

Effects of sample temperature on spall fracture in laser shock-loaded metals between 30 K and 1000 K

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Abstract. For many years, spall fracture of shock-loaded materials has been one of the most widely studied phenomena in shock physics, for both fundamental and technological motivations. Laser driven shocks provide a means to investigate this process over ranges of extremely high strain rates and short durations, and they allow recovering spalled samples more easily than plate impact or explosive loading techniques. In this paper, we present laser shock experiments on gold and aluminium in cryogenic conditions (relevant in the context of inertial confinement fusion), and on iron at high temperatures up to about 1000 K. Time-resolved measurements of the free surface velocity are used to determine the evolution of the spall strength with sample temperature. They are complemented by post-test observations of the recovered targets, which reveal clear changes in fracture surface morphology in the spall craters. In the case of iron, possible influences of pressure-induced phase transformations prior to tensile loading are discussed on the basis of hydrodynamic simulations.

1. Introduction

Spall fracture is one of the most widely studied phenomena in the field of shock compression of condensed matter, for both basic and applied motivations. It has been the subject of extensive work under explosive and impact loading [1]. For a few decades, laser shocks have been used to complement experimental data over ranges of very high strain rates and short durations of pressure application, where the destruction of both the sample and its environment is usually limited, which facilitates recovery for post-shot analyses.

In this paper, we investigate some temperature effects on spall fracture in laser shock-loaded metals. A first series of shots is performed on gold and aluminium at ambient and low temperatures (down to ~30 K) to investigate the possible role of cryogenic conditions on shrapnel generation in the experiments planned at Mega-Joule class laser facilities, where the risks associated to the impacts of such shrapnel must be carefully controlled [2]. A second series of shots is performed on preheated iron (up to ~1000 K) to complement existing data and explore the potential influences of polymorphic transformations upon the dynamic response of this metal of both technological and geophysical interest [3, 4].

Laser shock experiments have been conducted at the *Alisé* facility of the CESTA (CEA, Le Barp, France). A laser pulse of ~3 ns-duration, ~1 ns-rise time, 1.06 μm -wavelength and ~100 J-energy is

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focused on a 2 mm-diameter spot in the sample surface, which drives a short compressive pulse onto this surface. The amplitude and temporal shape of this pressure load are inferred from one-dimensional simulations of laser-matter interaction. The velocity of the opposite free surface is recorded with a Velocity Interferometer System for Any Reflector (VISAR), and spalled samples are recovered for post-shock observations.

2. Gold and aluminium at cryogenic temperature

The current scheme for inertial confinement fusion (ICF) involves a gold hohlraum at about 18 K that will be subjected to high energy (MJ order) laser irradiation. To anticipate the subsequent generation of shrapnel, the influence of cryogenic temperature on the dynamic strength of this metal has been investigated, using a flow of liquid helium to cool a cryogenic cell set in vacuum, with a specific chip sensor designed to measure the cell temperature [5]. Fig. 1 shows free surface velocity profiles recorded in 300 μm -thick gold samples shot at cryogenic (blue line) or ambient (black line, vertically shifted for clarity) temperature. Shock breakout produces a sharp velocity jump, followed by a deceleration called the velocity pullback. Its amplitude Δu (double arrows) provides an estimate of the so-called spall strength

$$\sigma_{sp} = \frac{1}{2} \rho_0 C_0 \Delta u \quad (1)$$

where ρ_0 and C_0 are the density and bulk sound speed, and its slope is indicative of the strain rate [1]. Thus, the tensile strength of gold at strain rates of about $3 \times 10^6 \text{ s}^{-1}$ is found to decrease from 3.2 GPa at room temperature to 1.7 GPa in cryogenic conditions. On the other hand, the fracture surface morphology observed in both recovered gold samples remains unchanged [5], typical of a ductile behaviour, with dimples resulting from the coalescence of spherical voids. Finally, the depth of the spall crater is smaller at cold temperature, which is consistent with a lower tensile strength.

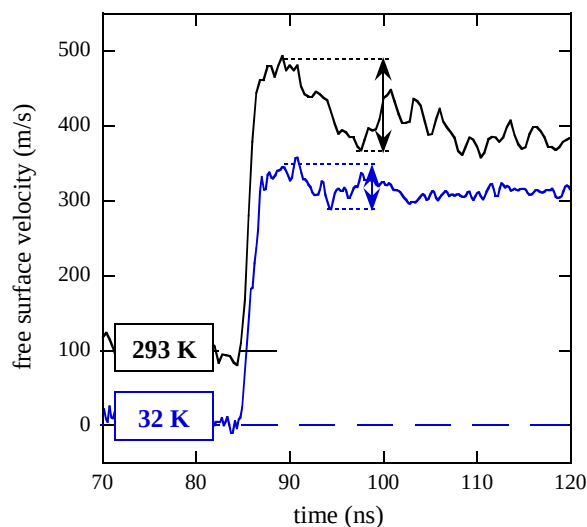


Figure 1. VISAR records of the free surface velocity in 300 μm -thick Au samples of initial temperature 32 K (blue line) or 293 K (black line, vertically shifted for clarity) subjected to laser shocks of about 35 GPa.

