Dynamic Yield Strength and Spall Strength of Alumina Short Fiber Reinforced ZL109 Cast Aluminium Alloy

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ABSTRACT This paper describes the results of plate impact experiments conducted on a alumina short fiber reinforced ZL109 cast aluminium alloy. The loading was produced by a 100mm bore light gas gun. The metal-matrix composite specimen was backed with a PMMA. Manganin gauges were used to measure the normal stress history at the interface between the specimen and the PMMA. The dynamic yield strength and spall strength of the metal-matrix composite were determined.

1. INTRODUCTION

Short fiber reinforced metal-matrix composites (MMC) are a class of advanced materials. These composites have extensive potential for the use in aerospace, automotive and telecommunication industries due to their lower densities and superior mechanical properties. It is imperative therefore to study the dynamic mechanical response of such MMC. In this paper, we present our research results on the dynamic yield strength (Y_d) and spall strength (σ_f) of a cast aluminum alloy (ZL109) matrix based composite, reinforced with alumina short fiber (ZL109/ Al_2O_3). A discussion of the mechanical characterization of the material is given.

2. MATERIAL SPECIFICATION

The nominal composition (wt.%) of the cast aluminum alloy (ZL109) is: Al bulk, Si 12, Mg 1.2, Cu 0.9, and Ni 0.8. The short fiber metal-matrix composite (ZL109/ Al_2O_3) contains 15% (in volume) alumina short fiber of average characteristic size $7.5\mu m$. Optical micrographs (400X) of this composite taken perpendicular and parallel to the direction of the impacted face of the specimen are shown in Figures 1(a) and (b), respectively. From these micrographs it is evident that the short fiber are randomly distributed, and therefore the composite could be treated as isotropic material.

Static mechanical properties for ZL109/ Al_2O_3 are determined by quasi-static tensile and compression tests, which were performed using a material testing machine named WDS-100B. These tests give the static mechanical properties as shown in Table 1. From the observation of the tensile stress-strain response in our

Table 1.
Static mechanical properties of the
ZL109/ Al_2O_3

Young's Modulus (E)	71GPa
Poisson's Ratio (ν)	0.31
Tensile Strength (σ_b)	0.12GPa
Compressive Yield Strength ($\sigma_{0.2}$)	0.24GPa

Figure 1. Optical micrographs (400X) of a ZL109/15%(in Volume)Al₂O₃ composite with short fiber, where (a) is the perpendicular view, and (b) is the parallel view.

test, the ZL109/Al₂O₃ appeared as a brittle material, Assuming that the composite (ZL109/Al₂O₃) property is uniform in each direction, the bulk moduli K and shear moduli G could be calculated as:

$$K = \frac{E}{3(1 - 2\nu)} = 62.3(GPa)$$

$$G = \frac{E}{2(1 + \nu)} = 27.1(GPa)$$

Using elastic wave theory, the bulk wave velocity (C_b) and longitudinal wave velocity (C_L) are related to the K and G as $C_b^2 = K/\rho_0$, $C_L^2 = (K + 4G/3)/\rho_0$. With the values for K and G given above and a initial density ρ_0 of 2.69g/cm³, we have $C_b = 4813\text{m/s}$ and $C_L = 6050\text{m/s}$, respectively.

3. EXPERIMENT AND RESULTS

The plate-impact experiments were performed with the 100mm bore light gas gun, at the Laboratory for Shock Wave and Detonation Physics Research, Southwest Institute of Fluid Physics of China. A schematic description of the experimental setup is shown in Figure 2. A 90mm in diameter and 2mm thick 45[#] steel disk was used as a flyer plate. A 4mm thick specimen was backed with a 12mm thick PMMA block. The longitudinal stress normal to the plane wave fronts was measured by a manganin gauge situated at the composite/PMMA interface. The gauge was carefully calibrated under shock loading condition. When the shock amplitude is within the range of 0-9GPa, the gauge behaves linearly with piezoresistance coefficient of $2.4 \times 10^{-2} \text{GPa}^{-1}$. The ratio of diameter to thickness of the specimen is 24, which assures that release waves propagating in from the outer edge of the sample do not have time to change the state of stress (strain) during the experimental measurement.

Figure 2. Schematic diagram of the experimental setup, where 1 is the projectile, 2, the impactor (45[#] steel); 3, the gap; 4, the velocity pins; 5, the target specimen; 6, the manganin gauge; 7, the trigger pins ; and 8, the PMMA backing

Figure 3. The stress history at the composite/PMMA interface of a typical experiment at an impacting velocity of 324m/s.

