The decrease in spall strength of polycrystalline metals was explained by premelting effects [10], however, the reasons of such different strength behavior of different metals remain unclear.

In this work, the results of the measurements of the elastic-plastic and strength properties of copper in the shock-wave loading conditions under the normal and increasing temperatures up to the melting point are presented. Copper has a higher melting temperature, than the metals tested before. In addition, the experiments with copper are interesting because the elementary mechanisms of plastic deformation and fracture are usually studied by the methods of molecular-dynamic simulation on its example.

2. Materials and Experimental Method

For investigation of the temperature influence on the elastic-plastic and strength properties of copper, two series of experiments with samples of commercial grade copper M1 and copper single crystals of high purity were carried out. The samples with the thickness of ~2 mm or 0.5 mm were cut from copper sheet with electrospark discharge machine and had crosscut sizes ~12×12 mm. The samples of copper single crystals with the chemical composition Cu 99.8661%, Si 0.086%, Fe 0.0479% were cut from cylindrical block, produced with the help of the crucibleless zone melting, in such a way that their flat surfaces coincided with the crystal planes <111> or <110>. The sizes of the single crystal samples were the same as the polycrystalline ones.

To study the influence of temperature on the strength properties of shock-compressed copper of different structure, two series of experiments on generation of shock waves on preheated samples were carried out. The experiments under the sample temperatures up to 600^0C were executed using the explosive generators of shock waves [11], which provided the projection of flat aluminum impactors of 0.2 – 2 mm in thickness with the velocity of ~700 m/s. The experiments under the higher samples temperatures were performed with the 58 mm bore 4-m length gas gun [12]. The samples were loaded by copper impactors of 0.5 or 1 mm in thickness accelerated up to ~400 m/s velocity. In both cases, the samples were heated with a resistive heater up to 1 KW of power during 5-10 minutes, their temperature was controlled with one or two thermocouples with accuracy ~5^0C [1,13].

The measurements of the strength characteristics of materials under the shock loading are based on the recording and the further analysis of full wave profiles [11]. In this work, the registration of the wave profiles (the dependences of sample free surface velocity on time) of the shock-loaded samples under different temperatures was carried out with laser velocimeter VISAR [14].

3. Experimental Results

The free surface velocity profiles of polycrystalline samples of copper M1 under the temperatures from 20^0C to 1081^0C are presented in figure 1. The table copper melting temperature is 1083.4^0C, i.e. the maximal temperature of the samples in the conducted experiments differed from the melting temperature of copper less than 3 degrees. Before the plastic compression wave, the output of the elastic precursor on the sample surface was observed, its amplitude increased with sample temperature growth. The compression stress in the precursor coincides with the Hugoniot elastic limit, determined from the velocity profile as: $\sigma_{HEL} = 1/2C_L\rho_0 u_{fs/HEL}$, where $u_{fs/HEL}$ – the maximal value of free surface velocity at the elastic precursor front, C_L – longitudinal sound speed, ρ_0 – initial material density. The material yield strength is proportional to the Hugoniot elastic limit and equals to $Y = 3/2\sigma_{HEL}(1-(C_0/C_L)^2$, where C_0 – bulk sound speed. The recorded wave profiles also demonstrate all the features of the spall fracture of the copper samples. The dynamic (spall) strength of the samples is determined as [11]: $\sigma_{sp} = 1/2\rho_0 C_0(\Delta u_{fs}+\delta u_{fs})$, where $\Delta u_{fs}=u_{fs/max}-u_{fs/min}$ – velocity "pullback", where $u_{fs/max}$ – the maximal sample velocity, $u_{fs/min}$ – the minimum sample velocity before the spall, δu_{fs} – the correction for distortion of the wave profile due to elastic-plastic behavior of the material tested.

In figure 1 the area of the elastic-plastic transition is shown in magnified view. It can be seen, that

the growth of the sample temperature from ambient to very close to melting leads to almost tenfold increasing of the elastic precursor amplitude of polycrystalline copper. In this case, the fast growth of the elastic precursor is observed under the sample temperatures near the melting point – the doubling of the precursor amplitude at the last hundred degrees before melting. The increasing of the Hugoniot elastic limit with temperature was observed earlier in the experiments with shock loading of aluminum [1,3], silver [8] and some other metals [2] and it is explained by increasing influence of the phonon friction in dislocation drag under high strain rates.
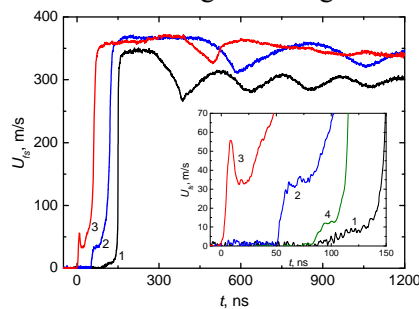

Figure 1. Free surface velocity histories of the polycrystalline copper under the room and elevated temperatures. $T_0 = 20^0$C (1), 1006^0C (2), 1081^0C (3), 592^0C (4).
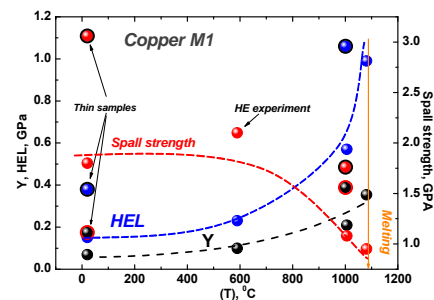
Figure 2. The dependencies of the HEL, the yield strength and the spall strength of copper M1 on the initial sample temperatures.