Similar tests have been performed on aluminium, which is a standard material in shock physics as well as another relevant constituent in the ICF design. However, reduction of the VISAR data recorded in those tests did not provide reliable velocity profiles, possibly because of insufficient time resolution (of ns-order in our configuration involving photomultipliers) so that the spall strength could not be quantified. Still, complementary results obtained by Photonic Doppler Velocimetry and optical shadowgraphy reported elsewhere [5] suggest slightly lower tensile and shear strength at low temperature. Besides, unlike in gold, a change of fracture surface morphology from ductile type at room temperature to brittle type in cryogenic conditions was evidenced in aluminium (Fig. 2).

Overall, although cryogenic conditions have significant effects on dynamic fracture of both metals, they should not drastically affect shrapnel generation to be anticipated in large scale laser facilities.

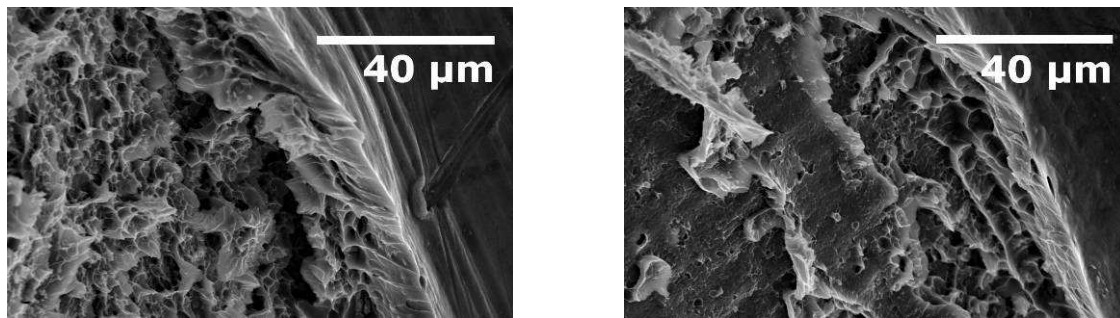


Figure 2. Scanning electron micrographs near the edges of the spall craters in the free surface of 200 μm -thick Al samples recovered after laser shock loading at ambient (left) and cryogenic (right) temperature.

3. Iron at elevated temperatures

To investigate the potential influence of preheating on dynamic response to shock loading, iron was chosen for engineering purpose (due to the wide use of this metal in technological applications where both high temperature and intense pulsed loading can be involved) and geophysical interest (since open questions remain on iron and its alloys for planetary science and interpretation of meteoritic impacts). The sample holder, insulated from the chamber by a ceramic plate, is inserted in a cylindrical heater set in vacuum. The sample temperature, assumed to be homogeneous after a few minutes, is monitored by a thermocouple placed in contact with the sample [6].

Free surface velocity profiles measured in 250 μm -thick iron samples of increasing temperature subjected to laser shocks of ~ 40 GPa-peak pressure are plotted in Fig. 3 (with a 200 m/s vertical shift between records for clarity). Unlike in gold, they start with an elastic precursor (empty arrows) ahead of a plastic compression wave, followed by a velocity pullback (double arrows) before a slight reacceleration due to stress relaxation accompanying spallation. To account for the elastic-plastic response evidenced from the precursor, the relationship giving the spall strength should be refined to

$$\sigma_{sp} = \rho_0 C_0 \Delta u \frac{1}{1 + C_0 / C_l} \quad (2)$$

where C_l is the longitudinal sound speed [1]. For each shot, the variations of ρ_0 with temperature (from 7.86 g/cm^3 at 293 K to 7.60 g/cm^3 at 1003 K) are used to correct the initial sample thickness. The C_l value derived from the arrival time of the elastic precursor at the free surface is found in close agreement with data from Ref. 3, then C_0 is taken from the same reference. Finally, Eq. 2 provides the spall strength, which is found to decrease linearly with sample temperature, from 5.4 GPa at 293 K to 4.3 GPa at 1003 K. The expansion rate inferred from the records is about $2.8 \times 10^6 \text{ s}^{-1}$ in all shots, with no significant dependence on temperature.

