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Dynamic Behavior of Metals at Elevated Temperatures and Ultra-High Strain Rates †

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Abstract: This paper presents the results of a series of reverse geometry normal plate impact experiments designed to investigate the onset of incipient plasticity in commercial purity polycrystalline magnesium (99.9%) under weak uniaxial-strain shock compression loading and elevated temperatures up to the melting point of magnesium. To enable the characterization of dynamic material behavior under extreme conditions, i.e., ultra-high strain rates (~10^6/s) and test temperatures up to sample melt (1000 °C), strategic modifications were made to the single-stage gas-gun facility at the Case Western Reserve University. In this configuration, thin metal samples (also representing the flyer plate), carried by a specially designed heat-resistant sabot, are heated uniformly across the diameter in a 100 mTorr vacuum prior to impact by a resistance coil heater at the breech end of the gun barrel. Moreover, a compact fiber-optics-based heterodyne normal displacement interferometer is designed and implemented to measure the normal component of the particle velocity history at the free surface of the target plate. Similar to the standard photonic Doppler velocimetry (PDV), this diagnostic tool is assembled using commercially available telecommunications hardware and uses a 1550-nm wavelength 2 W fiber-coupled laser, an optical probe and single mode fibers to transport light to and from the target. Using this unique approach, normal plate impact experiments are conducted on preheated (room temperature to near the melting point of magnesium) 99.9% polycrystalline magnesium using Inconel 718 target plates at impact velocities of 100–110 m/s. As inferred from the measured normal particle velocity history, the stress at the flyer/target interface shows progressive weakening with increasing sample temperatures below the melting point. At higher test temperatures, the rate of material softening under stress is observed to decrease and even reverse as the sample temperatures approach the melting point of magnesium samples. Scanning electron microscopy is utilized to understand the evolution of sample material microstructure including twinning following the impact event.

Keywords: normal plate impact; commercial purity polycrystalline magnesium; extreme conditions; incipient plasticity; elevated temperatures; longitudinal impedance

1. Introduction

Hexagonal close-packed (HCP) materials have seen increasing use in structural applications due to their high specific strength-to-weight ratio compared to traditional structural materials. This increased usage has led to a surge in research and development activities in the area of HCP materials for structural applications. However, the knowledge of the mechanical response of HCP materials at thermomechanical extremes (i.e., ultra-high strain rates and elevated temperatures) is still limited by the deficiency of experimental data. As compared to relatively high symmetry face-centered cubic (FCC) and body-centered cubic (BCC) materials, the HCP crystal structure exhibits significant anisotropic mechanical properties, which are mainly attributed to the different critical resolved shear stresses (CRSSs) of slip systems and twinning modes. In general, at room temperature, $\langle a \rangle$ type basal slip is the most easily activated system to accommodate plastic deformation in HCP magnesium. However, $\langle a \rangle$ basal slip is unfavorable for the accommodation of *c*-axis plastic deformation. In this case, despite the higher CRSS of the $\langle c + a \rangle$ pyramidal slip compared to that of the $\langle a \rangle$ type slip systems, the $\langle c + a \rangle$ pyramidal slip is considered as the only possible slip mechanism to accommodate the plastic strain along *c*-axis. The temperature dependence of the CRSS for the various slip systems has been investigated in quasi-static strain-rate regime. These investigations indicate basal slip to be nearly independent of temperature although lower CRSS of prismatic and $\langle c + a \rangle$ pyramidal slip was measured when the temperature was increased. Additionally, it is well established that increasing the applied strain rate (~10^3/s) increases the CRSS of the slips due to material strain rate sensitivity effects. At extremely high strain rates (and elevated temperatures), the dislocation motion can be further hindered by other mechanisms, such as phonon drag.

