A Review on Effect of High Strain Rate on Mechanical Behavior of Al based MMCs

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Abstract— In recent years Metal matrix composites (MMCs) are relatively new range of materials possessing several characteristics that make them useful in situations where low weight, high strength, high stiffness, and an ability to operate at elevated temperatures are required. Aluminium based MMCs exhibit an attractive combination of mechanical and physical properties such as high stiffness and low density, which favours their utilization in many structural applications. The ability to withstand dynamic loading is an important design criteria for many structures in aerospace, automotive, marine and civil engineering applications. Thus, increasing the structural applications of Al MMCs is the driving force for the need to adequately understand its deformation and dynamic behavior under various types of dynamic loading conditions. Kolsky introduced the SHPB technique for dynamic testing of specimens. In this investigation an attempt has been made to provide an extensive literature review on the effect of high strain rate on mechanical behavior of Al MMCs.

Keywords—Metal Matrix Composites (MMCs), High Strain Rate, Split Hopkinson Pressure Bar (SHPB), Dynamic Loads, Flow stress-strain behavior.

I. INTRODUCTION

Metal matrix composites (MMCs) are the forerunners amongst different classes of composites. Over the past two decades metal matrix composites (MMCs) have been transformed from a topic of scientific and intellectual interest to a material of broad technological and commercial significance. Metal-matrix composites (MMCs) are attractive engineering materials since their properties can be enhanced or tailored through the addition of selected reinforcement. Aluminium based MMCs have received increasing attention in recent decades as engineering materials with most of them possessing the advantages of high strength, hardness and wear resistance. In particular, light-weight aluminium-matrix composites (AMCs) have been the focus of much study an account of their outstanding specific properties at room or elevated temperatures. These properties make aluminium-matrix composites strong candidates for a wide range of applications in automobile, aerospace and defense industries (fig. 1).

However, the most demanding uses of 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 and fracture behaviour of AMCs under different dynamic loading is essential.
II. Split Hopkinson Pressure Bar Technique

Many techniques have been devised in attempts to study material behavior at high rates of loading. Of these, the split Hopkinson pressure bar (SHPB) technique is probably the most prominent (fig. 2). The concept behind the mechanism was initially introduced by Bertram Hopkinson [1] in 1914. Hopkinson developed a method to measure the pressure produced by a blow such as that produced by a bullet or the detonation of an explosive. The work done by Hopkinson was revisited by Robertson [2] in 1921 and later by Landon and Quinney [3] in 1923. Eventually in 1948, Davies [4] modified the technique to use condensers for measuring the displacements in the pressure bar. These could be related to the pressures in the explosion given that the elastic limit of the bar was not exceeded. This advancement made significant improvement in the certainties of the pressure histories.

In 1948, Kolsky [5] added a second pressure bar to the setup. Between two bars, he sandwiched a thin specimen. On the input bar, he used a cylindrical condenser microphone to measure the amplitude of the pressure pulse produced by firing a detonator at the free end of the input bar.

A striker bar is used to impact the end of the bar known as the incident bar. A gas gun is the most common method used to propel the striker. As a result of the impact, an elastic compression wave is generated in the incident bar. Strain gauges located on both the incident and transmitter bars are used to measure the waves as they travel along the respective bars. The reflected pulse \( (\varepsilon_r) \) yields information on the strain rate involved in the specimen ant the transmitted wave \( (\varepsilon_s) \) gives the stress in the specimen. The stress \( (\sigma) \), strain \( (\varepsilon) \) and strain rate \( (\dot{\varepsilon}) \) in the specimen are given by:

\[
\sigma(t) = \frac{A_b E_b s_i}{A_s}
\]

\[
\varepsilon = -\frac{2E_b}{L_s} \int_0^t (\varepsilon_r) dt
\]

\[
\dot{\varepsilon} = \frac{2E_b}{L_s} (\varepsilon_r)
\]

A, L, E and \( C_0 \) are cross-sectional area, length, modulus and elastic respectively, and \( s \) and \( b \) refer to the specimen and bar respectively. For the equations to be used for SHPB testing 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.

III. Previous Work Done on High Strain Rate Material Behavior of Al Based MMCS

I. W. Hall et al. [6] had experimentally tested the different metal matrix composites at strain rates from quasi-static to high strain rate up to 3000 s\(^{-1}\). Two further techniques were applied during the SHPB testing in this study. First, Longitudinal strain during the test was restricted using; loose-fitting, high strength steel collars placed around the cylindrical test pieces. The second technique was to reload, in the SHPB, samples that had already been pre-strained to a level determined either by the collars or by selection of the striker bar velocity. He obtained the typical stress-strain curves of Short fiber reinforced MMC, whisker reinforced MMC and Particulate reinforced MMC at increasing strain rates from quasi-static to high strain rate up to 3000 s\(^{-1}\). He found that short fiber-reinforced MMC’S showed significantly greater strain rate sensitivity of the flow stress than the unreinforced alloy. He summarized that Whisker reinforced MMC showed rate insensitive flow stress behavior at 5% strain and experienced decreasing flow stress at high strain rates. And for Particulate-reinforced MMC was observed to be rate sensitive at all strain values.