The dependences of the spall strength, Hugoniot elastic limit and yield strength of polycrystalline copper M1 on temperature are shown in figure 2 over the temperature range. In the strength characteristic calculations, the values of sound speeds and material density were used according to their temperature dependences [15]. From this figure one can see that the Hugoniot elastic limit grows nonlinearly with temperature, moreover its maximal growth is observed under the temperatures close to the melting temperature. The growth of the copper yield strength has a smoother character even in the region of high temperatures, and its total increasing is about three times. The copper spall strength under the sample heating remains nearly at the same level up to temperatures $700 – 800^0$C and then it decreases quickly approaching the melting temperature. Nevertheless, unlike aluminum and magnesium [1], the spall strength of polycrystalline copper remains at a level around 50% of the initial one.
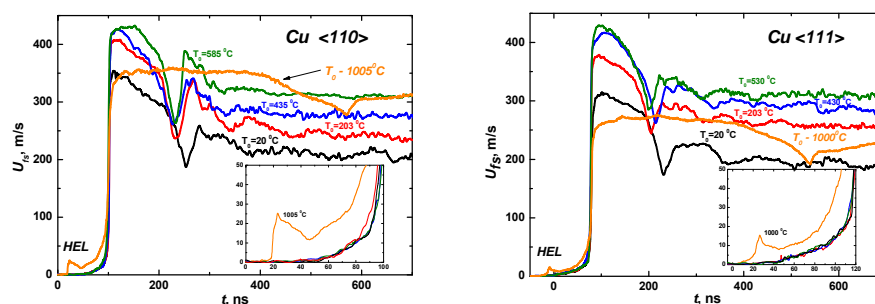

Figure 3. Free surface velocity histories of copper single crystals of both orientations, obtained under the room and elevated temperatures.

Similar experiments on dynamic loading of samples under different temperatures were carried out with single crystals of copper. The thickness of these samples was 1.5 – 2 mm, and the sample planes of the collision with impactors coincided with the crystal planes <111> or <110>. In figure 3, the free surface velocity histories of the copper single crystal samples of both crystal orientations are presented. The area of the elastic-plastic transition is shown in magnified view. It is seen very well, that in the temperature range from room temperature to ~600^0C at the wave profiles for the samples of both orientations a weak smooth rising of velocity is observed only without any velocity jump at the

elastic precursor front. It means that the material has a negligible elastic limit, which is practically impossible to measure exactly from these experiments. The increasing of the sample temperature up to ~1000[0]C leads to the forming of the sharp velocity jump behind the elastic compressive wave, so called "yield drop". From comparison of the wave profiles, it is seen, that under this temperature the copper single crystal samples with plane <110> have the Hugoniot elastic limit 65% higher, than the samples of the other orientation.

The dependences of spall strength of the polycrystalline copper M1 and copper single crystals of both orientations on temperature are presented in figure 4. The spall strength values of copper M1 under the room temperatures practically agree with the data published earlier [17]. The spall strength of copper single crystal measured in this work is slightly lower (15-20%) in comparison with the earlier measurements [18,19], what is possibly connected with the difference in initial inner structure of single crystals. Respectively, the difference of the spall strength values of the copper single crystals and the commercial grade copper is a little bit less, but it remains high enough. For all types of copper samples the dependences have the threshold species – the spall strength maintains roughly at the same level up to the temperatures $600 – 700^0$C. With further increase of the temperature, its value decreases by up to ~50%, nevertheless staying high enough till the melting temperature. It is necessary to note, that in the region of high temperatures, the difference in the spall strength of single crystals and polycrystalline samples is negligible.
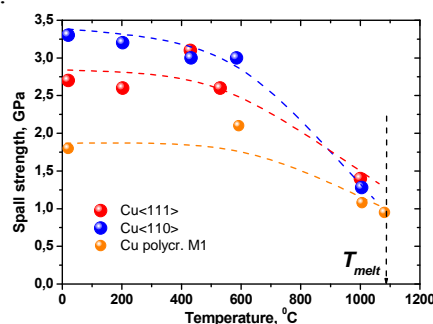

Figure 4. The spall strength of copper under the normal and elevated temperatures.

The single crystals of <110> orientation demonstrate a little bit higher resistance to the spall fracture under moderate temperatures, than the crystals of the other orientation. In the earlier measurements [19,20] some anisotropy of the fracture stresses in copper single crystals also was observed relative to the load direction. Perhaps, the deformation in [111] direction is accompanied by the forming of coarser structure defects, which can then act as nucleation sites for spall fracture, but this difference under high temperatures disappears.

4. Conclusion.
Both polycrystalline copper and copper single crystals demonstrate high athermic hardening near the melting temperatures – intensive growth of the Hugoniot elastic limit Heating the single crystal samples up to 1000[0]C leads to a sharp increase in their Hugoniot elastic limit, and the value of the HEL depends on crystal orientation of the sample relative to the loading direction. The spall strength dependences for all types of copper samples have the threshold species – up to ~700[0]C, a weak decreasing of fracture stresses with temperature is observed. In the immediate vicinity of the melting point the spall strength of copper decreases by half. Over the whole temperature range the spall strength of copper single crystals is higher than the one of the polycrystalline samples, but this difference becomes negligible near the melting point.

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