

High strain rate response of A356/Al₂O₃ Aluminum Alloy MMCs using Split Hopkinson Pressure Bar

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Abstract

Aluminum Alloy Metal Matrix Composites (MMCs) have evoked a keen interest in recent times for potential applications in aerospace, defense and automotive industries. The ability to withstand dynamic loading is an important design criteria for many structural applications. The Split-Hopkinson Pressure Bar (SHPB) also referred to as Kolsky bar is a commonly used setup for high strain rate testing. As high strain rate data are not easily available in open literature need was felt for setting up such high strain rate testing machine. The dynamic compressive mechanical behavior of A356 aluminum alloy and MMCs of the same alloy reinforced with 4, 8 and 12% Aluminum oxide (Al₂O₃) particles were characterized using compressive SHPB technique under strain rates range from 100 to 1200 s⁻¹. The high strain rate results of compressive SHPB for all specimens were obtained in the form of stress-strain graphs, which strongly indicates that the high strain rate as well as percentage of fiber volume fraction affects on the dynamic mechanical behaviour of Aluminum alloy MMCs. These results are helpful to select the MMC materials for structural applications where materials go under dynamic loading.

Keywords: metal matrix composite (MMC), Dynamic loading, strain rate, Split Hopkinson Pressure Bar (SHPB), mechanical behaviour and structural applications.

1. INTRODUCTION:

Metal-matrix composites (MMCs) are attractive engineering materials since their properties can be enhanced or tailored through the addition of selected reinforcement. Currently, the interest in MMCs has concentrated on the light alloys, such as aluminum, aluminum-lithium and magnesium, reinforced with particulates. This interest is mainly due to the advent of new processing technologies and the availability of ceramic particulates, such as Silicon Carbide (SiC) and Aluminum oxide (Al₂O₃), at relatively low costs. Due to improvement in wear resistance, strength, stiffness, hardness, and chemical compatibility with aluminum alloy, Al₂O₃ is considered an ideal reinforcement

candidate. Compared with their unreinforced alloy counterparts, MMCs usually provide higher strength and modulus, enhanced high temperature strength and wear resistance. Despite the higher manufacturing costs, their outstanding thermo-mechanical properties make MMCs suitable materials in aerospace, defense and automobile industries where improved material performance may outweigh the cost penalty. However, the most demanding uses of Aluminum-matrix composites (AMCs) are dependent on the high-strain-rate properties. To achieve the high performance required in the material's projected applications, a good understanding of the dynamic deformation of AMCs under different strain rates is essential.

Dynamic loading response is an important design parameter, which is critical in severe applications where impact loading occurs, but has not been greatly investigated to date for MMCs. Under impact conditions, the strain rate in the composite may locally reach strain rates in excess of 1000 s⁻¹, rates which cannot be reached using conventional testing methods. The Split Hopkinson Pressure Bar (SHPB), also called the Kolsky Bar, was originally designed by Kolsky to test materials at these moderately high strain rates. The SHPB method is now well established and has been widely used to test conventional metallic materials for about 50 years and more recently, high strength composite and ceramic materials have also been tested.

Those MMCs which have been tested at high strain rates so far have been diverse in terms of matrix alloy and reinforcement type, size and shape, making comparisons difficult. Harding and Taya [8] carried out tensile tests on SiC whisker (SiC_w) reinforced 2124-T6 aluminum alloy with 15 and 25 % volume of fiber content over a strain rate range of 10⁻³- 1500 s⁻¹ and they observed that yield stress and fracture strain of the composite increased at high strain rates compared with the quasi-static values. Vaziri and co-workers [11] conducted high strain rate compression tests on SiC particulate (SiC_p) reinforced 6061-T6 Al alloys over a strain rate range from quasi-static to near about 5000 s⁻¹ and found that composites experienced a higher rate sensitivity of the flow stress than their unreinforced alloys. Perng and co-workers [12]

conducted high strain rate tensile testing on Al_2O_3 particulate reinforced 6061-T6 Al alloy at different temperatures over a strain rate range of 10^{-3} to 400 s^{-1} and found the ultimate tensile strength and fracture strain of the composite to be more rate sensitive than in the unreinforced alloy. The same composite material was also tested by Chichili and Ramesh [13] who observed that the tensile fracture strain of the composite increased at high strain rates, 800 s^{-1} , compared with the quasi-static values.