The results at room temperature are fully consistent with data from plate impact experiments [7] where the tensile strength of iron was reported to increase linearly with the expansion rate from about 2.9 GPa to 7.6 GPa between about $1 \times 10^5 \text{ s}^{-1}$ and $5 \times 10^6 \text{ s}^{-1}$, and with measurements under similar laser shock experiments [8] in the case where iron at the spall plane was not cycled through extensive α - ϵ - α transformation. The slight, continuous decrease of the spall strength with increasing temperature is similar to that observed under explosive or impact loading in other metals. Nucleation of vacancies and microvoids is probably enhanced by thermal fluctuations, then the lower yield strength at high temperature (evidenced by the decreasing amplitude of the elastic precursor in Fig. 3) is expected to favour subsequent void growth leading to spallation.

Fig. 4 shows optical micrographs of cross sections in two iron samples recovered after laser shock loading at room temperature (bottom) and 673 K (top), then etched to reveal grain boundaries. The fracture surface morphology at ambient temperature is typical of the brittle behaviour of iron at high strain rate [8], with smooth facets resulting from the propagation of straight cracks, both transgranular and intergranular, distributed over a depth of several tens of μm beneath the main spall plane. A clear

change to ductile failure, governed by the nucleation, growth and coalescence of spherical pores, is evidenced in the pre-heated sample.

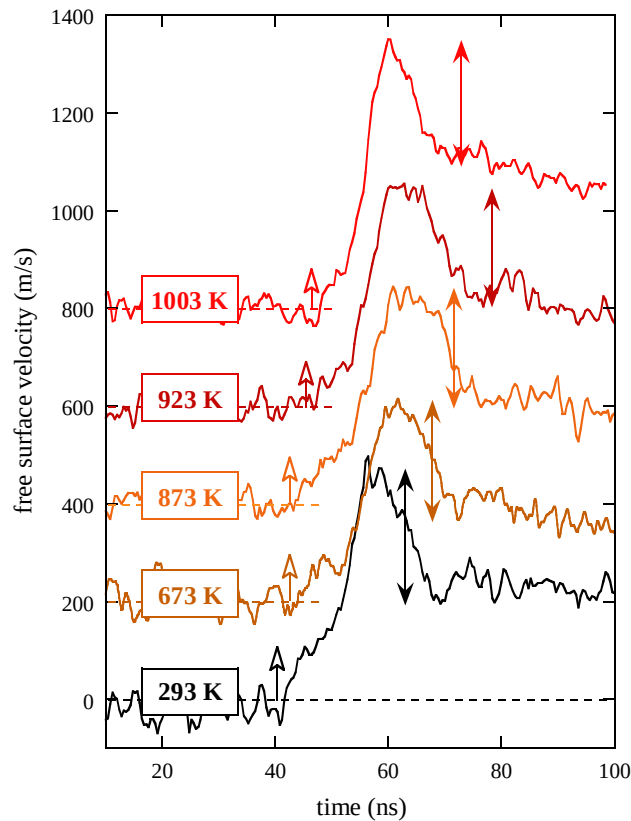
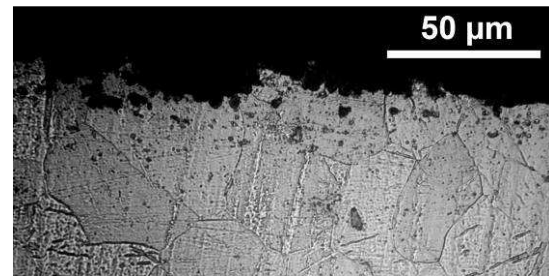
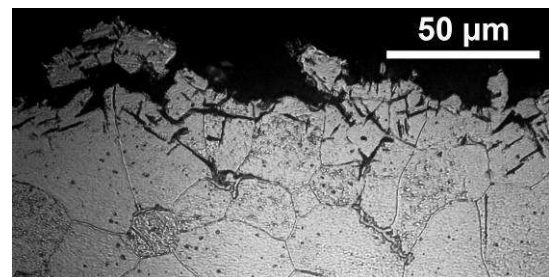


Figure 3. VISAR records of the free surface velocity in 250 μm -thick Fe samples of increasing initial temperature (vertically shifted for clarity) subjected to laser shocks of about 40 GPa.



673 K



293 K

Figure 4. Micrographs of cross sections through spall craters in Fe samples recovered and etched after laser shocks at room (bottom) and elevated temperature (top).

