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On the residual yield stress of shocked metals

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Abstract.

Precise measurement of the free-surface velocity can be a rich source of information on the effects of time and strain on material strength. With this objective, we performed a careful comparative measurement of the free-surface velocity of shock loaded aluminium AD1 and magnesium alloy Ma2 samples of various thicknesses in the range 0.2 mm to 5 mm. We observed the expected decay in the elastic precursor state with increasing sample thickness for both aluminium and magnesium alloy. However, we also observed a small change in the magnitude of hysteresis in the elastic-plastic compression-unloading cycle; where qualitatively the peak free-surface velocity also increased with increasing specimen thickness. Interestingly, the observed change in hysteresis as function of specimen thickness for the Ma2 alloy was relatively smaller than the AD1, in contrast with the larger change in precursor magnitude observed for the magnesium. We propose that softening due to multiplication of dislocations is relatively large in Ma2 and results in a smaller hysteresis in the elastic-plastic cycle.

1. Introduction

The strength of metals under ultra-high strain-rate loading has been extensively studied for many decades. While there has been significant progress; relating the underlying micro-scale phenomena such as dislocation generation, motion, and interaction to the observed macroscopic material response remains a formidable problem. In particular, measurement of the strength of a material in a compressed state remains experimentally challenging. Nonetheless, several techniques have been developed which directly, or indirectly give a measure of compressive strength at high pressures and strain-rates, these include; comparison to hydrostatic response, lateral-stress measurement using embedded transducers [1], pressure-shear loading [2], x-ray diffraction [3], growth of Rayleigh-Taylor instabilities [4], magnetically applied pressure-shear [5], and the self-consistent strength measurement method [6]. In general however, these methods can be practically difficult to implement, sometimes require restrictive assumptions, and are obviously not free from experimental uncertainties. Consequently, it is always desirable to find additional experimental geometries or methods which can contribute towards the understanding of material strength under dynamic loading.

In this sense, careful measurements of the magnitude of hysteresis in the elastic-plastic compression-unloading cycle may provide complementary data to more direct strength measurements. The peak free-surface velocity (u_{fs}) of a weakly shocked elastic-plastic material should be slightly less than twice the particle-velocity (u_p) behind the shock front [7]; this difference being proportional to the yield stress in the shocked state. In the case of an ideal elastic-plastic material the difference or magnitude of hysteresis Δu is:

$$-\Delta u = 2u_p - u_{fs} = \frac{u_{HEL\_fs}}{2}\left(\frac{C_l}{C_b} - 1\right), \tag{1}$$

where u_{HEL_fs} is the free-surface particle velocity at the Hugoniot Elastic Limit (HEL), and C_b and C_l the bulk and longitudinal sound speeds respectively [7]. Equation (1) suggests that at least in the ideal case, the magnitude of the hysteresis is directly proportional to the HEL.

However, many metals have been observed to exhibit the phenomenon of precursor decay [8], where for thin samples (typically less than several mm) the magnitude of the HEL relaxes with propagation distance as a result of the kinetics of plastic flow. For a material demonstrating precursor decay, the amplitude of the HEL as measured at the free-surface increases with decreasing specimen thickness. Consequently, taking a simplistic view, inspection of equation (1) suggests we might also expect a corresponding change in the magnitude of hysteresis and hence peak free-surface velocity with specimen thickness.

In this study we present some initial measurements of hysteresis in the elastic-plastic compression-unloading cycle during planar shock loading of aluminium AD1 and magnesium alloy Ma2-1 specimens of different thickness. The main difficulty in making such measurements is that any change in the magnitude of hysteresis is manifest by a small change (order few m s^{-1}) in the peak free-surface velocity. To be sensitive to such small changes it was necessary to simultaneously load specimens of different thickness whilst monitoring the rear surface velocity of each sample using Photonic Doppler Velocimetry (PDV). This paper presents the experimental method, initial results, and draws some limited conclusions. Future efforts involving appropriate rate-dependant simulations will attempt to improve our interpretation of the measured results and reconcile them with more direct measurements of material strength.

2. Materials

Two previously well characterised materials were selected for this initial study; a commercially pure aluminium, AD1, (average grain size 100-125 μm, $C_b = 5350 \pm 20$ m s^{-1}, $C_l = 6400 \pm 5$ m s^{-1}) [9], and magnesium alloy Ma2-1 (average grain size 20-30 μm, , $C_b = 4500 \pm 20$ m s^{-1}, $C_l = 5735 \pm 5$ m s^{-1}) [10]. Both materials have been observed to demonstrate precursor decay in the regime to be investigated making them suitable candidates to investigate hysteresis in the loading-unloading cycle. The aluminium AD1 specimens were prepared from a larger 100 mm diameter rod and annealed for 20 minutes at 450 ^{o}C. The specimens were nominally 25 mm in diameter with a thickness in the range 0.18 mm to 5 mm. Each specimen was hand lapped and polished to the desired thickness and surface finish. The magnesium alloy specimens were prepared in a similar manner from rod stock and also annealed for 20 minutes at 450 ^{o}C.