ZHANG Xin-ming and et al. [15] investigated Impact behavior of aluminum alloy 2519A at strain rates of $600\text{-}700 \text{ s}^{-1}$ and temperatures of $20\text{-}450 \text{ }^\circ\text{C}$ by a split Hopkinson pressure bar. They observed that the flow stress was dominated by temperature which increases with strain rate and decreases with deformation temperature. Wojciech MOCKO and et al. [16] investigated the mechanical properties of the aluminum (A359) based MMCs reinforced by SiC of volume fraction equal to 0%, 10%, 20% and 30% at wide range of strain rates. Experimental investigations were carried out and were compared with data calculate by means of constitutive model developed in the form of equation. H. Zhang ant et al. [14] fabricated Aluminum 6092/ B_4C_p (boron carbide) MMC by extrusion and sintering/hot isostatic-pressing (HIPing) and tested over wide range of strain rates. They observed that the strength of these MMCs increases with increasing volume fraction of particulate reinforcement and Strain hardening increase with increasing volume fraction of reinforcement at lower strains ($<5\%$), but tends to be insensitive to volume fraction at higher strains. Woei-Shyan lee and et al. [10] studied Dynamic compressive behaviour of $5\approx 15 \text{ Vf } \%$ carbon fiber reinforced 7075 Al metal matrix composite has been studied at room temperature at strain rates from about 10^{-1} to 3500 s^{-1} . They observed that the impact response of the tested composite is affected both by applied strain rate and fiber volume fraction, resulting in variations of work hardening rate, strain rate sensitivity and activation volume. Rama Arora and et al. [17] studied high strain rate mechanical characterization of aluminum alloy LM-13 reinforced with rutile particles with concentration of 5% and 15% by weight. Quasi-static and Dynamic compressive tests were carried out. They observed that the material shows negative strain rate sensitivity i.e. compressive strength decreases with increase in strain rate when rutile reinforcement is 5%. But when the rutile concentration is increased to 15%, the strain rate sensitivity become positive i.e. compressive strength increases with increase in strain rate. The brief summary given above shows that MMCs are more prone to dynamic loading effects than the corresponding unreinforced alloys and the major effects of increasing strain rate on the composites are increasing fracture strain and flow stress.

In the present study, dynamic compression tests have been conducted on A356/ Al_2O_3 Aluminum alloy MMCs reinforced with 0, 4, 8 and 12% fiber volume fraction

using conventional compressive SHPB. The objective of this study was to investigate experimentally a mechanical response of aluminum alloy MMC over wide range of strain rates and different volume fraction of reinforcement.

2. MATERIALS AND FABRICATION:

The materials investigated in this study are an A356 aluminum alloy and MMCs of the same alloy reinforced with 4, 8 and 12% Al_2O_3 particles. The A356 aluminum alloy was obtained from Shree Laxmi Alloys, Bhosari MIDC, Pimpri-Chinchvad in the form of ingots. The composition of the A356 aluminum alloy matrix is (wt. %): 6.7 Si, 0.3 Mg, 0.5 Fe, 0.005 Mn, 0.003 Zn, 0.003 Cu, 0.11 Ti with the balance being aluminum. The MMCs were manufactured in the form of a cast bar of 20 mm in diameter using Stir Casting process. The mechanical properties of the all MMCs were obtained from ELCA material testing laboratories, Pune. The reports of chemical composition of MMCs were obtained using Spectrographic testing machine. Then by using machining processes the specimens were prepared in the form of cylinder of $d12 \text{ mm} \times 10 \text{ mm}$ from available cast rods.

3. EXPERIMENTAL METHODOLOGY

The compressive SHPB setup is typically equipped with a Striker bar, Incident bar and the Transmitted bar as shown in figure 1. The incident, transmission and striker bars of the set-up are of Aluminum Alloy 7075-t6 (yield strength of 503 MPa), all having the same diameter of 20 mm. The length of incident and transmission bars is 750 mm each. The bars have a straightness of 0.1 mm/m. The striker bar is of length 300 mm. At the center of each pressure bar two strain gauges are bonded on diametrically opposite sides and electrically connected in a half wheatstone bridge circuit. Strain gauges on opposite arms of Wheatstone bridge help to remove the effect of bending. Bars are supported with darlin bushing on steel plates which are clamped over steel C-channel with a straightness of 0.1 mm/m. The C-channel rests on legs which have adjustable levelling pads. The incident and transmission bars move freely in the longitudinal direction through the darlin bushing. A foam with wooden block at the right end of transmission bar acts as a stopper.

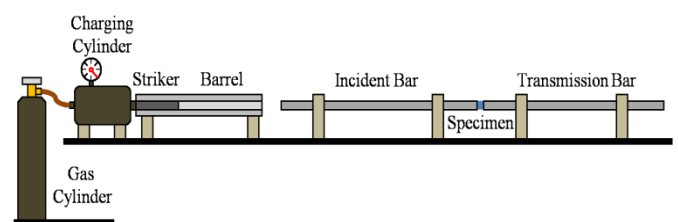


Fig. 1: Simplified schematic of compressive SHPB experimental setup.