Deformation twinning is a major mode of plastic deformation for HCP metals due to the restricted number of the independent slip systems available for dislocation glide. Moreover, deformation twinning is particularly important at high strain rates, where twinning has been observed to be more prevalent. Three types of deformation twinning modes are commonly observed in magnesium—extension twinning, contraction twinning and double twinning. Extension twinning is understood to be the most easily activated twin system in magnesium. The CRSS for extension twinning is understood to be insensitive to both temperature and strain rates. In contrast, the CRSSs of contraction twinning and double twinning have been observed to decrease with increasing temperatures, and decreasing strain rates. Previous work [1] on annealed pure magnesium single crystals shock loaded at test temperatures in the range 20–503 °C and at strain rates of 10^4–10^6/s, have indicated that the Hugoniot Elastic Limit (HEL), which corresponds to the dynamic strength of the material under uniaxial strain shock compression, was observed to increase with increasing temperatures along both the *c*-axis and at 45° to the *c*-axis. Despite advances in our understanding regarding the dynamic behavior of magnesium, significant questions still remain on the dynamic deformation of HCP metals at elevated temperatures and ultra-high strain rates.

The experimental study described in here is especially motivated by the critical need for experimental data on the dynamic response of commercial purity polycrystalline magnesium at ultra-high loading rates and elevated temperatures, which can aid in providing a better understanding of the dominant deformation mechanisms in magnesium under extreme thermo-mechanical loading conditions.

2. Materials and Methods

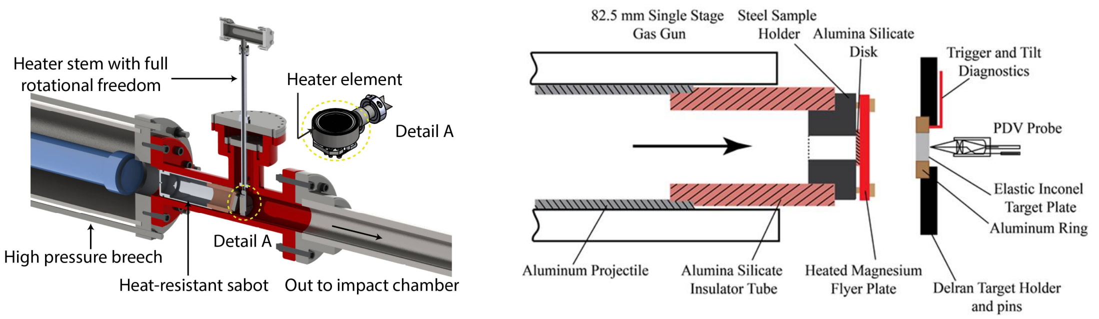
The experiment examines the impact of a 99.9% commercial purity polycrystalline magnesium flyer plate mounted on an H13 tool steel sample holder carried by the sabot with a stationary target plate fabricated from Inconel 718 [2]. The important physical properties of 99.9% pure polycrystalline magnesium and Inconel 718 are provided in Table 1. The dimensions of the magnesium flyer plate include a diameter of 76 mm and a thickness of 5.6 mm. The dimensions of the Inconel 718 target plate include a diameter of 25 mm and a thickness of 7 mm. Both sides of the flyer and the target plates are ground flat to within 12 μm, before being lapped to within 2–3 Newton's rings across the diameter [3]. The rear surface of the Inconel 718 disk is polished to a mirror surface using 1-μm diamond polishing paste to enable laser interferometry measurements of the normal component of the particle velocity at the free surface of the target plate [4-7].

Previous investigations have demonstrated the feasibility of adding either resistive heater or induction coil heating elements to the impact chamber of a gas-gun to heat the sample (target) assembly. However, these methods give rise to several experimental challenges: first, heating the metal target (sample) using an induction coil heating system or a resistive heater, subjects various elements of the target holder and/or the alignment-fixture to differential thermal expansion, requiring remotely controlled alignment adjustment tools with continuous feedback for maintaining parallelism of the target and flyer plates; second, experimental hurdles related to optical probe/diagnostics being too close to the heated target assembly; and lastly, differential thermal expansion, particularly for targets that utilize an optical window, is a perpetual issue in elevated temperature plate impact experiments, since precise tolerances between the sample, bond layer, coating(s), and window are difficult to maintain over large temperature ranges.

Table 1. Important Physical Properties of 99.9% pure polycrystalline magnesium and Inconel 718 alloy.

