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# Mechanical response of 99.999% purity aluminum under dynamic uniaxial strain and near melting temperatures

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ABSTRACT

A series of reverse geometry normal plate impact experiments are employed to investigate the incipient plastic behavior of commercial purity polycrystalline aluminum under ultra-high strain-rates ($\sim 10^5$ /s) and test temperatures up to melt (i.e. 643 °C). The applied stress at the aluminum/target interface, as inferred from the measured normal free-surface particle velocity record, shows progressive weakening with increasing test temperatures ranging from 23–620 °C; at higher temperatures (470–620 °C) this rate of weakening is observed to decrease, and at the highest test temperatures employed in the study, i.e. temperatures approaching the melt point of aluminum (643 °C), a net increase in the longitudinal stress is observed. Additionally, estimates of longitudinal elastic impedance of the sample material, as inferred via impedance matching from the particle velocity states at shock plateau show similar monotonic decrease with temperature, except for the highest test temperature case, in which reversal of this trend is observed. Though slight, these noticeable changes in the impedance, and stress/velocity states likely indicate variances in the strengthening/hardening response of the material, which can be linked to transition in the dominant plastic flow mechanisms as the sample approaches the melting point. Scanning electron microscopy of the impact surface of the post-test samples reveal coarsening of the sample grains due to static recrystallization during the heating phase of the experiment. Additional experiments are performed on annealed specimens to probe the effects of microstructural changes, i.e. grain size, and/or relief of residual strains in the interpretation of the measured response of aluminum. The results, which show a decrease in the longitudinal acoustic impedance, and decrease in the levels of stress/particle velocity under shock loading, indicate that the effects of annealing may play a role in the observed response by promoting softening of the dynamic strength, and/or lessening of the rate of hardening in a post-yield regime.

## I. Introduction

The mechanical response of polycrystalline and single crystal aluminum has been studied extensively by several researchers in the past. Similar to other FCC metals, at low and intermediate plastic strain rates ($\sim 10^{-4}$ –$10^3$), the flow stress in aluminum is understood to be controlled by a thermally activated mechanism [1,2], in which thermal fluctuations assist motion of dislocations in overcoming barriers and hence negatively affect the dynamic strength of the material. However, at higher plastic strain rates (i.e. beyond $10^3$ /s), the increase in the rate sensitivity of the flow stress is interpreted as a transition in the dominant plastic flow mechanism [3–5], where phonon drag and/or Frenkel disorders [6] are two of some possible mechanisms that are hypothesized to play a dominant role in hindering the motion of dislocations [7,8]. Consequently, at sufficiently high strain-rates, temperature becomes positively related to the dynamic strength of the material. In support of this, plate-impact studies on aluminum, silver, iron, magnesium, and several other metals, have revealed growth in their dynamic strength while being subjected to high plastic strain-rates and temperatures approaching their melt [9–14]. For example, normal plate-impact experiments performed by Zaretsky et al. [12] revealed progressively increasing Hugoniot elastic limit (HEL) with temperature at onset of plasticity in pure aluminum. While pressure-shear plate impact experiments performed by Grunschel [13] on pure aluminum revealed thermal softening at plastic strain rates $\sim 10^6$ /s and temperatures ranging from room to 495 °C; higher flow stresses were observed at larger plastic strains and sample temperatures of 584 °C.

Due to the acceptance of these findings and the importance of the understanding of the dominant mechanisms that control the dynamic strength of metals at ultra-high plastic strain rates and elevated temperatures, several models have been put forth that combine thermal activation and viscous drag; however, the availability of experimental data is still not enough for the development of informed physics-based models that fully capture the resultant mechanical response caused by

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the combined effects of these mechanisms especially at elevated temperatures [15–21]. In particular, longitudinal acoustic impedance at elevated temperatures, correlations between the viscous drag coefficient and temperature, and levels of dislocation density need to be investigated further. The present study is especially motivated by the critical need for experimental data on the dynamic response of aluminum over a wide range of temperatures, loading rates and stress/velocity states.

Recently, reverse-geometry plate impact experiments have been shown to be attractive for investigating the dynamic behavior of metals under thermomechanical extremes [22]. In contrast to most conventional experimental techniques employed to investigate the dynamic behavior of materials, this approach for performing elevated temperature plate impact experiments alleviates several experimental challenges related to optical probe/diagnostics being too proximate to the heated elements, as well as the possible loss of alignment between target and flyer plates due to differential heating of various sub-elements of the target holder, especially for oblique plate impact experiments where carrying the sample either at the target-end, or the flyer-end produce similar results. For these reasons, a direct extension of the latter approach serves as the primary tool in the current investigation. Our results reveal higher levels of stress/particle velocity states, and higher levels of longitudinal acoustic impedance at the aluminum/target interface at near melting temperatures which may indicate an increase in the strength, and/or an increase in the post-yield hardening behavior of aluminum at near melting temperatures. Moreover, as a consequence of heating samples to near melt temperatures, the effects of annealing, i.e. grain coarsening, and/or relief of existing residual strains is also investigated in order to better understand the mechanisms for the observed macroscopic response of the material.