3. Experimental Method

Plate-impact experiments were performed using the 100 mm bore single stage gas gun at Imperial College London, UK. The experimental configuration is shown in figure 1, where an array of six specimens, of varying thickness in the approximate range 0.2 mm to 5 mm were mounted on the rear of an aluminium Al6061-T6 driver plate. The impact of an aluminium (Al6082-T6) flyer on the driver generated a shock wave which loaded the specimens. The samples were clamped onto, but offset from the rear surface of the aluminium driver plate using a 50 μm aluminium

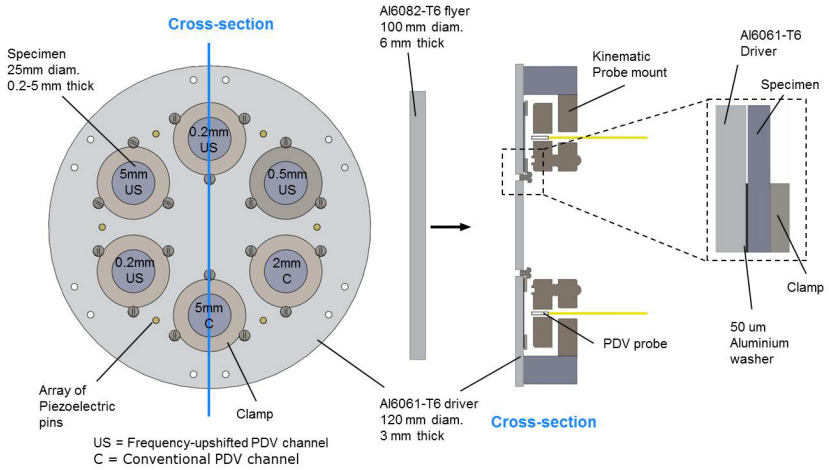

Figure 1. Schematic of the multi-target assembly showing the top down view together with a cross-section. A detailed view shows the specimen clamp arrangement.

washer. This geometry avoided contamination of the measured wave profiles by the elastic-plastic behaviour of the aluminium driver. Impact tilt was measured to be less than 0.5 mrad using an array of 3 piezoelectric pins lapped flush to the impact surface of the aluminium driver.

The free-surface velocities of the six specimens were measured using a combination of four frequency-upshifted [11] and two conventional configuration PDV [12] channels as indicated in figure 1. The frequency-upshifted PDV employed two lasers operating with wavelengths near 1550 nm generating a zero velocity beat frequency in the region of 7 GHz, sufficiently high to facilitate the nanosecond resolution required to diagnose shock structure in thin foils. The conventional PDV measurements were obtained from the homodyne mixing of the reflected Doppler shifted signal and a designated reference signal split from the source laser. Light was delivered and collected from the specimens using AC photonics probes with -60 dB back reflectance, a nominal spot size of 400 μm, and were aligned to the rear surface of the specimen using gimble mounts. The resulting beat signals were measured with 12.5 GHz bandwidth receivers sampled at up to 50 GS/s. An additional conventional PDV channel also measured the impact velocity of the aluminium flyer.

4. Results and Discussion

We present the results from two plate experiments, the first on aluminium AD1 specimens, and the second using Ma2 samples, both performed with an impact velocity in the region of 450 m s^{-1}. The raw PDV beat signals were processed using STFT (Short-Time Fourier Transform) techniques [12], yielding a spectrogram displaying the distribution of spectral power density as a function of time and frequency for each channel. The STFT analysis necessarily leads to a trade off between velocity uncertainty and temporal resolution. In the present study the rear surface velocity histories recorded using the frequency-shifted PDV channels were extracted using a Hamming window function with 75% overlap, of time duration $\tau = 2.5 - 5$ ns ($\tau = 2.5$ ns used to resolve the HEL, $\tau = 5$ ns used in the analysis of the peak state), and 20000 frequency bins in the STFT analysis. The final velocity was extracted from a Gaussian fit to the peak frequency of the power spectrum. The conventional PDV channels encoded the velocity histories with a lower beat frequency (< 1 GHz) and hence required a longer Hamming window in the range of 20-25 ns to adequately resolve the velocity histories. The limitations in temporal resolution and the ability to resolve low velocity features such as elastic precursors when using

