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13. Dynamic behavior of metals at elevated temperatures and ultra-high strain-rates †

Tianxue Wang [1], Bryan Zuanetti [1] and Vikas Prakash [1,*]

[1] Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH 44106.
Emails: txw208@case.edu, bxz135@case.edu, vikas.prakash@case.edu.
* Correspondence: vxp18@case.edu; Tel.: +01-(216) 368-6440 (office), +01-(330) 998-2845 (cell)
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Abstract: This paper presents 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 and elevated temperatures up to melt. Strategic modifications made to the existing single-stage gas-gun facility enable dynamic material behavior characterization under extreme conditions, i.e. ultra-high strain-rates (~10^6/s) and test temperatures up to 1000 °C. In this custom configuration, thin metal samples (flyer plate) carried by the specially designed heat-resistant sabot are allowed to be heated uniformly across the diameter in a 100 mTorr vacuum prior to impact by a resistance coil heater with axial and rotational degrees of freedom at the breech end of the gun barrel. Moreover, a compact fiber-optics-based heterodyne combined normal and transverse displacement interferometer is designed and implemented. Like the standard PDV, this diagnostic tool is assembled using commercially available telecommunications hardware and uses a 1550 nm wavelength 2W 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 melt point of magnesium) 99.9% polycrystalline magnesium using Inconel 718 target plates at impact velocities ranging from 100 m/s to 110 m/s. The stress at flyer/target interface, as inferred from the measured normal particle velocity history at the free (rear) surface of the target plate shows progressive weakening with increasing sample temperatures below melt; at higher test temperatures, the rate of softening in stress is observed to weaken and even reverse as the sample temperatures approach the melt point of magnesium samples. Scanning electron microscopy is utilized to understand the evolution of sample material microstructure 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 owing to their high specific strength to weight ratio relative 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, knowledge of the mechanical response of HCP materials at thermomechanical extremes (i.e. ultra-high strain-rates and test temperatures up to melt) 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, 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 accommodation of c-axis plastic deformation. In this case, despite the higher CRSS of the $\langle c + a \rangle$ pyramidal slip than 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 each slip system has been investigated in quasi-static strain-rate regime. The basal slip was observed to be nearly independent of temperature, however lower CRSS of prismatic and $\langle c + a \rangle$ pyramidal slip have been measured when the temperature is increased. Additionally, it is well established that increasing the strain-rate increases the CRSS of slips by decreasing the time for a given dislocation to overcome a barrier to its motion. At extremely high strain-rates, the dislocation motion can be further hindered by mechanisms such as phonon drag.

Owing to the restricted number of the independent slip systems, plastic deformation in HCP magnesium involves twinning mechanisms which always lead to reorientation of the crystal lattice around a given plane and in a given direction, thus change the favorability of the deformation modes within the twinned regions and introduce rather complicated material behaviors compared to those of twin-free metals. Deformation twinning is particularly important at high strain-rates, where it has been observed that twinning becomes more prevalent. Three types of twinning modes are commonly observed in magnesium: extension twinning, contraction twinning and double twinning. Due to the relatively low CRSS, extension twinning is understood to be the most easily activated twin system in magnesium. The CRSS of extension twinning is known to be insensitive to either temperature or strain-rates. In contrast, the CRSSs of contraction twinning and double twinning are observed to decrease with increasing temperature and strain-rates. At high strain-rate regime in the range 10^4 to 10^6/s, annealed pure magnesium single crystals were shock-loaded at temperatures ranging from 20 to 503 °C [1]. In these experiments, Hugoniot Elastic Limit (HEL), corresponding to the dynamic strength under uniaxial strain shock compression was observed to increase with increasing temperatures along both the c-axis and at 45° to c-axis. Despite the advances in our understanding regarding the dynamic behavior of magnesium, significant questions still remain — in particular with regards to whether hcp metals exhibit an increase in strength for all orientations at elevated temperatures and ultra-high strain-rates.

The present series of experiments 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 up to the melt point of magnesium, which can aid in providing a better understanding of the dominant deformation mechanisms in polycrystalline magnesium under extreme thermomechanical conditions.

