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## Dynamic Strength of Tin and Lead Melts

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The dynamic tensile strength (spall strength) of tin and lead melts has been measured by a found method. Comparison with similar measurements of the spall strength of these metals at room temperature shows that melting reduces the spall strength by at least an order of magnitude. The spall strength of liquid metals is a smaller fraction of the extremely possible (“ideal”) strength than that for water and organic liquids.

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The problem of the dynamic strength of metal melts appears in analysis of the operation of liquid-metal heat carriers of promising pulsed power facilities, calculations of the operation of meteorite protective shields of spacecrafts, analysis of the kinetics of the nucleation and growth of a vapor phase, and in other similar problems. In the submicrosecond range of load durations, the tensile strength of solids and liquids is determined by analyzing spalling phenomena appearing at the reflection of a compression pulse from the free surface of a sample. In this case, fracture stresses at spallation is determined by analyzing the measured free surface velocity history by the method of characteristics [1, 2].

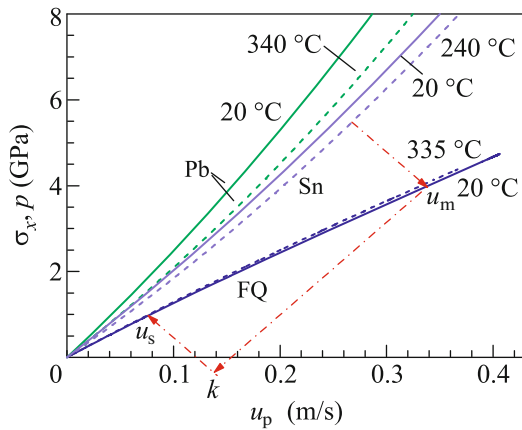
Such measurements were performed for numerous metals and nonmetallic materials in a solid state [1–3] in a wide range of load durations at normal and high temperatures, as well as for water [4, 5] and some organic liquids [6]. In this case, very high negative pressures in a liquid at spall reach 15–20% of the extreme possible value, the so-called ideal strength [2, 6]. In this respect, liquids are similar to homogeneous metal single crystals. At spall fracture of polycrystalline metals, usually reached pressures are a twice smaller fraction of the ideal strength because of the presence of numerous fracture nucleation centers.

The authors of [7, 8] attempted to estimate the spall strength of tin and lead heated to the melting temperature by shock compression to high pressures. When the residual (after unloading) temperature approached the melting temperature, the spall strength of tin decreased almost to zero. Experiments with lead also revealed a significant decrease in its spall strength. At the same time, experiments with a preliminarily heated aluminum alloy [9] demonstrated a high resistance to spall fracture in two-phase (solid + liquid) states at concentrations of the liquid phase up to 20%. Lack of experimental data stimulates theoretical inves-

tigations of the pulsed fracture of liquids, including molecular dynamics studies [10, 11].

Shock heating is associated with a number of effects complicating measurements and increasing measurement errors. Entrance after shock compression into the two-phase region and further into the melt region is accompanied by the fast development of the instability of the surface of the sample under study, which significantly reduces its reflectivity and complicates the detection of its motion by optical interferometric methods. The degree of thermal homogeneity of states appearing after the shock compression of a solid is unclear. The temperature of a melt before its spall fracture can hardly be varied. These circumstances stimulate the search for the possibility of experiments directly with melted metals.

In known experiments on the measurement of the spall strength of water and organic liquids, in order to record wave profiles with the use of laser Doppler interferometry [12], one of the walls of a cuvette with the liquid under study was made of a thin metal foil to reflect probe laser radiation. The wetting force acting between the liquid and the surface of the foil ensured their good contact during the entire experiment. However, it appeared difficult to choose a foil that would be wetted by, e.g., tin or lead without any flux. The solubility of metals in each other is an additional complicating factor. On one hand, because of solubility, it is difficult to ensure the lifetime of the reflecting foil sufficient for reaching the desired temperature and preparing measurements. On the other hand, the chemical composition of the material under study changes in the process of preliminary heating. For this reason, after numerous unsuccessful attempts to measure the velocity profiles of the free surface of melted metal samples with the use of reflecting foils of various metals with various protective coatings, we implemented an alternative scheme of measurements of the spall



**Fig. 1.** (Color online) Hugoniot curves of lead, tin, and fused quartz (FQ) and the scheme of the determination of a state at the point  $k$  (spall strength) by the characteristic method from the measured velocities  $u_m$  and  $u_s$ .

strength. It is based on the recording of the velocity history  $u_i(t)$  of the interface between a sample and a barrier from a material with a lower dynamic impedance  $\rho C$ .

