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Shock compression and spall formation in aluminum containing helium bubbles at room temperature and near the melting temperature: Experiments and simulations

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ABSTRACT

The influence of helium bubbles or boron inclusions in aluminum targets is studied by plane impact experiments with a gas gun. The experiments were done for targets with initial temperatures of 25 °C and near melting at 600 °C. The free surface velocity was measured with velocity interferometer for any reflector (VISAR) diagnostic. From these measurements the elastic yield strength and the spall strength were calculated.

The experiments are analyzed by using a one dimensional (1D) hydrodynamic simulation coupled to a spall model. This model describes the time development of ensemble of growing voids or helium bubbles. The simulations of the VISAR free surface velocity are in a good agreement with the experiments. The impact experiments and the appropriate simulations are done for three distinct targets: pure Al, Al + 0.15%wt.^{10}B and Al + 0.15%wt.^{10}B with helium. The Hugoniot Elastic strength limit (y_{HEL}) for the target with helium at room temperature is smaller than the appropriate target without helium. The y_{HEL} for all targets becomes substantially higher at 600 °C preheating temperature. Furthermore, the preheated (600 °C) pure Al has y_{HEL} significantly larger than all other targets. For the preheated Al–^{10}B with helium, the shape of the velocity trace does not show a well defined Hugoniot elastic limit. The spall strength for all targets becomes substantially lower at 600 °C. The preheated pure aluminum has significantly higher spall strength in comparison to all other preheated targets. However, at 600 °C the spall strength of Al–^{10}B with helium bubbles is significantly reduced in comparison to Al–^{10}B without helium, while at 25 °C the spall strength is the same for both cases. The simulation revealed that this effect might be explained by a reduction of the viscosity in the aluminum with helium at the pre-heating conditions.

1. Introduction

The creation of helium atoms is one of the main damaging mechanisms in neutron irradiated metals. The energetic helium nuclei (α) (as well as fast neutrons, hydrogen, electrons, and photons) that are produced during the irradiation penetrate the metal's lattice and change its mechanical properties [1,2]. Research at static loading conditions showed that creation of helium atoms in metals is very significant, since their precipitation into bubbles can cause substantial deterioration of the mechanical properties of materials, where drastic embrittlement due to helium bubble formation at the grain boundary is found [2–4]. Research at dynamic loading conditions is quite rare and therefore investigation of the influence of helium bubbles in metal on its dynamic properties is important. The dynamic strength of aluminum containing an initial distribution of microscopic defects and nanometric bubbles was calculated by Kubota et al. [5] using molecular dynamics method and development of equation of state (EOS) for aluminum with helium bubbles based on Sesame EOS for aluminum and hard sphere EOS for helium was done by Raicher et al. [6].

In previous study we investigated the structure of recovered Al–^{10}B samples, with or without helium, impacted by aluminum 1100 impactor with velocities of ~320 and ~430 m/sec [7]. Bubbles growth and coalescence were observed by transmission electron microscope (TEM). The dynamic tension strength (spall) and the Hugoniot elastic limit extrapolated from the free surface velocity

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profiles are similar for both, Al—^{10}B with and without helium bubbles, probably because the influence of the bubbles growth is small in comparison to the aluminum matrix strength. Therefore, study of the helium influence on the dynamic response should be done in conditions where the aluminum loses its strength. Zaretsky et al. [8,9], Kanel et al. [10,11] and Garkushin et al. [12,13] measured the dynamic yield strength and the dynamic tensile strength (spall) of aluminum over a wide range of preheating temperatures. They found a precipitous drop in the spall strength of preheated samples as temperatures approached 0.94 Tm, where Tm = 993 K (660 °C) is the aluminum melting point.

In the current research we studied the influence of the helium bubbles on the elastic yield strength and spall strength of aluminum in plane impact experiments, at room temperature and near melting temperature (600 °C), in order to achieve conditions where the aluminum strength is reduced. The experiments were performed by accelerating aluminum 1100 impactors in a gas gun at velocity of 950 m/sec into three types of targets: Al-0.15%wt.^{10}B with and without helium bubbles and also pure Al. The free surface velocity signals were measured by velocity interferometer for any reflector (VISAR) [14]. Two sets of experiments were performed: 1) the targets were hold at room temperature. 2) The targets were preheated to 600 °C. The preheated target is with reduced bulk strength which opens the possibility to get spall failure by growth and coalescence of helium bubbles. The measured free surface velocity vs. time includes information about the elastic yield strength limit and the spall temporal behavior. The free surface first minimum includes its spall strength through the pullback velocity. The transition rate from the first minimum to the following maximum can be related to the development of an ensemble of growing voids or growing helium bubbles, which coalesce and generate the spall. The long live oscillations following the maximum after spall in the free surface velocity signal, are depend on the rate the energy is transferred and captured in the spall.