2. Materials and Methods

The experiment involves the impact of a 99.9% pure 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 select physical properties of 99.9% pure polycrystalline magnesium and Inconel 718 are provided in Table 1. The dimensions of the magnesium flyer plate are 76 mm diameter and 5.6 mm thickness. The dimensions of the Inconel 718 target plate are 25 mm diameter and 7 mm thickness. Both sides of the flyer and the target plates are ground flat to within 12 μm and then 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 [4-6].

The addition of the heating elements to the impact chamber of the gas-gun to heat the target assembly has been shown to be feasible, however, this method leads to several experimental challenges: first, while the target assembly is heated, various elements of the target holder and/or the alignment-fixture are subjected to differential thermal expansion at elevated temperatures, thus requiring remotely controlled alignment adjustment tools with continuing feedback for maintaining parallelism between the flyer and target plates; second, possible thermal softening could result in the yielding of the heated target plate that must remain elastic during impact to allow unambiguous interpretation of the experimental results; and lastly, possible thermal softening could result in the yielding of the heated target plate that must remain elastic during impact to allow unambiguous interpretation of the experimental results.

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

Material	**Density** (Kg/m^3)	**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 to the single-stage gas-gun at CWRU [7] are made to enable heating the flyer plate carried by a heat-resistant sabot at the breech end of the gun barrel, as shown in Figure 1 (a). The schematic of the reverse geometry normal plate impact experimental configuration is shown in Figure 1 (b). To ensure the generation of plane-waves with a wave front sufficiently parallel to the impact face, the flyer and target plates are aligned to be parallel to within 5×10^{-4} radians by using an optical alignment scheme. 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 to 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 combined NDI/TDI [8] 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.

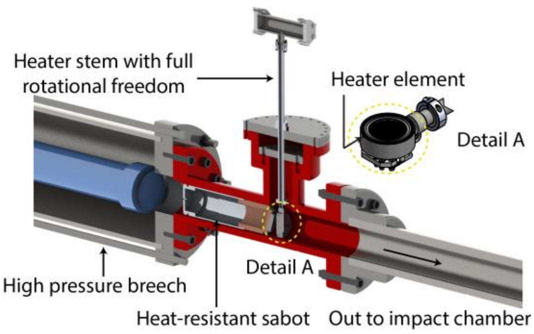

Figure 1 (a). Schematic of the custom designed heater system with axial and rotational degrees of freedom at the breech-end of the gas gun

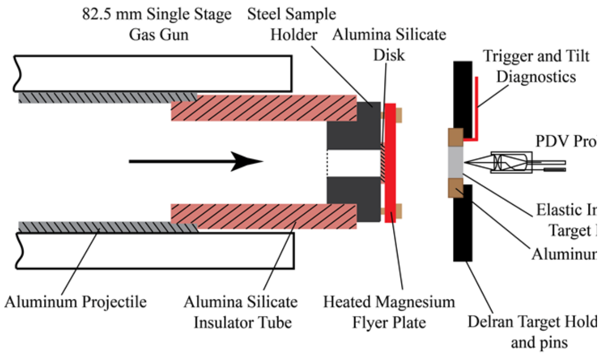

Figure 1 (b). Schematic of the elevated temperature normal plate impact experimental configuration used in the present study

Using a simple wave strain-rate independent longitudinal wave analysis, the dynamic material stress in the heated magnesium sample at the target-flyer interface, $\sigma_F(t'^n)$ can be estimated at 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 discritzed time interval represented as $t^n = nh$, where h is the inverse of the sampling rate of the oscilloscope. And denoting $t^n - L/C^n$ 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 denoted 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