The test specimen usually goes in between the Incident bar and the Transmitted bar. This entire apparatus is aligned in such a way that the stress can travel in a uniaxial direction. The cylindrical test specimen is pressed between two cylindrical Incident and Transmitted bars. The striker bar produces a constant amplitude elastic compressive wave in the incident bar; this wave propagates down the bar to the bar/specimen interface where it is partly reflected back into the incident bar as a tensile pulse and partly transmitted to the transmitter bar as a compressive pulse. The reflected pulse (ϵ_r) yields information on the strain rate involved in the specimen and the transmitted wave (ϵ_t) gives the stress in the specimen. The stress (σ_s), strain (ϵ_s) and strain rate ($\dot{\epsilon}_s$) in the specimen are given by;

$$\sigma_s = E \frac{A_b}{A_s} \epsilon_t \quad (1)$$

$$\epsilon_s = \frac{-2C_b}{L_s} \int_0^t (\epsilon_r) dt \quad (2)$$

$$\dot{\epsilon}_s = \frac{-2C_b}{L_s} (\dot{\epsilon}_r) \quad (3)$$

A , L , E and C are cross-sectional area, length, modulus and elastic wave velocity respectively, and s and b refer to the specimen and bar respectively. For the equations to be used for SHPB testing, the following assumptions must be valid: (a) the material deforms homogeneously during the test; (b) the wave propagates through the bars with minimal dispersion and, finally, (c) the stress in the bars never exceeds the elastic limit of the bar material. In order to investigate the different deformation behaviors under dynamic load condition, four strain rates including 100, 400, 800 and 1200 s^{-1} were employed for the study.

4. RESULTS

Figure 2 shows the experimental stress-strain behavior of A356 aluminum alloy matrix for different strain rates indicating the stress-strain behavior is the function of strain rate. The matrix material shows clearly visible work hardening effect independently of the deformation rate. The slope of the stress-strain curve can be used to define the work hardening rate of the tested composite. Figure 3 represents the variation of the work hardening rate of A356 aluminum alloy matrix as a function of strain and strain rate. It is clear that for a given fiber volume fraction under a specific strain rate, the work hardening rate, decreases rapidly for small strains and very slowly for large strains.

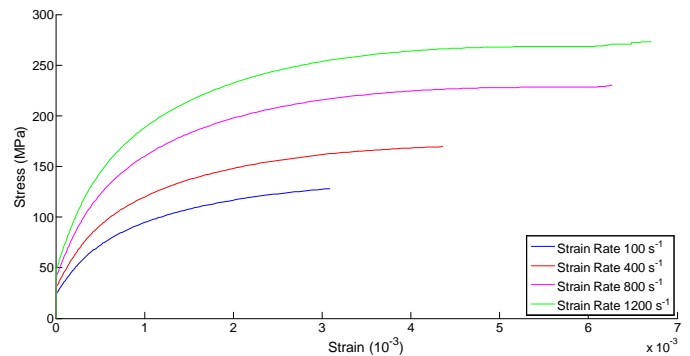


Fig. 2: Stress-Strain behavior of A356 Aluminum alloy matrix at high strain rates.

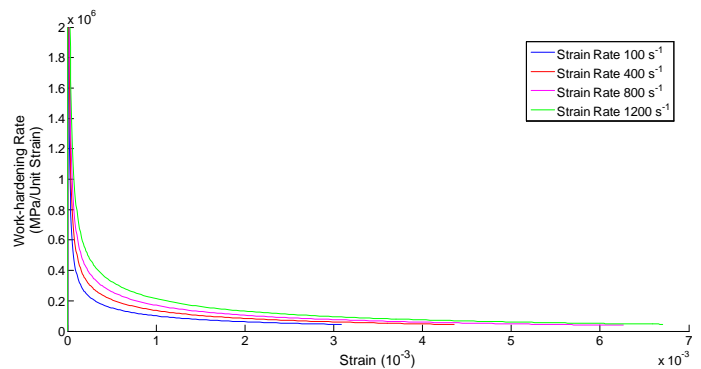


Fig. 3: Strain Rate hardening of A356 Aluminum alloy matrix.