We consider 1D hydrodynamic simulations of ductile targets coupled to an ensemble of voids or bubbles growing under tension [15–20]. The computation includes in detail the nucleation, growth and coalescence of the ensemble of voids or bubbles and the surface velocity vs. time compared to the experiments. The growing voids or bubbles are presented by an inertial dependence Rayleigh type equation [21–29]. The voids or bubbles are growing spherically under tension with a time dependent radius R which dependent on the local hydrodynamic conditions. The equation of motion for R is based on the Kirkwood—Bethe hypothesis [20–22,30,31]. The void expansion is limited by static yield strength and a viscosity term presenting the high strain rate dependence of the plastic flow of the solid at the void surrounding ($\dot{R}/R = 10^8 \ \text{sec}^{-1}$). High strain rate is obtained due to fast volume change by the voids expansion implying fast increase in the porosity. The viscosity dependence applied is similar to this in Refs. [15,16].

The plan of the paper is as follows: In section 2 sample preparations are considered. Section 3 presents the experimental results and discussions. The simulation model and results are presented in section 4 and 5, respectively. Concluding remarks are in section 6.

2. Sample preparation

2.1. Helium bubbles formation in aluminum

In most of the research on helium—metal interaction, the helium bubble distribution in metals is accomplished by helium implantation [32,33] and tritium decay [34]. The disadvantages of these techniques are the non-homogeneous bubble growth effect in near surface (within a depth of few hundred nanometers) for implantation and the long-term preparation for the tritium decay. For investigation of the mechanical properties of metals with bubbles, an approximately uniform distribution of the bubbles in the bulk of the target is required. Therefore, we use in this work a method to induce helium in metals based on neutron irradiation of aluminum—boron samples [35].

Pure aluminum (99.9999%) was melted with 0.15%wt.^{10}B powder in an arc furnace. After solidification the Al—^{10}B alloy was neutron irradiated in the Soreq nuclear reactor for 20 h with a flux of $\varphi_N = 3 \times 10^{13}$ [n/(cm^2 s)] to obtain helium. The density of the helium atoms N_{He} that were created in the bulk of the sample from the reaction $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$ is given by $N_{\text{He}} = \phi_N \sigma N_{10_B}\, t = 2.1 \times 10^{18} [\text{cm}^{-3}]$, where $\sigma = 4.0 \times 10^{-21}$ [cm^2] is the cross section, $N_{10_B} = 2.43 \times 10^{20} [\text{cm}^{-3}]$ is the number of ^{10}B atoms per unit volume, and $t = 20$ h is the irradiation time in the nuclear reactor. After irradiation, the sample was rolled and 20 mm diameter disk samples were prepared for the plane impact experiments. In order to get bubbles, each sample was heated to an appropriate temperature of 600 °C during 48 h, a time that was estimated from an analytical approximation of the solution to a diffusion equation with a sink [36]. Transmission electron microscopy measurements revealed that the average bubble radius is 5–10 nm. It is also found that not all of the bubbles can be seen in one imaging condition in TEM or scanning TEM (ADF-STEM), therefore it is hard to obtain a reliable estimation of the helium bubbles concentration in the bulk aluminum directly from the inter bubbles distance. Another approach to estimate the helium bubbles concentration is by electron energy loss spectrum (EELS) measurement. It is found that the EELS measurements give reliable results only when they are applied inside the helium bubble. Therefore the helium bubbles concentration was estimated from the ratio between the amount of helium atoms in one bubble measured by EELS to the density of helium atoms in the whole bulk known from the irradiation conditions. The average density of helium atoms in the bubbles is found to be 1.7×10^{22} cm^{-3}, under the assumption that all of the helium atoms were clustered into the bubbles, the maximum estimated concentration of 7.5 nm radius helium bubbles is 7.0×10^{13} cm^{-3}. However, it is known that not all the helium atoms clusters develop into nanometric bubbles; therefore this value is over estimated. Indeed we find in the free surface velocity simulations that helium bubbles concentration of 3.0×10^{13} cm^{-3} describes more adequately the experimental results.

2.2. Metallurgical characterization

While inducing helium in aluminum by neutron irradiation of aluminum-boron samples, the influence of the ^{10}B additive and the long term heat treatment (48 h at 600 °C) on the mechanical and metallurgical properties of the aluminum should be addressed. Therefore, in the present research three types of samples were used as targets in the experiments: (1) pure aluminum, (2) unirradiated Al—^{10}B, and (3) neutron irradiated Al—^{10}B to obtain helium. The materials were cold rolled and 20 mm diameter disk samples were prepared for the plane impact experiments. Since long term heat treatment is necessary to obtain helium bubbles by diffusion in the neutron irradiated Al—^{10}B samples, the other samples were also heat treated at the same conditions (48 h at 600 °C) in order to eliminate the heating effects. After heat treatment the targets were machined to the final dimensions. Metallurgical analysis of the unimpacted samples with the same treatments was made. It is found that the average grain size of the pure aluminum is 500–2000 μm, larger than the average Al—^{10}B grain size, 280–600 μm. In addition it is also found that the Al—^{10}B samples contain 1–2 μm impurities along the grain boundaries. The amount of ^{10}B in the samples (0.15%) is solute in the aluminum at the elevated temperatures in the arc furnace during the specimens preparation, but after cooling