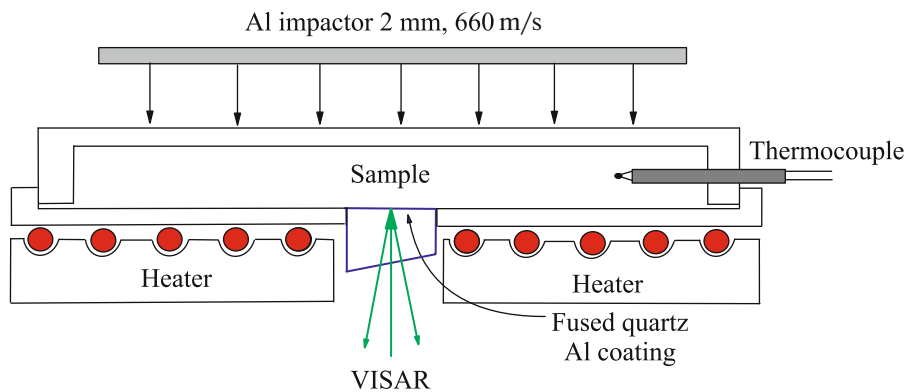
This scheme is well known [1] and was previously used by experimentalists who did not have a technique for the recording of free surface velocity histories. Polymers or liquids were usually used as low-impedance barriers. In this work, barriers from fused quartz were used to measure the spall strength of tin and lead melts. The dynamic elastic limit of fused quartz is 8.8 GPa. Below this stress, the dynamic compressibility of quartz is reversible, which should ensure a high accuracy of the results obtained. The compressibility of fused quartz is anomalous up to stresses of 2.5–3.0 GPa: the speeds of sound decrease with compression in this range [13].

Figure 1 shows Hugoniot curves of fused quartz at normal and high temperatures, as well as shock adiabats of lead and tin in the solid and melted states. The details of the diagram will be discussed below when

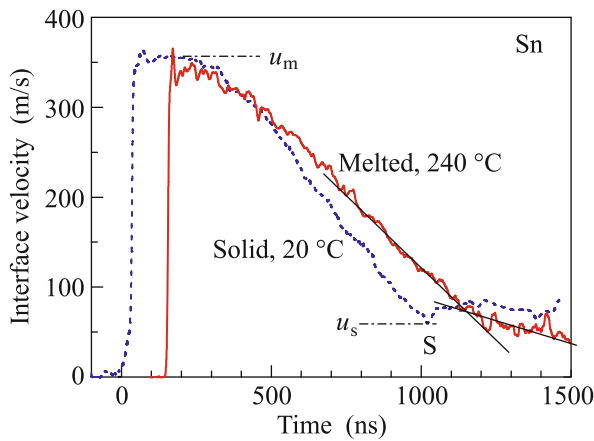
analyzing the measurement results. The mutual positions of adiabats demonstrates the real possibility of using fused quartz as a barrier in measurements of the spall strength of lead and tin.

Here, we report the first preliminary results of measurements of the dynamic tensile strength of tin and lead melts. We studied high-purity tin and lead of technical purity. Figure 2 shows the layout of experiments. A sample with a thickness of about 8 mm was placed in an aluminum ampule with a fused quartz window glued in one of the walls. The thickness of the second wall—the bottom of the ampule—was 1.8 mm. The surface of the window facing the sample was slightly etched in order to ensure diffuse reflection. Then, a reflecting aluminum layer was deposited on this surface by vacuum deposition. Aluminum in air was spontaneously coated by an oxide film, which prevented the direct contact of aluminum with the melted metal and their mutual solution in the experiment. Before measurements, the ampule with the sample was heated by a resistive heating to a temperature slightly above the melting temperature of the material of the sample. The temperature of the sample was continuously monitored by a chromel–alumel thermocouple with an accuracy of 3 °C. A compression pulse was excited in the assembly by an impact of a 2-mm-thick aluminum plate moving at a velocity of  $(660 \pm 20)$  m/s. The velocity profiles  $u_i(t)$  of the contact interface between fused quartz and the sample were recorded in experiments by a VISAR laser Doppler velocimeter [12].

