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Yield strength measurement of shock-loaded metal by flyer-impact perturbation method

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ABSTRACT

Yield strength is one of the most important physical properties of a solid material, especially far from its melting line. The flyer-impact perturbation method measures material yield strength on the basis of correlation between the yield strength under shock compression and the damping of oscillatory perturbations in the shape of a shock front passing through the material. We used flyer-impact experiments on targets with machined grooves on the impact surface of shock 6061-T6 aluminum to between 32 and 61 GPa and recorded the evolution of the shock front perturbation amplitude in the sample with electric pins. Simulations using the elastic-plastic model can be matched to the experiments, explaining well the form of the perturbation decay and constraining the yield strength of 6061-T6 aluminum to be 1.31–1.75 GPa. These results are in agreement with values obtained from reshock and release wave profiles. We conclude that the flyer-impact perturbation method is indeed a new means to measure material strength.

1. Introduction

During the implosion process of nuclear weapon, ensuring the flying metal layer has stable spherical geometry is an important component to achieve a spherical implosion, so it is required that the shock wave driving the flying metal layer need to be shaped. Usually, the non-ideal spherical shock front with geometry disturbance damps, and eventually evolves into approximately spherical shock wave by the dissipation of energy and momentum in shocked material. It is very important to investigate the relation between the attenuation of the shock front with geometry disturbance and the material characteristics under high pressure and high temperature, especially the strength of relevant material [1]. Yield strength, which is one of important physical properties of a solid material, is focused in his paper.

Last century, Sakharov et al. [2] put forward an experimental technique, in which a shock wave with sinusoidal shock front is used to determine the material viscosity. They used an explosive to drive a shock into a driver machined a serial of sinusoidal grooves on the surface. When the shock came into the driver, a shock wave with sinusoidal perturbation shock front was created, then propagated into sample which was designed to wedge shape, thus the amplitude of the sinusoidal shock front perturbation in shocked material of sample attenuated with its thickness. The shock profile in sample was recorded by streak camera. Then Mineev et al. [3–7] reported more results for aluminum, lead, sodium chloride, water and mercury utilizing the same technique. For extracting the shear viscosity coefficients of above sample materials, Zaidel [8] used analytic solutions for the amplitude of perturbation at the shock front. Later Miller and Ahrens [9] reexamined Zaidel's solutions in details and reformed them for a more general non-uniform initial condition.

For using a two-stage light-gas gun to measure the damping of oscillatory perturbations of shock front, our group [10–14] modified Zaidel's experiment instead by flyer-impact perturbation experiments, some details will be discussed later. At the same time, we found the initial flow was very complex, it is could not characterized by Zaidel or Miller's initial condition, even it is difficult to find a mathematic equation to describe it. So, we proposed a finite difference analytic method [15] for actual experiments, and got the effective viscosity coefficients of aluminum and iron which were determined to be about 10^3 Pa·s.

However, the viscous coefficients deduced by the molecular dynamics simulation were only 10^{-3}~10^{-2} Pa·s [16–18] because the viscous characteristic depends on the momentum dissipation caused by atomic diffusion for liquid metals. Comparing above material viscosity value in different state, it can be deduced that the strength of solid is the

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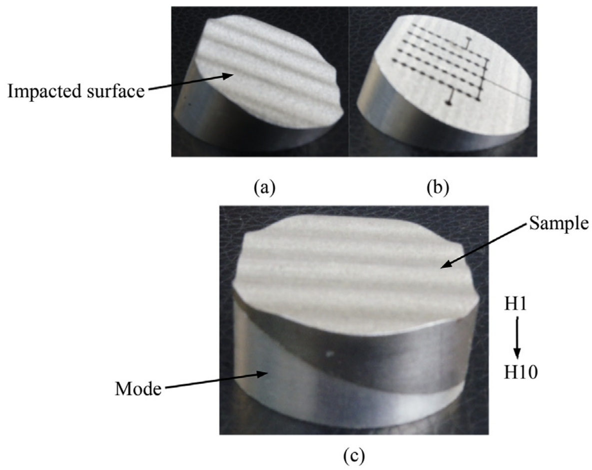

Fig. 1. (a) The wedged sample, (b) The mold for electric pins and (c)matching of the two parts.

significant factor to affect the effective viscosity. In fact, a solid material under shock loading remains solid, especially it is far from its melting line [19,20]. At our early paper [11] our group had noticed the influence of material strength on the damping process, and recently we found the strength tremendously influenced the oscillatory damping process of the disturbed shock front as same as its viscosity at early stage [21].

In this paper, the quantitative correlation between yield strength and the character of the amplitude of perturbation on the shock front will be discussed when 6061-T6 aluminum is shocked to 32–61 GPa. The evolution processes of shock front with propagation distance in shocked 6061-T6 aluminum are measured by flyer-impact perturbation method. The actual experimental procedures are simulated using the finite difference method. Then the yield strength of 6061-T6 aluminum can be obtained.