Material	Density (kg/m³)	Elastic Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio	Longitudinal Wave Speed (m/s)	Shear Wave Speed (m/s)
99.9% Polycrystalline	1740	44.7	17.3	0.291	5810	3032
Inconel 718	8260	208	80	0.3	5820	3112

In an attempt to alleviate the above experimental challenges, strategic modifications are implemented to the single-stage gas-gun at CWRU [8] to enable the heating of the flyer plate carried by an especially designed heat-resistant sabot at the breech end of the gun barrel, as shown in Figures 1a and 1b. Prior to the acceleration of the sabot, the magnesium sample (flyer plate) is heated to the desired temperature using a resistive coil heater accommodated in a custom designed heater extension at the breech end of the gas gun. A sabot carrying the magnesium sample is accelerated down the gun barrel by compressed gas and is made to impact the Inconel 718 target. The impact velocity is measured utilizing a laser-based velocity system and a high-frequency photodiode. An in-house built custom fiber optics-based heterodyne normal displacement interferometer [9] is utilized to measure the normal particle displacement at the rear surface of the target plate. An IPG Photonics 2W Erbium fiber coupled laser with the wavelength of 1550 nm is used to provide the linearly polarized light source.



(**a**) (**b**)

Figure 1. (**a**) Schematic of the custom designed heater system with axial and rotational degrees of freedom to heat the flyer plate at the breech-end of the gas gun. (**b**) Schematic of the elevated temperature normal plate impact experimental configuration used in the present study.

Using a simple wave strain rate independent longitudinal wave analysis, the dynamic material stress in the heated magnesium sample at the flyer/target interface, $\sigma_F(t'^n)$, can be estimated under the conditions of incipient plasticity and post yield in terms of the measured particle velocity at the free surface of the target plate, V_{fs} [2]:

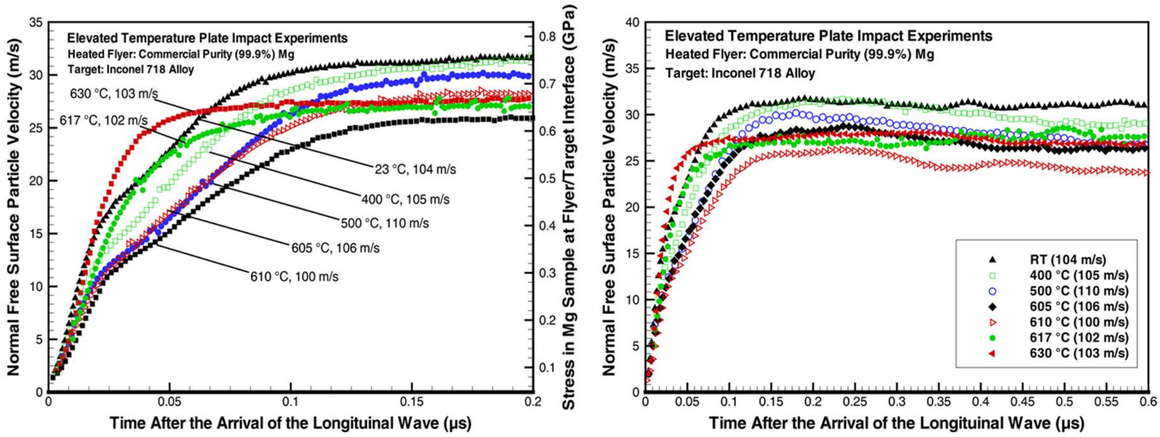
$$\sigma_F(t'^n) = \rho_T C_{LT} \frac{1}{1+\frac{C_{LT}}{C^n}} V_{fs}(t^n), \tag{1}$$

where t^n is a discretized time interval represented as $t^n = nh$, where h is the inverse of the sampling rate of the oscilloscope. Furthermore, we can denote $t^n - L/C^n$ by t'^n, where L is the thickness of the target plate and C^n is an average stress-dependent speed of plastic wave propagation in the target plate measured at the free surface at time t^n. The density and elastic longitudinal wave speed of the target plate are represented by ρ_T and C_{LT}, respectively. Additionally, the loci of all stress and particle velocity states for the target are represented by the line passing through the origin with a slope of $\rho_T C_T^{(p)}$. Thus, from the measured free surface particle velocity level at the shock plateau, $V_{fs}^{(p)}$, the longitudinal acoustic impedance of the flyer (sample), $\rho_F C_F^{(p)}$, can be expressed as:

$$\rho_F C_F^{(p)} = \frac{\rho_T C_T^{(p)} V_{fs}^{(p)}}{\left(1 + \frac{C_T^{(p)}}{C_{LT}}\right) V_o - V_{fs}^{(p)}}. \quad (2)$$

3. Results and Discussion

Figure 2a shows the free surface particle velocity profiles obtained from a series of seven normal plate impact experiments conducted on commercial purity (99.9%) polycrystalline magnesium samples at test temperatures ranging from room to near melting (~630 °C) temperatures under dynamic uniaxial shock compression loading. The profiles show three distinctive regions: an initial sharp rise, followed by a less steep rise region, which eventually reaches a plateau. The initial linear rise in the particle velocity profile is controlled by the elastic behavior of the flyer and target materials, while the subsequent ramp region provides information on the dynamic stress in the magnesium samples at the onset of plasticity and post-yield. These profiles indicate progressively lower dynamic stresses for the shock-loaded magnesium as the test temperatures are increased from room temperature to 500 °C. However, no apparent net change in the dynamic material stress is observed at test temperatures of 500–610 °C, indicating that dynamic strengthening mechanisms come into play that compete with thermal softening. At even higher test temperatures that approaches the melting point of magnesium (617 °C and 630 °C), a clear reversal in this trend occurs with a distinct increase in the dynamic material stress when compared to those observed at test temperatures of 23–610 °C. In addition, the free surface particle velocity at the wave-front is observed to increase in an almost linear manner before reaching a plateau at 617 °C and 630 °C, where strengthening effects overtake the thermal softening. Figure 2b shows that the particle velocity levels in the plateau region decrease continuously as the test temperatures are increased from room to 610 °C. However, with a further increase in sample temperatures (i.e., at test temperatures of 617 °C and 630 °C), this decreasing trend in particle velocity is reversed and the particle velocities are observed to increase at the highest temperatures employed in these experiments.



(**a**) (**b**)

Figure 2. Wave-front and the plateau regions of the measured free surface particle velocity profiles used to estimate: (**a**) the dynamic material stress at the onset of plasticity in commercial purity polycrystalline magnesium samples in the temperature range of 23–630 °C; and (**b**) Longitudinal plastic impedance of the shocked magnesium samples in the temperature range of 23–630 °C.

Based on Equation (2), the plastic impedance of the magnesium flyer (sample) at different test temperatures are estimated. The longitudinal (plastic) impedance of magnesium samples decreases continuously from 7,312,862 to 5,851,555 kg/m²s as the sample test temperatures are increased from room temperature to 610 °C. At the highest test temperatures, this trend is observed to reverse and the longitudinal impedance increases to 6,413,393 and 6,417,704 kg/m²s at 617 °C and 630 °C, respectively, which indicates an increase in material strength.

The through-thickness cross section in the central region of the post-test shocked magnesium samples was chosen for microstructural analysis. The recovered samples were first sectioned using a low speed diamond saw, and then polished and etched using 10% nitric acid in distilled water for ~30 s to identify the grain boundaries and twin bands. The etched surface was rinsed using ethanol and air dried and then immediately transferred into the SEM vacuum chamber to minimize surface oxidation. The SEM images in Figure 3 show intense twinning at 23 °C due to the restricted number of independent slip systems in magnesium. As the test temperatures increase from room temperature to 610 °C, the number density of twins decreases progressively. However, this trend is observed to reverse at the highest test temperatures used in the study (617 °C and 630 °C), where the shock impedance of magnesium is observed to increase with increasing temperatures. An anomalous increase in the twinning activity is observed for samples tested at 630 °C. The higher twinning activity is indicative of possibly higher material strength, thus favoring twinning over slip to accommodate the dynamic plastic deformation.