Figure 3 shows the typical wave profiles measured in experiments with solid tin at room temperature and tin melt at 240 °C. The arrival of an elastoplastic shock wave and a subsequent rarefaction wave at the interface was detected in the experiment at room temperature. After the reflection of the compression pulse in the tin sample from the interface with fused quartz, tensile stresses appear inside the sample and result in its destruction through spall. The spall fracture zone does not support tensile stresses and does not transmit the remaining part of the rarefaction wave to the inter-



**Fig. 2.** (Color online) Layout of experiments on the determination of the spall strength of melted metals.

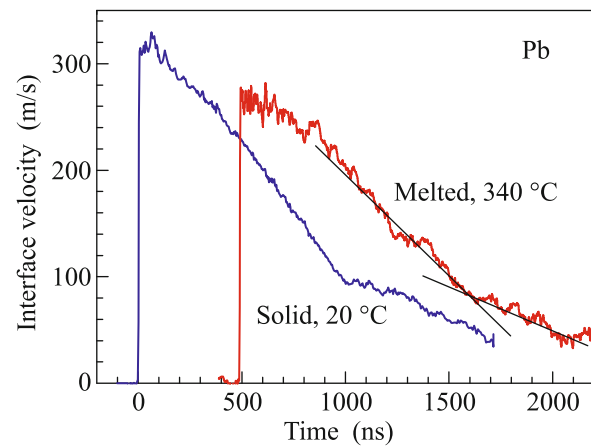


**Fig. 3.** (Color online) Measured velocity histories of the interface between solid and melted tin samples with a fused quartz window. The temperature of melted tin was 240°C.

face. The relaxation of tensile stresses at fracture generates in the extended material a compression wave, which arrives at the interface at the time marked by the letter S in the diagram and causes an increase in the velocity. With the use of the measured maximum velocity of the interface behind the shock wave  $u_m$  and the velocity  $u_s$  immediately ahead of the front of the spall pulse, the tensile stress immediately before fracture (point  $k$  in Fig. 1), which is called spall strength, was calculated by the method of characteristics [1, 2]. Since solid tin has a quite high elastic limit [14], when determining the spall strength, the velocity  $u_s$  was corrected [1, 15] taking into account the distortion of the wave profile because of the difference between the velocities of the front of the spall pulse and the incident rarefaction wave ahead of it.

The spall strength thus calculated for tin at room temperature is 1.2 GPa. This value almost coincides with the results of measurements [14] based on the recording of free surface velocity history under similar loading conditions. According to experiments with solid tin at high temperatures [14], its spall strength decreases only slightly near the melting temperature. A sharp decrease in the spall strength began above 0.99 of the melting temperature.

The spall strength of melted tin is obviously lower than the spall strength of solid tin; for this reason, the spall pulse on the wave profile is not pronounced in the high-temperature experiment. The corresponding  $u_s$  value was sought at the intersection of linear extrapolations of the segment of the wave profile corresponding to the incident rarefaction wave and the segment formed after the beginning of cavitation of the melt under the action of tensile stresses. In this case, the relation between the slopes of the mentioned segments of the wave profile was calculated by analyzing the dynamics of the cavitation region at the reflection



**Fig. 4.** (Color online) Measured velocity histories of the interface between solid and melted lead samples with a fused quartz window. The temperature of melted tin was 340°C.

of the compression pulse from the interface between two media [16].

The Hugoniot curves of liquid tin and fused quartz at a temperature of 240°C were used in calculations. The adiabat of fused quartz was plotted in the simple-wave approximation with the use of the results of the special measurement of the free surface velocity history at 240°C taking into account the thermal expansion with the use of the tabulated temperature dependence of the speed of sound [17]. The Hugoniot curve of melted tin in the form  $U_s = c_0 + bu_p$  was plotted with the use of the tabulated speed of sound  $c_0 = 2.46$  km/s [18, 19] and the coefficient  $b = 1.76$  found from the experimental Hugoniot curve of liquid tin at 400°C [20, 21]. In this pressure range, variations of this coefficient insignificantly affect the position of the shock adiabat. The spall strength of melted tin at 240°C thus determined is  $(0.12 \pm 0.02)$  GPa, which is an order of magnitude lower than the spall strength of solid tin.

The ideal strength of tin melt is  $\sigma_{id} \approx \rho_0 c_0^2 / 4b = 6$  GPa. Thus, the fraction of the ideal strength at spall in liquid tin is much lower than that in water and organic liquids: 2% against 15–20%.

Figure 4 shows the results of the experiments with solid and melted lead. The spall strength of solid technical lead was found to be  $(0.32 \pm 0.08)$  GPa, which is in the “spread band” of the data reported for this material [1, 7, 22, 23]. After melting, the spall strength of lead is close to zero and is certainly no more than 0.03 GPa. The spall strength of melted lead was estimated with the use of the Hugoniot curve with the tabulated speed of sound  $c_0 = 1.8$  km/s [18, 19] and the coefficient  $b = 1.55$  found from the experimental shock adiabat of liquid lead at 400°C [21].