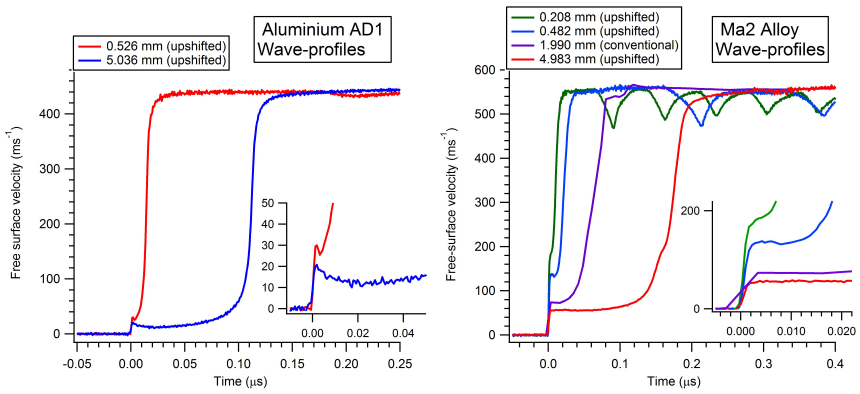

Figure 2. Rear surface velocity histories obtained for the aluminium AD1 (left) and magnesium alloy Ma2-1 (right) specimens. The plot legends indicate the type of PDV measurement upshifted/conventional and the specimen thickness. The timebase has been offset to align the elastic precursor for each trace. The inset presents a magnified view demonstrating the magnitude of precursor decay evident for both materials.

conventional (homodyne) PDV are well documented [11]. Unfortunately, in the present study, these limitations prevented adequate resolution of the wave profile to make quantitative analyses possible and consequently not all conventional PDV channels are considered in the following analysis. A number of the frequency-upshifted PDV also demonstrated poor resolution of the wave profile for some of the thin foils tested and are also not considered further.

Figure 2 shows the measured free-surface velocity histories indicating a two-wave structure for both the aluminium AD1 and magnesium alloy specimens. The profiles clearly demonstrate the expected decay in the magnitude of the elastic precursor with increasing specimen thickness whereas any difference in the peak free-surface velocity is less obvious. The magnitude of decay and structure of the precursor wave are consistent with previous studies [9, 10], providing confidence that the PDV has adequately resolved the wave profile.

In order to examine any change in the magnitude of hysteresis present in the loading and unloading cycle it was necessary to normalise the wave-profiles with respect to sample thickness. This minimises any differences between wave profiles that scale linearly with thickness; such as the wave reverberations of the elastic precursor from the free-rear surface which give rise to apparent steps in the peak free-surface velocity [7]. Figure 3 plots the normalised wave-profiles. It is evident that the peak-surface velocity increases with increasing sample thickness as expected from equation (1). Figure 4 presents quantitatively this qualitative observation. The peak state was determined from an average over a defined region of the plateau for each wave profile (indicated by the dotted rectangular regions in figure 3). Uncertainty in the peak state was estimated from the maximum and minimum velocity values in the selected region in a similar manner to Dolan [11]. Uncertainty in the HEL was conservatively estimated from the full range of velocities observed between the first and second wave arrivals. We assume that by selecting an appropriate late time region of the free-surface velocity history (where the plateau appears constant in normalised distance time plot shown in figure 3) we obtain the best estimate for the complete unloading within the bulk of material, free from surface effects associated with the reverberation of the elastic precursor [7].

Figure 4 plots the relative peak-surface velocity as a function of the relative elastic precursor state for both the AD1 and Ma2 specimens. The relative peak state was calculated from the difference in peak-surface velocity measured for each specimen and that for the 5 mm thick