A description of our experimental approach is discussed in Section II, while results from the reverse geometry normal plate impact studies on commercial purity aluminum at test temperatures in the range 23 °C to 643 °C are presented in section III, followed by a detailed analysis of our results. Lastly, the effects of high temperature, and annealing are carefully considered in the interpretation of our results, which are discussed and later summarized in Sections IV, and V, respectively.

## 2. Experimental procedures

### 2.1. Materials and specimens

In the symmetric plate impact experiment, the sample is made from precipitation hardened (high strength) Inconel 718 alloy procured from High Temp Metals Inc. Select physical properties of precipitation hardened Inconel 718 alloy are shown in Table 1. Flyer plates, having a diameter and thickness of 25 mm and 7 mm, respectively, were machined from a 25.4 mm diameter rod. Both sides of the flyer plates were ground flat to within 12 μm and then lapped to within 2–3 light bands across the diameter. Lapping was performed on a Lapmaster 15 machine using 15 μm alumina powder in mineral oil. To observe light bands, the surfaces of the samples were polished on a Texmeth cloth using a 1 μm diamond paste, wiped clean, and then placed in contact with a green monochromatic light source.

In the first set of reverse geometry normal plate impact experiments, as-received 99.999% commercial purity polycrystalline aluminum, acquired from Goodfellow Corporation was used as the sample material. Select physical properties of the polycrystalline aluminum are shown in Table 2. The samples were sectioned from bar stock and then machined into disks with a diameter of 76 mm and thickness of 5.6 mm. Three thru-thickness holes 5.08 mm in diameter were drilled 120° apart on a 62 mm diameter bolt circle onto the sample. These holes enable the sample disks to be secured reliably to the H13 steel sample holder on the sabot using 3.63 mm diameter ceramic screws. The bolt circle and clearence diameters were strategically designed to prevent failure of ceramic screws, and deformation of the flyer plate in the axial, and radial directions due to the thermal expansion of the sample during the heating process. In the current configuration, the flyer plate is prevented from coming into contact with the shank or threads of the ceramic screw during heating, and this reduces the possibility of applied forces on the screws and flyer plate. Both sides of the sample disks were ground flat to within 12 μm and then lapped to within 2–3 light bands across the diameter.

Electron backscatter diffraction (EBSD) was used to characterize the grain size and morphology of the specimens at a strategic location on the impact surface. Shown in Fig. 1 are pole and inverse pole figures taken parallel to the normal of the impact surface; the y and x directions both refer to the radial direction of the disk. These figures reveal a large variance in grain size and morphology, most likely due to residual strains from the manufacturing process of the samples. A grain orientation spread of 3.05° is also indicative of some level of residual plastic strains within the material. A slight [100] \ [111] texture is present, and a weighted average of the EBSD data yielded an average grain size of 304 μm, with a range from 17 – 565 μm.

In the second set of experiments, sample disks were annealed for at least 0.5 hours at 620 °C, and allowed to cool slowly in vacuum. This "mock" heating experiment was performed in order to simulate microstructural changes in the sample during the heating process prior to conducting the experiment. Pole and inverse pole figures of these annealed samples are shown in Fig. 2. These reveal significant levels of grain coarsening. Interestingly, a much lower grain orientation spread of 0.933° was found for this sample, which indicates some relief of residual stresses in the as-received material. A weighted average yielded a grain size of approximately 1.12 mm, with a range of 17 μm–1.429 mm. Moreover, a more prominent [100] texture was apparent in this sample.

In both experiments, the target plates are made from precipitation hardened (high strength) Inconel 718 alloy. Inconel 718 target disks, having a diameter and thickness of 25 mm and 7 mm, respectively, were machined from a 25.4 mm diameter rod. These target plates were then adhered to a precision machined aluminum ring using Hysol 9340 epoxy. The outer and inner diameters of aluminum ring were 41 mm and 30 mm, respectively, and the rings comprise of six equi-spaced 1.5 mm radial slots on a bolt circle of diameter 34.5 mm. These radial slots house six copper pins, secured in the slots with non-conductive epoxy. The six copper pins are lapped flush to the target surface to within 2 to 3 Newton's rings across the target diameter, and are used to monitor the degree of tilt between the flyer and target plates during impact and also provide the trigger signal to the oscilloscopes for data recording. The target plate and the aluminum ring assembly are mounted within a larger diameter Delrin ring, which is bolted securely to a target holder [23,24].

### 2.2. Plate impact experimental configuration

In the present study, high temperature reverse geometry normal

**Table 1**
Select physical properties of precipitation hardened Inconel 718 alloy procured from High Temperature metals.

| Material | Density (Kg/m$^3$) | Elastic modulus (GPa) | Shear modulus (GPa) | Poisson's ratio | Longitudinal wave speed (m/s) | Shear wave speed (m/s) |
|---|---|---|---|---|---|---|
| Precipitation hardened inconel 718 | 8260 | 208 | 80.0 | 0.300 | 5820 | 3112 |