The experimental stress-strain curves of A356 aluminum alloy particulate MMC material reinforced with four different carbon fiber volume fractions of 0, 4, 8 and 12 % Al_2O_3 particles, deformed at room temperature under strain rates ranging from 100 to 1200 s^{-1} were obtained in the form of graphs. The effect of reinforcement volume fraction on the stress-strain behavior of the MMC materials for different high strain rates is illustrated in figure 4. The curves show average results of the three samples tested at each strain rate. Some scatters, observed in these stress-strain curves as a result of geometric dispersion of the wave in the composite, are found because of the microscopic heterogeneity in the material. These results show that the stress-strain behavior of the tested composite is fairly sensitive both to strain rate and fiber volume fraction. The composites demonstrated increasing strength with 8% reinforcement volume fraction at these high strain rates.

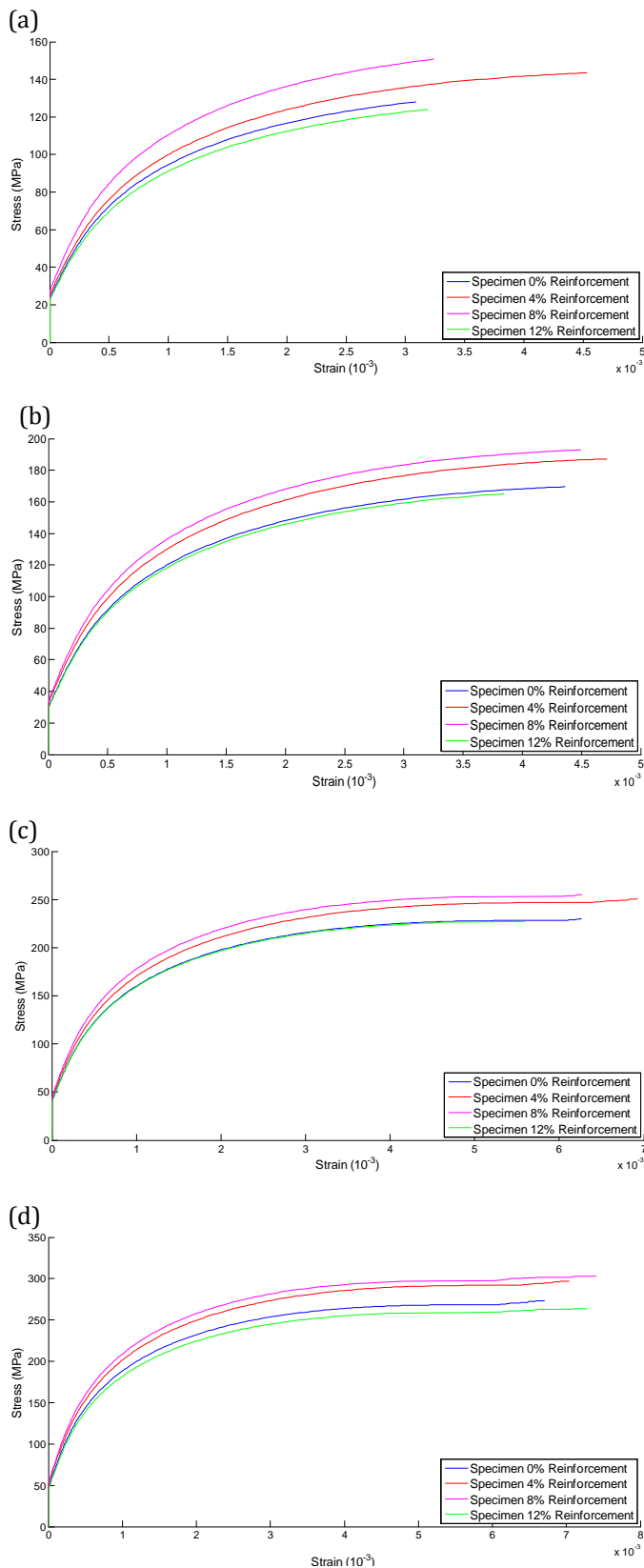


Fig. 4: Stress-strain behaviour of A356/Al₂O₃ MMC materials at strain rates: (a) 100 s⁻¹ (b) 400 s⁻¹ (c) 800 s⁻¹ (d) 1200 s⁻¹.

5. CONCLUSION

Experimental investigations were carried out in order to capture stress-strain curves of the composite over wide range of strain, strain rate using four levels of reinforcement volume fraction. Following are the few important conclusions of the work.

- At higher strain rates SHPB proved to be a successful method to obtain the stress-strain curves of the material.
- A356 Aluminum alloy MMC mechanical behavior is dependent on percentage of reinforcement and rate of strain of specimen at the time of dynamic loading.
- The A356 + 8% Al₂O₃ aluminum alloy MMC shows the better dynamic mechanical behavior as compared to other fiber volume reinforced MMCs.

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