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

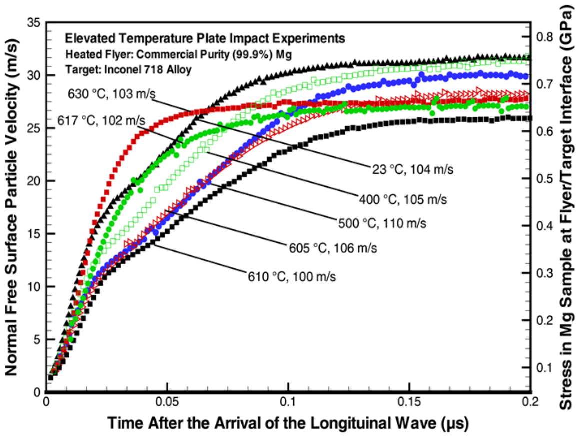

Figure 2 (a). The onset of incipient plasticity in commercial purity 99.9% polycrystalline magnesium samples in the temperature range 23 to 630 °C.

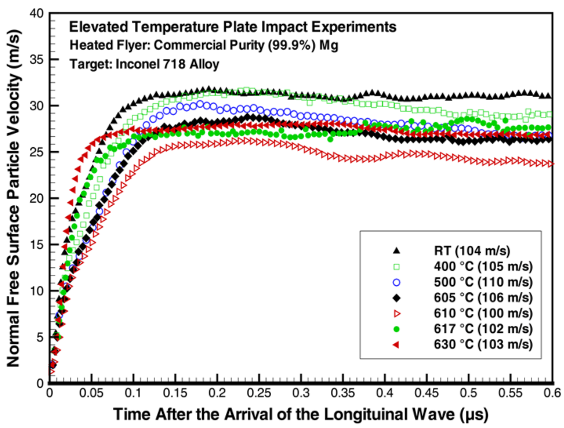

Figure 2 (b). Shock impedance of commercial purity 99.9% polycrystalline magnesium samples in the temperature range 23 to 630 °C.

3. Results and Discussion

Figure 2 (a) shows the free surface particle velocity versus time record obtained a series of seven normal plate impact experiments conducted on commercial purity (99.9%) polycrystalline magnesium samples at test temperatures in the range from room to near melt (~630 °C) under dynamic uniaxial strain shock compression. 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 (strength) in the magnesium samples at the interface between the flyer/target plates at onset of plasticity and post-yield, while the particle velocity level in the plateau region is correlated to the longitudinal impedance of the flyer and target plates via Eqn. (2). 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 from 500 to 610°C, indicating that dynamic strengthening mechanisms come into play that compete with thermal softening. At even higher test temperatures, approaching the melt 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 in the range 23 to 610 °C. In addition, the free surface particle velocity at the wave-front is observed to increase nearly linearly before reaching a plateau at 617 °C and 630 °C, where strengthening effects overtake the thermal softening. In Fig. 2 (b), it is observed that the levels of particle velocities at plateau decrease continuously as the test temperatures are increased from room temperature to 610 °C. As the sample temperatures are increased, the decreasing trend in particle velocity is reversed and the particle velocity is observed to increase at test temperatures of 617 °C and 630 °C.

Based on Eqn. (2), the plastic impedance of magnesium flyer (sample) at different test temperatures are estimated. The longitudinal (plastic) impedance of magnesium samples decrease continuously from 7312862 to 5851555 kg/m^{2}s as the sample test temperatures are increased from room to 610 °C. At even higher test temperatures, this trend is observed to reverse and the longitudinal impedance increases to 6413393 and 6417704 kg/m^{2}s at 617 °C and 630 °C, respectively, indicating an increase in material strength.

