The preheating effect on the dynamic strength of aluminium containing helium bubbles

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Abstract. The influence of helium bubbles or boron inclusions in an aluminum target is studied by plane impact experiments with a gas gun and VISAR diagnostic. The experiments were carried out on targets with initial temperatures of 25 °C and near melting at 600 °C. The Hugoniot elastic limit $y_{HEL}$ for all targets becomes substantially higher at 600 °C, related to the phonon drag mechanism at high strain rates and high temperatures. The spall strength for all targets becomes substantially lower 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. This effect might be explained by a local strength reduction of the aluminium at pre-heating conditions, allowing the helium bubbles to be more dominant in the spallation process.

1. Introduction
In previous study we investigated the structure of recovered Al-$^{10}$B (0.15%wt.) samples, with or without helium, impacted by aluminum 1100 impactor with velocities of ~320 and ~430 m/s [1]. Bubble 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 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 [2;3], Kanel et al [4;5] and Garkushin et al [6;7] 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 Al-0.15%wt.$^{10}$B targets: with and without helium bubbles. The free surface velocity signals were measured by velocity interferometer for any reflector (VISAR) [8]. Two sets of experiments were performed: 1) the targets were held at room temperature. 2) The targets were preheated to 600 °C.

This paper addresses the material preparation and the experimental setup in section 2, the experimental results in section 3. We end in section 4 with a short discussion and our conclusions.
2. Experimental procedure

2.1. Sample preparation
Pure aluminum 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 hours to obtain helium. 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 hr, a time that was estimated from an analytical approximation of the solution to a diffusion equation with a sink [9]. Transmission electron microscopy measurements revealed that the average bubble radius is 5-10 nm.

2.2. Experimental setup
Shock wave experiments were performed by accelerating 1 mm thick aluminum 1100 impactor with velocity of 950 (m/sec) into different 2 mm thick targets: (1) Al-$^{10}$B, and (2) Al-$^{10}$B with helium bubbles. Two sets of experiments were done: at the first set the aluminum targets were held at room temperature. At the second set of experiments, the targets were preheated with four resistive heaters, 30 W each, placed on aluminum ring surrounding the target. The targets were thermally isolated from the target holder by ceramic layer. The target's temperature was measured by a thermocouple. Using this setup, the initial temperature of the impacted targets is 600 °C. The peak compression pressure in targets without preheating is 76 kbar and in the target with preheating to 600 °C is 73 kbar. The experimental setup is shown in figure 1.

![Figure 1. The experimental setup consists an Al-0.15%wt.$^{10}$B target (black) and aluminium 1100 projectile.](image)

The density of the samples at room temperature was measured using the Archimedes technique. The longitudinal, $c_l$, and the transversal (shear), $c_t$, speeds of sound were obtained by the ultrasonic method. The bulk speed of sound was calculated from the relation,

$$c_0 = \left(c_l^2 - \frac{4}{3}c_t^2\right)^{1/2} \quad (1)$$

It is found that at room temperature, the density and speed of sound for the aluminum, with or without $^{10}$B or helium are the same; hence, the acoustic impedance of the samples is similar to the impactor acoustic impedance and the experiments are symmetric. At elevated temperatures, the speeds of sound were calculated from available elastic constants for single crystal aluminum over temperatures range from 273 K to 919 K [10]. At T = 600 °C (873 K), the density and the speeds of sound in the preheated samples are slightly lower in comparison to the non preheated aluminum; hence, the acoustic impedance is 5% lower.
3. Results

The targets response to the dynamic loading is obtained from the free surface velocity profiles that were measured by VISAR. The free surface velocity profiles of the experiments at ambient (room) temperature are shown in figure 2 and the experiments with preheating to 600 °C are shown in figure 3.

![Figure 2. Experimental measurements of the free surface velocity of Al-10B with and without helium. The samples were held at room temperature. The inset is an enlargement of the Hugoniot elastic limit area in the velocity profile](image)

![Figure 3. Experimental measurements of the free surface velocity of Al-10B with helium and Al-10B without helium. The samples were preheated to 600 °C. The inset is an enlargement of the Hugoniot elastic limit area in the velocity profile](image)

3.1. HEL results

The Hugoniot elastic limit (HEL) stress can be calculated by:

\[ \gamma_{HEL} = \rho \cdot c \cdot u_{HEL} \]  

(2)

where \( u_{HEL} \) is the particle velocity calculated from the surface velocity at the elastic-plastic transition (determined at the first break in the velocity profile). For all experiments a distinct value of the Hugoniot elastic limit is obtained as given in table 1. For the preheated Al-10B with helium, two relatively small breaks in the velocity profile can be observed (inset in figure 3): the first one at 19 m/s and the second at 92 m/s. The Hugoniot elastic limit value given in table 1 refers to the second break. It is apparent from figure 3 that the presence of helium in the preheated Al-10B smoothed the wave profile, i.e. the rise time is longer, implying for rate dependent effects and including onset of plasticity. In this case the elastic precursor is less clear than the elastic precursor in the preheated target without bubbles.