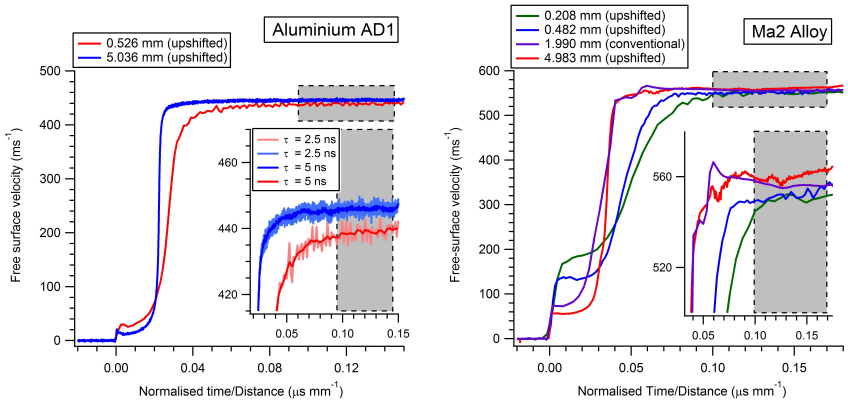

Figure 3. Normalised velocity histories obtained for the aluminium AD1 (left) and magnesium alloy Ma2-1 (right) specimens. The velocity data plotted were reduced using $\tau = 2.5$ ns STFT analysis windows. The timebase for each trace has been normalised by dividing by the specimen thickness to enable comparison of approximately equivalent states between specimens of different thickness. The inset in each plot presents a magnified view of the peak-velocity region, clearly demonstrating that the peak-surface velocity increases with increasing sample thickness as expected. The AD1 inset demonstrates the benefit from using $\tau = 5$ ns rather than $\tau = 2.5$ ns when determining the peak state. The dashed grey rectangles indicate the specific regions averaged to estimate the peak velocity state. Uncertainty in the peak state was from the maximum and minimum variations in the assumed constant peak state.

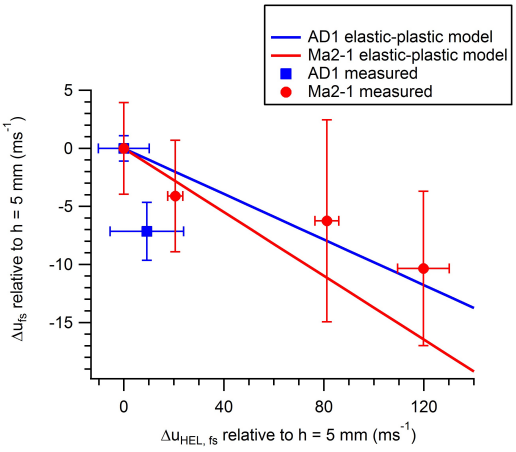

Figure 4. A plot of the relative change in peak-surface velocity as a function of the relative magnitude of the elastic precursor for both AD1 and Ma2. Both variables are plotted relative to the values measured for the 5 mm thick sample in each case, assumed to best represent the bulk material response free from relaxation phenomena. The solid lines indicate an estimate for the relative change in peak-surface velocity assuming ideal elastic-plastic behaviour given by equation (1).

sample, believed to be the most representative of the bulk material response. The relative precursor state was determined in a similar manner. The error bars plot the uncertainty in the difference values, estimated using standard error propagation of the uncertainty in the measured states used in the calculation. For comparison, figure 4 also plots the expected magnitude in hysteresis according to equation (1) using the presented material parameters for AD1 and Ma2 [9, 10]. From figure 4 it is evident that both materials demonstrate an increase in hysteresis with decreasing specimen thickness and hence increasing precursor magnitude. Aluminium demonstrates a significantly greater hysteresis than predicted from equation (1). In comparison, the magnesium alloy more closely matches the idealised elastic plastic model demonstrating if anything a smaller degree of hysteresis than predicted.

Further interpretation of these results, into for example a simple measure of material strength in the shocked state, is complicated as the observed change in peak free-surface velocity is necessarily a convolution of all of the time-dependent, thermal, and micro-structural effects which occur both during loading and unloading. For example, during loading the plastic strain-rate immediately behind the elastic precursor has been reported to reduce by approximately two orders of magnitude over the investigated sample thicknesses for both pure aluminium [8, 9] and the Ma2 alloy [10]. The strongly rate-dependent behaviour which gives rise to the dependence of the precursor magnitude on specimen thickness can equally, at sufficiently short time-scales influence the peak shock state, or more significantly the unloading process. Obviously, the ideal elastic-plastic behaviour described by equation (1) is an oversimplification and it is no surprise that the measured hysteresis data differs from that predicted. Nonetheless, a possible explanation for the observed difference in behaviour between AD1 and Ma2 may be a relative softening of the magnesium alloy caused by an intense multiplication of dislocations during the compression, a mechanism previously suggested to occur in this alloy [10].

5. Conclusions

We report preliminary measurements of the hysteresis in the compression-unloading cycle as a function of sample thickness for AD1 and Ma2-1 by employing a multi-target assembly interrogated using an array of PDV channels. Frequency-upshifted PDV demonstrated sufficient temporal and velocity resolution to both resolve the well documented precursor decay and the until now unreported small differences in the peak free-surface velocity for thin foil samples (200 μm). We observed an increase in peak-surface velocity with increasing specimen thickness, demonstrating a greater degree of hysteresis in the compression-unloading cycle for thin specimens. However, significant further efforts are required both in terms of interpretation and additional experiments for this to be conclusive. In particular, simulations capturing the rate-dependant and observed relaxation phenomena need to be performed to understand the complex interactions occurring near the released rear surface of the specimen. While efforts are ongoing to understand these details, it is hoped that when coupled with other experimental methods which more directly measure strength in the shocked state, this technique will provide a rich source of data for validation of dynamic strength models.

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