Polymorphic transformations prior to tensile loading may strongly affect the fracture behaviour. For instance, the transition of iron from the α (bcc) to the ϵ (hcp) phase, although reversible, was reported to increase its resistance to tension and produce a characteristic “smooth spall” [8, 9]. To determine the sequence of thermodynamic and structural states of iron prior to fracture in our experiments, simulations have been performed with the one-dimensional hydrocode ESTHER, based on the multi-phase, tabulated equation of state SESAME 2150 [10]. Some results of such computations are illustrated in Fig. 5, for 250 μm -thick iron samples subjected to laser shocks at ambient and elevated initial temperatures (arrows on the vertical axis). Iron phase boundaries [11, 12] used in the SESAME model are plotted in green mixed lines. For each shot, the round dot indicates the shocked state computed near the loaded surface (15 μm deep) and the square dot is the shocked state near the spall plane (40 μm beneath the free surface) after pulse decay with propagation distance. Dotted lines show the unloading paths from these states to ambient pressure. They follow the phase boundaries during the phase transformations as long as two phases coexist. According to these computed predictions, the material near the spall plane (square dots) would be shocked either to the α - ϵ boundary (293 K and 673 K), to the γ - ϵ boundary (873 K, not shown here for clarity), or to the γ phase (1003 K). Subsequent spall fracture would take place (under negative pressure to the left, not shown) after reversion to the α phase upon release (which allows using parameters of α -iron in Eq. 2). The decreasing temperature dependence of the spall strength would then be governed by thermal effects in α -iron rather than by the history of former phase transformations.

The change in fracture mode between 293 K and 673 K does not seem correlated to the predicted phase transitions either. However, it was inferred recently from planar impact experiments that in the highly dynamic regime considered here, iron would follow phase boundaries significantly different from the equilibrium phase diagram [3]. These new boundaries, plotted in blue dashed lines in Fig. 5, suggest that in all our tests, the material near the loaded surface would be shocked to ϵ -iron (round dots), while the compressed state near the spall plane would lie in the α - ϵ mixture region (pale blue shaded area). Such overall similarity between the shots seems more consistent with our experimental results. The observed change from brittle to ductile behaviour might be related to a significant amount of ϵ -phase predicted in the high temperature shots, compared to a much smaller amount (or even none, within our experimental and computational uncertainties) in the shot at room temperature.

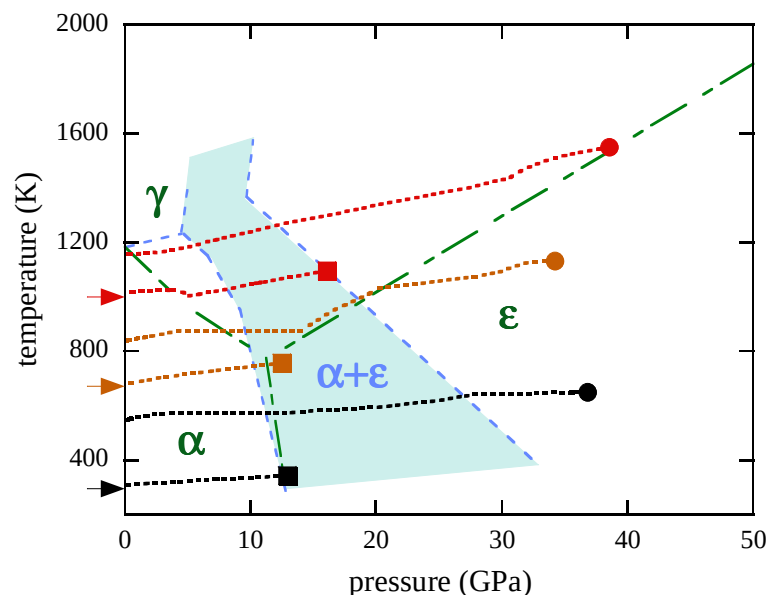


Figure 5. Computed results for three shots on 250 μm -thick iron samples of increasing temperature (arrows). Material states after shock loading near the loaded surface (round dot) and near the spall plane (square dot) with subsequent release paths (dotted lines) are plotted in the iron phase diagram (green mixed lines). Blue dashed lines show the “dynamic” phase boundaries proposed in Ref. 3.

4. Conclusion

The effects of initial temperature on the dynamic behaviour of metals at strain rates of about $3 \times 10^6 \text{ s}^{-1}$ have been investigated using laser driven shocks, to complement experimental data reported under explosive and impact loading. On one hand, the influence of cryogenic conditions involved in ICF on dynamic fracture of gold and aluminium has been evaluated down to about 30 K, to help assess the risks of damage associated to shrapnel impacts in Mega-Joule class laser facilities. On the other hand, the dynamic response of pre-heated iron has been explored up to about 1000 K, to provide some insight into the role of temperature on shock-induced polymorphic transformations and spall fracture in this metal. Such insight may be useful for modelling the breakup of Fe-Ni based meteorites upon entry into the Earth’s atmosphere [13] where large thermal gradients are involved.

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