International Journal of Impact Engineering 100 (2017) 56–61

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Dynamic strength measurement of aluminum under magnetically driven ramp wave pressure-shear loading

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ARTICLE INFO

Article History:
Received 10 August 2016
Revised 21 October 2016
Accepted 25 October 2016
Available online 1 November 2016

Keywords:
Dynamic compression
Strength measurement
Magnetic loading
Ramp wave
Pressure-shear loading

ABSTRACT

The strength of a material at high pressure is an important physical parameter in shock physics and material science. In this work, a magnetically applied pressure shear loading technique, combining magnetically driven longitudinal and shear waves, was developed to measure material strength in high pressure and high strain rate experiments. Using theoretical and numerical analysis, we obtained a relationship between the deviatoric stresses and the yield stress, and demonstrated the strength calculation method. Experiments were then conducted on pulsed power generator CQ-4, with a newly established quasi-static magnetic field generator to produce shear stresses, and transverse velocity measurement techniques to determine the results. The experiments measured the strength of polished and cold rolled aluminum at high pressure. The strength of polished aluminum agreed well with previous data measured using self-consistent methods under ramp wave loading. The strength of cold rolled aluminum was larger due to differences of initial plastic deformation. Meanwhile, the strength of both polished and cold rolled aluminum increased with pressure.

1. Introduction

The strength of material plays an important role in many dynamic processes such as armor penetration, debris shielding for spacecraft, and the growth of instabilities in the fuel capsules of inertial confinement fusion experiments. In order to model structure failure under high strain rates and high pressure loadings, accurate measurements of the strength and constitutive relations of materials are required besides equation of states. Up till now several methods have been developed to measure these parameters including: the hydrostatic comparison method [1], lateral stress gauges [2–4], pressure-shear impact loading [5, 6], the growth of Rayleigh–Taylor instabilities [7,8], and the self-consistent method [9,10]. However as each technique accesses different stress states, uses different loading strain rates, and introduces different temperature increments, the values of strength obtained are sparsely scattered over a wide range of pressure, density and temperature parameters [11,12]. Further many techniques use gross assumptions in their calculation of strength, potentially leading to large errors in measurements. It is necessary to develop new measurement methods and minimize assumptions in material strength calculations under high pressure, which will help reveal how pressure, temperature, strain rate, initial deformation and polycrystalline structure affect material strength. Magnetically driven ramp wave compression offers a way to study material strength under quasi-isentropic compression to several hundred GPa, and strength measurement techniques based on the self-consistent method under ramp wave compression have been greatly developed in past several years [13–20]. Recently, a more direct measurement of material strength under high pressure - magnetically applied pressure-shear (MAPS)– has been explored by Alexander [21], and this new method shows great potential. In this work, we further developed the magnetic applied pressure-shear loading technique at Institute of Fluid Physics, CAEP. We analyzed the stress state of material under combination of uniaxial compression and transverse shear loading, and compared this to detailed numerical simulations. To perform this work, we developed a quasi-static magnetic field generator coupled to pulsed power generator CQ-4 [22,23], and conducted the strength measurement experiments of both polished and cold rolled aluminum. The results show that polycrystalline structures have obvious effects on material strength.

2. Principle of strength measurement under magnetic pressure-shear loading

When a large current flows through a strip-line conductor loop, and intense magnetic field is generated in the loop gap. If an external quasi-static magnetic field B_0 is applied perpendicular to the current J and its self-induced magnetic field B, the conductor will suffer longitudinal force, $J \times B$, and shear force, $J \times B_0$, at the same time as

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http://dx.doi.org/10.1016/j.ijimpeng.2016.10.010
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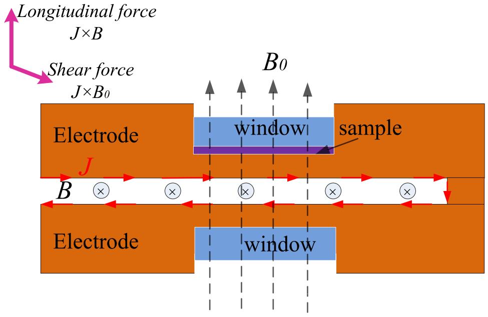


Fig. 1. Sketch of magnetically driven compression and shear combination loadings.

shown in Fig. 1. The stresses generate at the inner surface of conductor and propagate into sample and then to window. By measuring the free surface velocity of window material, we can infer the loading pressure and the yield stress of sample at the peak pressure as illuminated below.