Thus, the spall strength of tin and lead after melting decreases by an order of magnitude. According to the

existing theories [24], the strength of a liquid and the time until its cavitation destruction under tension are determined by the rate of spontaneous nucleation of bubbles with the critical dimension, which in turn increases strongly with the temperature. From this point of view, a low strength of melted metals means a high rate of nucleation of bubbles at these temperatures. The inclusion of the kinetics of growth of bubbles reduces the implemented fracture resistance by 20–30% [11]. At the same time, the dynamic fracture strength of lead estimated in the molecular dynamics simulation of cavitation in liquid metals [10] is 4–5 GPa at a tension rate of about  $10^7 \text{ s}^{-1}$ . Further works are needed to reveal whether such a large difference from the experimental data obtained in this work is due to a lower deformation rate, to a possible contribution from heterogeneous nucleation of bubbles on impurity particles, or to other effects.

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### REFERENCES

1. T. Antoun, L. Seaman, D. R. Curran, G. I. Kanel, S. V. Razorenov, and A. V. Utkin, *Spall Fracture* (Springer, New York, 2003).
2. G. I. Kanel, *Int. J. Fract.* **163**, 173 (2010).
3. S. I. Ashitkov, P. S. Komarov, E. V. Struleva, M. B. Agranat, and G. I. Kanel', *JETP Lett.* **101**, 276 (2015).
4. A. A. Bogach and A. V. Utkin, *Prikl. Mat. Tekh. Fiz.* **41**, 198 (2000).
5. J. M. Boteler and G. T. Sutherland, *J. Appl. Phys.* **96**, 6919 (2004).
6. A. V. Utkin, V. A. Sosikov, A. A. Bogach, and V. E. Fortov, *AIP Conf. Proc.* **706**, 765 (2004).
7. G. I. Kanel, S. V. Razorenov, A. V. Utkin, and D. E. Grady, *AIP Conf. Proc.* **370**, 503 (1996).
8. T. de Resseguier, L. Signor, A. Dragon, M. Boustie, G. Roy, and F. Llorca, *J. Appl. Phys.* **101**, 013506 (2007).
9. E. B. Zaretsky and G. I. Kanel, *J. Appl. Phys.* **112**, 053511 (2012).
10. T. T. Bazhurov, G. E. Norman, and V. V. Stegailov, *J. Phys.: Condens. Matter* **20**, 114113 (2008).
11. Yu. Kuksin, G. E. Norman, V. V. Pisarev, V. V. Stegailov, and A. V. Yanilkin, *Phys. Rev. B* **82**, 174101 (2010).
12. L. M. Barker and R. E. Hollenbach, *J. Appl. Phys.* **43**, 4669 (1972).
13. L. M. Barker and R. E. Hollenbach, *J. Appl. Phys.* **41**, 4208 (1970).
14. E. B. Zaretsky and G. I. Kanel, in *Proceedings of the 9th International Conference on the Mechanical and Physical Behaviour of Materials under Dynamic Loading DYMAT 2009, Brussels, Belgium, September 7–11, 2009* (EDP Sciences, Les Ulis, France, 2009), p. 27.
15. G. I. Kanel, *Prikl. Mat. Tekh. Fiz.* **42**, 194 (2001).
16. G. I. Kanel and A. V. Utkin, *Prikl. Mat. Tekh. Fiz.* **4**, 23 (1991).
17. H. J. McSkimin, *J. Acoust. Soc. Am.* **31**, 287 (1959).
18. M. B. Gittis and I. G. Mikhailov, *Sov. Phys. Acoust.* **12**, 131 (1966).
19. O. J. Kleppa, *J. Chem. Phys.* **18**, 1331 (1950).
20. K. V. Volkov and V. A. Sibilev, *Prikl. Mat. Tekh. Fiz.* **4**, 125 (1981).
21. R. F. Trunin, M. V. Zhernokletov, N. F. Kuznetsov, and V. V. Shutov, *Teplofiz. Vysok. Temp.* **33**, 222 (1995).
22. V. K. Golubev, S. A. Novikov, Yu. S. Sobolev, and N. A. Yukina, *Prikl. Mat. Tekh. Fiz.* **6**, 108 (1982).
23. C. S. Speight and P. F. Taylor, in *Proceedings of the International Conference Explomet-85 on Metallurgical Applications of Shock-Wave and High-Strain-Rate Phenomena*, Ed. by L. E. Murr, K. P. Staudhammer, and M. A. Meyers (Marcel Dekker, New York, 1987), p. 805.
24. S. Balibar and F. Caupin, *J. Phys.: Condens. Matter* **15**, S75 (2003).

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