2. The flyer-impact perturbation experiment

The flyer-impact perturbation method is based on the correlation between the yield strength of shock compressed materials and the amplitude oscillation of an initial sinusoidal disturbance on shock front in concerned substance. Thus, how to produce and measure the disturbed sinusoidal shock wave in the shocked material are the key steps.

2.1. Sample and the generation of disturbed shock wave

The experimental configuration had been presented in our earlier papers [10–14]. Some details are summarized here. The sample with diameter of 28 mm was machined to be wedge shape, see Fig. 1(a), and some sinusoidal grooves with wavelength λ (6 mm or 8 mm) and depth h (0.3 mm or 0.4 mm) were processed on its impacted surface, the design parameters about the sample in every experiment shown in Table 1. The fabrication precision of our grooved sample is about 0.05 mm. For insulating the inclined surface of sample was coated by silica film with 50 μm thickness, the effect of which on the oscillation process of the perturbation was neglected.

When the high-speed planar flyer with diameter of 24 mm, which was glued to the front of the projectile launched by a two-stage light-gas gun, impacted the crests of grooves on the sample surface, a shock wave in it was formed. Until the flyer touched the troughs of the grooves, a shock wave with nearly sinusoidal disturbance was generated, which was the initial disturbed shock wave. The amplitude of this shock front was the initial amplitude a_0 which can be calculated by $(D\text{-}w)\,h/w$, in which h was the amplitude of grooves, w and D were respectively the velocity of flyer and shock wave. And then the disturbed shock wave started its oscillatory damping process which was governed by the yield strength of sample under high pressure.

In our experiments the speeds of the flyer were measured with a precision of 1% by an electromagnetic induction technique. The shock velocity was satisfied with the linear relationship of Rankine-Hugoniot $D = c_0 + sup$, the particle velocity up and shock pressure P were calculated from the impedance matching method, in which the initial density of aluminum ρ_0 was 2.704 g/cm^3 and its Hugoniot parameters c_0 and s are 5.35 km/s and 1.34 [22]. The uncertainty of Hugoniot parameters were about 2%, so the errors of some parameters in experiments can be calculated [23], which were shown in Table 1.

2.2. Evolution of the disturbed shock front

How to measure the evolution of the disturbed shock front in the shocked material? See Fig. 2, along the tilting back of sample ten electric pins as one column (pin column 3) were placed on the correspondence of trough of the groove on the sample surface and limited by mode (Fig. 1(b)). In actual experiments, there were other four pin columns facing crest (pin column 2 and 4) or trough (pin column 1 and 5) of the

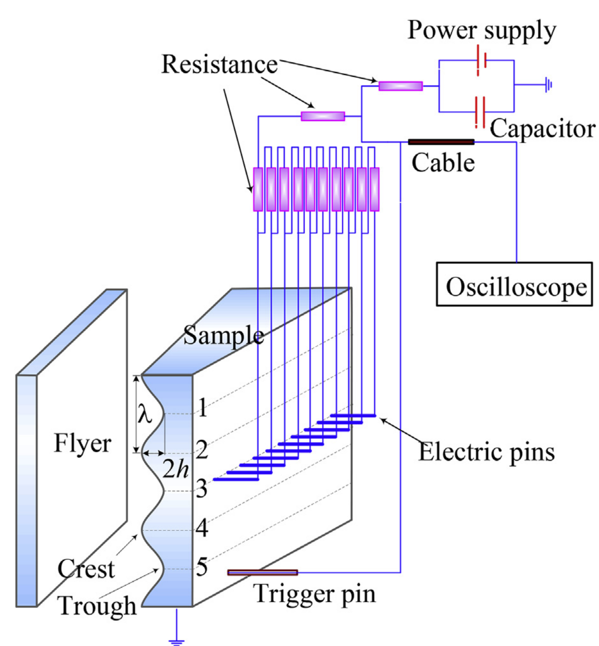

Fig. 2. The diagram of the flyer-impact experiment.

Table 1
The parameters in flyer-impact experiments.

Shot	λ(mm)	h(mm)	a_0(mm)	x/λ[a]	w (km/s)	D (km/s)	P (GPa)
119	6	0.3	0.41 ± 0.02	0.87 ± 0.02	3.15 ± 0.03	7.46 ± 0.12	31.57 ± 0.85
120	8	0.4	0.52 ± 0.02	0.86 ± 0.01	3.25 ± 0.03	7.50 ± 0.12	33.08 ± 0.89
121	6	0.3	0.23 ± 0.01	0.69 ± 0.01	4.87 ± 0.05	8.59 ± 0.14	56.71 ± 1.52
123	8	0.4	0.29 ± 0.02	0.64 ± 0.01	5.05 ± 0.05	8.71 ± 0.14	60.62 ± 1.61

[a] The relative distance value of the zero-amplitude point.