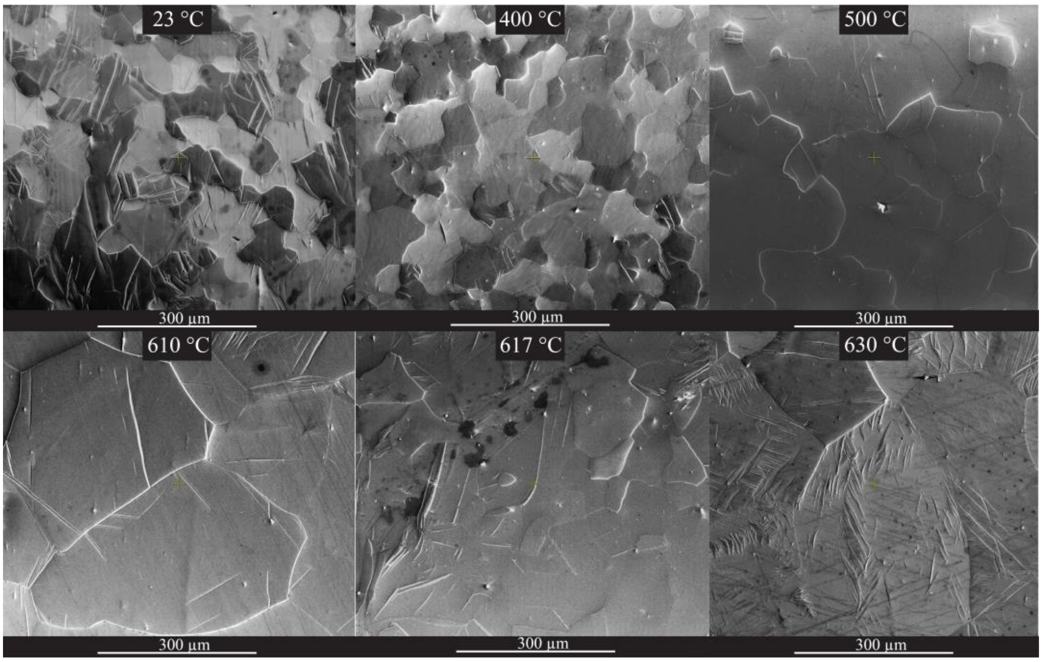

Figure 4. SEM images of 99.9% commercial pure magnesium showing the central region on the cross-section of shock compressed samples recovered from normal plate impact experiments.

The central region of the shocked magnesium sample was chosen for microstructural analysis as this region is the least affected by the unloading waves from the boundary. The recovered magnesium samples were first sectioned using a low speed diamond saw, polished, and then 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. Then the sample was immediately transferred into the SEM vacuum chamber to minimize the surface oxidation of magnesium. The SEM images in Figure. 3 show intense twinning at 23 °C due to the restricted number of the independent slip systems in HCP magnesium at room temperature. As the temperature increases from room temperature to 610 °C, the number density of twins decreases progressively with increasing temperature. However, this trend reverses at even higher test temperatures of 617 °C and 630 °C where the shock impedance of magnesium is observed to increase with increasing temperatures. An anomalous increase in 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 in magnesium.

4. Conclusions

In the present study, a series of normal plate impact experiments on 99.9% pure polycrystalline magnesium have been conducted at test temperatures in the range 23 to 630°C. To achieve the designed test temperatures without encountering the conventional experimental challenges, a unique approach which is capable to conduct normal and/or combined pressure-shear plate impact experiments with initial sample temperatures up to 1000 ˚C is utilized. Additionally, an in-house built custom fiber optics-based heterodyne combined NDI/TDI is utilized to measure the normal particle displacement at the rear surface of the target plate. The measured free-surface particle velocity profiles are used to gain insights into the temperature dependence of dynamic material stress at incipient plasticity as well as the longitudinal impedance of the commercial purity polycrystalline magnesium. The results indicate progressively lower dynamic stresses for the shock loaded magnesium as the test temperatures are increased from room temperature to 500 °C, whereas, no apparent net change in the dynamic material stress is observed at test temperatures from 500 to 610°C, at even higher test temperatures, approaching the melt point of magnesium (617 °C and 630 °C), a clear reversal in this trend occurs. The longitudinal (plastic) impedance of magnesium samples decreases continuously as the sample test temperatures are increased from room to 610 °C, however, as the sample temperatures are increased to 617 °C and 630 °C, this trend is observed to reverse indicating an increase in material strength. From the scanning electron microscopy, unexpected higher twinning activity is observed at test temperatures of 617 °C and 630 °C where the shock impedance of magnesium is observed to increase with increasing temperature.

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

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