A typical stress history at the composite/PMMA interface determined from the gauge recorded is shown in Figure 3. The impact velocity in this experiment is 324m/s. In this experiment result, we can see the elastic precursor amplitude is $\sigma_A=0.20$ GPa, the main shock peak is $\sigma_B=1.52$ GPa, and the σ_C represented spall signal is of 0.75GPa.

In fact, the gauge did not record the stresses in the specimen directly. It only recorded the stresses transmitted to the PMMA. To obtain Y_d and σ_f of the ZL109/ Al_2O_3 specimen, it is necessary to account for the acoustic mismatch between the specimen and the PMMA backing. In our planar experimental conditions, the compressive waves propagate forward into the target and back into the impactor are both the elastic-plastic double compressive wave structure. Under linearly elastic-ideal plastic response, the Hugoniot elastic limit (σ_{HEL}) and maximum compression stress (σ_M) for ZL109/ Al_2O_3 were calculated according to the following expressions:

$$\sigma_{HEL} = \frac{\sigma_A}{2} \left[1 + \frac{(\rho_o C_L)_t}{(\rho_o C_L)_p} \right] - \frac{(\sigma_{HEL})_p}{2} \left[\frac{(\rho_o C_L)_t}{(\rho_o C_b)_p} - \frac{(\rho_o C_L)_t}{(\rho_o C_L)_p} \right];$$

$$\sigma_M = \sigma_{HEL} + \frac{\sigma_B}{2} \left[1 + \frac{(\rho_o C_b)_t}{(\rho_o C_b)_p} \right] - \frac{\sigma_A}{2} \left[1 + \frac{(C_B)_t}{(C_b)_p} \right];$$

where ρ_o , C_b , and C_L are initial density, bulk wave velocity, and longitudinal wave velocity, respectively. Subscripts t and p refer to the ZL109/ Al_2O_3 and the PMMA backing respectively. If we use the HEL values, then the dynamic yield strength Y_d can be obtained from the well-known relation

$$Y_d = \frac{1-2\nu}{1-\nu} \sigma_{HEL},$$

The spall strength σ_f is determined by [1]:

$$\sigma_f = \frac{1}{2} \left\{ \sigma_B \left[\frac{(\rho_o C)_t}{(\rho_o C)_p} - 1 \right] - \sigma_C \left[\frac{(\rho_o C)_t}{(\rho_o C)_p} + 1 \right] \right\};$$

where $C=2C_b C_L/(C_b+C_L)$. It might be noted that in this formula, the elastic-plastic double wave interaction occurring during the fracture process have been ignored.

Table 2 lists the values of σ_{HEL} , Y_d and σ_f for ZL109/ Al_2O_3 , respectively. In the calculations, we used $\nu=0.31$ for ZL109/ Al_2O_3 as well as $\rho_0=1.20\text{g/cm}^3$, $C_b=2240\text{m/s}$ and $C_L=2740\text{m/s}$ for PMMA. For comparison with some relevant static mechanical performance parameters, they are also listed in this Table.

Table 2. Some mechanical performance parameters for ZL109/ Al_2O_3

$\sigma_{0.2}$ (GPa)	σ_b (GPa)	σ_{HEL} (GPa)	Y_d (GPa)	σ_f (GPa)	$Y_d/\sigma_{0.2}$	σ_f/σ_b
0.24	0.12	0.54	0.30	0.74	1.25	6.17

4. DISCUSSION

The dynamic yield and spall experiments have been researched on metal-matrix composites ZL109/ Al_2O_3 , which is observed to possess a higher yield and spall strength than the corresponding uniaxial quasi-static strength (Table 2). This can be explained as the imposition of a hydrostatic stress, the process of damage accumulation is suppressed thereby enhanced ductility and increasing the spall strength of the composite [2].

The results presented in this paper are preliminary. Hixson's experiments showed that the particle shape of the ceramic reinforcement plays a major role to the spall strength of a composite, as well as the volume fraction[3]. It is necessary to determine the effects of alumina short fiber size, sharp, orientation and volume fraction to the spall response of this kind of composite. Micro-structural analysis of virgin and recovered shocked material are also needed, which may indicate the response of inter or intragranular failure. These will be investigated in future.

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