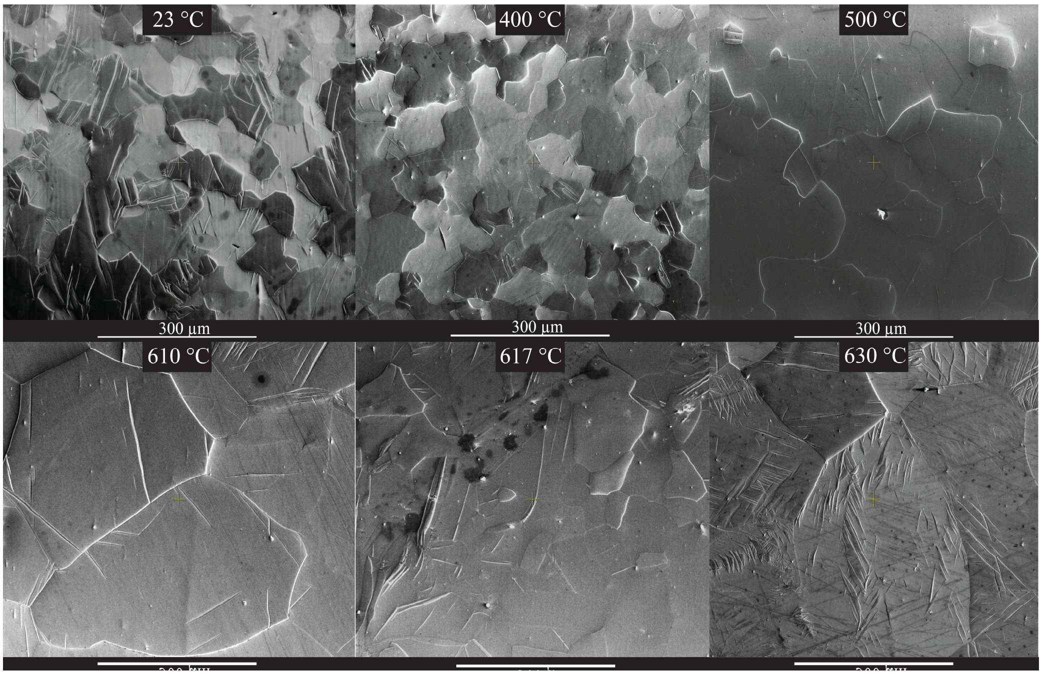


Figure 3. SEM images of commercial purity (99.9%) magnesium showing the central region on the cross-section of shock-compressed samples recovered from normal plate impact experiments.

4. Conclusions

In the present study, a series of normal plate impact experiments are conducted on commercial purity (99.9%) polycrystalline magnesium at test temperatures in the range of 23–630 °C. To conduct the elevated temperature experiments, strategic modifications were made to the single stage gas-gun facility at Case Western Reserve University. An in-house built custom fiber optics-based heterodyne interferometer is utilized to measure the normal particle displacement at the rear surface of the target plate. The measured particle velocity profiles are used to gain insights into the temperature dependence of the dynamic material strength at incipient plasticity as well as the longitudinal impedance of magnesium in its shocked state. The results indicate progressively lower dynamic yield and flow strengths for the samples as the test temperatures are increased from room to 500 °C. However, as the test temperatures approach the melting point of magnesium (i.e., 617 °C and 630 °C), a clear reversal in this trend is observed. Further, the longitudinal (plastic) impedance of magnesium in its shocked state is observed to decrease continuously as the test temperatures are increased from room to 610 °C. However, at the highest test temperatures, this trend is also observed to reverse, indicating an increase in the material's stress carrying capability. Post-test SEM images of the samples indicate an anomalous increase in twinning at test temperatures of 617and 630 °C, indicating an anomalous growth in dynamic strength as temperatures approach the melting point of magnesium.

Author Contributions: T.W., B.Z. and V.P. conceived and designed the experiments; T.W. and B.Z. performed the experiments; T.W. and B.Z. analyzed the data; T.W., B.Z. and V.P. wrote the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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