2.1. Stress analysis at pressure-shear state

Under uniaxial pressure and one dimensional shear loadings, the stress tensor can be expressed as:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix} + \begin{bmatrix} 0 & S_{xy} & 0 \\ S_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{1}$$

where $\sigma_{yy} = \sigma_{zz}$, $S_{xy} = S_{yx}$. Providing the material yield behavior satisfies the Von–Mises criterion, the relation between stress tensor components and yield stress is

$$(\sigma_{xx} - \sigma_{yy})^2 + 3S_{xy}^2 - Y^2 = 0 \tag{2}$$

Rewriting the stress as the hydrostatic (spherical) and deviator parts, we get

$$(S_{xx} - S_{yy})^2 + 3S_{xy}^2 - Y^2 = 0 \tag{3}$$

Given that

$$\begin{aligned} S_{xx} + S_{yy} + S_{zz} = 0 \\ S_{yy} = S_{zz} \end{aligned} \tag{4}$$

we can then write

$$\frac{9}{4} {S_{xx}}^2 + 3{S_{xy}}^2 = Y^2 \tag{5}$$

Hence, under uniaxial pressure and one dimensional transverse shear loadings, the yield stress can be expressed as a function of deviatoric stresses. Under magnetically applied pressure-shear loading, deviatoric stress S_{xy} increases with discharging current, and S_{xx} decreases to zero when S_{xy} reaches yield surface. At this time, the relation of yield stress and deviatoric stress is therefore:

$$Y = \sqrt{3} S_{xy} \tag{6}$$

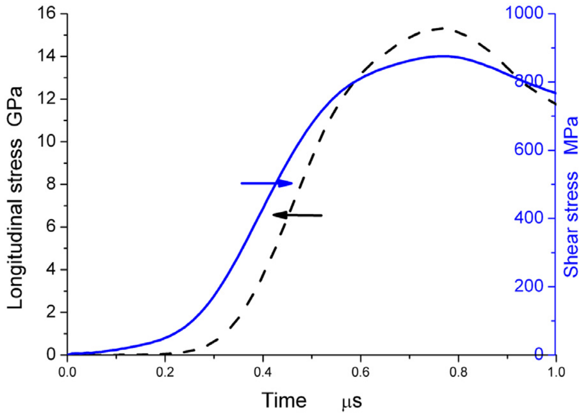


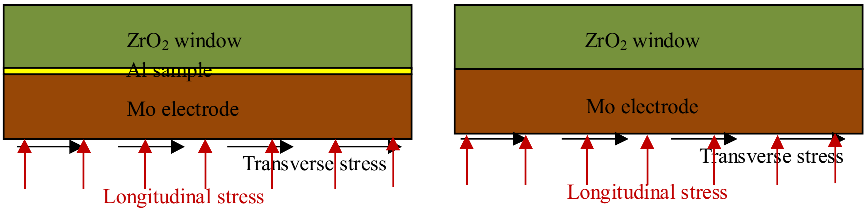
Fig. 3. Loading history of pressure-shear combination in computation model.

2.2. Numerical analysis of ramp wave pressure-shear loadings

The finite element solver, LS-DYNA 2D, was used to simulate how materials were expected to respond to magnetically applied pressure shear. The two sides of the stripline were modeled – one side had a ZrO2 window attached directly to a Mo stripline; the other included an Al sample between the window and the stripline (Fig. 2). The sizes of electrode, sample, and window were Mo 12 mm × 1.5 mm, Al 12 mm × 0.12 mm, and ZrO2 12 mm × 1.5 mm. The different stress inputs – longitudinal and shear - to the stripline were calculated from the current waveform of CQ-4 device. Gruneisen equation of states and SG constitutive models are used for Mo and Al, and kinematic hardening plasticity model is used for ZrO_2 crystal. Material model parameters are shown in Table 1.

The longitudinal and shear stresses at the sample position are shown in Fig. 4. Because the sample is thin, longitudinal stress waves rapidly reflect back and forth at the Mo/Al and Al/ZrO_2 interfaces and stress equilibrium is soon achieved in sample. Shear stress in sample is approximately uniform, but its amplitude is much lower than in the Mo / at the mo-ZrO2 interface. The difference is caused by the shear strength of pure aluminum being much lower than molybdenum. Due to the difference of longitudinal and transverse wave speed, maximum longitudinal and transverse stresses do not arrive at sample at the same time although they are generated isochronously. Note that longitudinal stress is almost invariable over a wide time window (100 s of ns) at the peak, hence shear stress just need to achieve the yield of sample material within the time window.

The relation of deviatoric stress and Von-Mises yield stress is shown in Fig. 5. When shear stress S_{xy} increases to yield surface, deviatoric stress S_{xx} decreases to zero. Deviatoric stress S_{xy}, S_{xx} and Von-Mises stress meet the confinement defined by Eq. (5) during loading process.



A. Mo-Al-ZrO_2 model B. Mo-ZrO_2 model

Fig. 2. Computation models of pressure-shear loadings.