A comparison between the experimental results for the two types of targets reveals the following findings: a) The amplitude of the elastic precursor, and hence the Hugoniot elastic limit, for all targets becomes substantially larger as temperature approaching the melting temperature (figure 3) than its value at ambient temperature (figure 2). This result is the opposite of the well known behaviour under low strain rates loading conditions, where both the yield strength and the tensile strength of materials decrease with heating. This finding can be related to the dominancy of phonon drag mechanism at high temperatures and high strain rates as follows: For sufficiently high strain rate exceeds \( 10^4 \) s\(^{-1}\), the
phonon drag mechanism becomes dominant [11]. Because the phonon drag is proportional to the temperature, for very high strain rates the shear stress increases with temperature increase. b) The Hugoniot elastic limit of Al-10B without helium at room temperature is higher than this of the Al-10B with helium. c) It is apparent from figure 3 that the presence of helium in the preheated Al-10B smoothed the elastic precursor wave profile, i.e. the rise time is longer.

**Table 1.** $Y_{HEL}$ obtained from the experiments.

|                      | $Y_{HEL}$ at room temperature [kbar] | $Y_{HEL}$ at preheating to 600 °C [kbar] |
|----------------------|-------------------------------------|----------------------------------------|
| Al-10B without helium bubbles | 1.64                                | 6.58                                   |
| Al-10B with helium bubbles        | 0.95                                | 7.13                                   |

3.2. The spall strength

The spall strength, $p_s$, in the experiments can be calculated using the relationship in reference [12], taking into account the signal distortion caused both from the stress gradients acting ahead the spall pulse (plastic tail) propagating at the bulk sound velocity $c_0$ and at its front, i.e., elastic recompression of plastically tensed material propagating at the longitudinal sound velocity $c_l$:

$$p_s = \frac{1}{2} \rho_0 c_0 (\Delta u + \delta)$$

$$\delta = h \left( \frac{1}{c_0} - \frac{1}{c_l} \right) \frac{|\dot{u}_1 - \dot{u}_2|}{|\dot{u}_1| + |\dot{u}_2|}$$

where the pull-back velocity, $\Delta u$ is the difference between the first maximum and the first minimum of the free surface velocity, $\delta$ is a correction for the profile distortion, $h \approx 1$ mm is the distance between the spall plane and the free surface, $\dot{u}_1$ and $\dot{u}_2$ are the slopes in the free surface velocity profile as shown in figure 2. The spall strength results are summarized in table 2. The experimental results with the targets hold at initial ambient temperature revealed that neutron irradiation of the Al-10B to get helium, did not change its spall strength. Initial preheating to temperature of 600 °C (figure 3) revealed that the amplitude of the pull-back velocity, and hence the spall strength reduces for all targets as temperature approaching the melting temperature in comparison to the value at ambient temperature. Furthermore, the spall strength of Al-10B with helium is half than the spall strength of Al-10B without helium, unlike the experiments at ambient temperature where the spall strength of the Al-10B with or without helium is the same.

These findings can be associated to partial strength reduction of the aluminum as follows: in polycrystalline solids, lattice disorder may start along grain boundaries at temperatures below the melting temperature of the crystal [13,14]. In particular Lu and Szpunar [15] have found that this effect had occurred at grain boundary in aluminum at temperatures above 0.94 $T_m$ (600 °C) implying for partial melting and strength reduction, consistent with the spall strength reduction in the same heating conditions found in the current research. Furthermore, at 600 °C the helium bubbles can
overcome the significantly reduced strength of the aluminum and become more dominant in the spallation process.

| Table 2. Spall strength. |
|-------------------------|
|                         |
| P_s at room temperature |
| [kbar]                  |
|                         |
| P_s at preheating       |
| to 600 °C [kbar]        |
|                         |
| Al-10B without helium   |
| bubbles                |
| 16.4                   |
| 9.3                    |
| Al-10B with helium      |
| bubbles                |
| 16.7                   |
| 4.0                    |

4. Conclusions and Discussion
The influence of helium bubbles in aluminum matrix on the elastic yield strength and the spall strength at room temperature and near melting (600 °C) is studied in plane impact experiments with a gas gun. It is found that at room temperature the Al+0.15%wt.10B without helium exhibit higher elastic strength than the Al+0.15%10B wt.10B with helium. In the case of preheated samples with helium a distinct value of $u_{HEL}$ cannot be obtained. As temperature approaching melting the Hugoniot elastic strength limit (HEL) for all targets becomes substantially higher than its value at ambient temperature. This finding can be related to the dominancy of phonon drag mechanism or to decreasing rate of the elastic precursor decay at high strain rates and high temperatures. Near melting the spall strength of Al-10B with helium is significantly reduced in comparison to Al-10B without helium. It seems that the bubbles in the preheated targets lowering the plastic flow (and hence the viscosity) and assist the expansion of the growing voids.

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