Woei-Shyan Lee et al. [7] studied the dynamic compressive strength and failure of carbon fiber reinforced Al MMC. Dynamic compressive behavior of 5-15 Vol% carbon fiber reinforced 7075 Al MMC was studied at room temperature at strain rates from about 10\(^{-1}\) s\(^{-1}\) to 3.5×10\(^3\) s\(^{-1}\). Typical flow stress-strain curves of carbon fiber reinforced 7075 Al MMC at various strain rates for different carbon fiber volume fractions were obtained. The flow stress-strain behavior and fracture strain was found to be sensitive both to strain rate and fiber volume fraction. It was found that, the dynamic yielding strength increases with the fiber volume fraction. He studied the deformed microstructure and observed that the breakage of fiber was produced mostly by shearing and tension. More extensive debonding and pull-out of fibers from the Al matrix during the fracture process were observed in low strain rate specimens, and, conversely, high rate fracture surfaces show much less debonding and very much less fiber pull-out.
The effects of temperature and strain rate on the properties of carbon-fiber-reinforced 7075 aluminum alloy MMC was studied by Woei-Shyan Lee et al. [8]. He studied the mechanical properties and fracture behavior of 7075-T6 aluminum alloy reinforced with 0.15 Vf of laminated carbon fiber for the effects of strain rate between $10^{-1}$ s$^{-1}$ to $3.3 \times 10^3$ s$^{-1}$ and temperature between 25-450°C. He obtained Stress-strain curves of Al fiber-reinforced MMC deformed at 25, 200, 300°C under strain rate ranging from $10^{-1}$ s$^{-1}$ to $3.3 \times 10^3$ s$^{-1}$. He observed that the flow stress of composite is sensitive to both strain rate and temperature, and that temperature increase noticeably reduces the strain-rate dependence of the flow stress (fig 3 & 4). Fracture strain was found to be greater at low strain rates, increasing, however, with strain rate and temperature in the dynamic range. He observed that at strain rates below $10^3$ s$^{-1}$, the strain rate had only a slight influence on the flow stress and above $10^3$ s$^{-1}$, the strain-rate sensitivity increased rapidly, and stress is a linear function of strain rate. He also summarised that ductile fracture occurs more frequently with an increasing temperature and strain.

K. T. Ramesh et al. [9] studied the mechanical response of an A359/SiC$_p$ MMC and the A359 aluminum matrix to dynamic shearing deformations by using a new design of the thin-walled tubular specimen for the torsional Kolsky bar. This approach has been used to characterize the high shear strain rate ($10^3$ s$^{-1}$) behavior of an A359/SiC$_p$ and its corresponding A359 monolithic alloy with the torsion Kolsky bar. He studied and observed the tensile stress-strain curves for both materials for quasi-static and high strain rate loading and characterized the torsional response and the damage mode associated with the shearing stress state in these MMCs. He observed that the flow stress of the composite in shear increases in the presence of SiC particles which results in strengthening of the composites, whereas the failure strain is reduced. High strain rate response of Aluminum 6092/B$_4$C composites were studied by K. T. Ramesh et al. [10]. Aluminum 6092/B$_4$C (boron carbide) MMCs were fabricated by two different powder consolidations routes, extrusion and sintering/hot isostatic-pressing (HIPing) and were tested over a wide range of strain rates ($10^{-4}$ s$^{-1}$ to $10^4$ s$^{-1}$). He observed that the strength of these MMCs increase with increasing volume fraction of particulate reinforcement. Strain hardening was observed to increase with increasing volume fraction at lower strains, but tends to be insensitive to volume fraction.
He observed that the fabrication route affects the strength of the matrix material as a result of changes in the microstructure. He found that Monolithic matrix material produced by extrusion shows higher strength than similar materials that had undergone sintering and HIPing.

Experimental study on tensile behavior of carbon fiber and carbon fiber reinforced aluminum at different strain rates was carried out by Yuaxin Zhou et al. [11]. Dynamic and quasi-static tensile behaviors of carbon fiber and unidirectional carbon fiber reinforced aluminum composites were investigated. The high-rate tensile tests were carried out using the bar-bar tensile impact apparatus (BTIA). The experimental results were obtained which show that carbon fiber is a strain rate sensitive material. He observed the Strength loss in carbon fiber in carbon fiber reinforced aluminum. High temperature processing not only decreased the strength of fiber, but also change scatted of strength. A one-dimensional statistical constitutive equation was established to describe tensile stress–strain relationship of the composite at different strain rates.

Wojciech Mocko et al. [12] developed the constitutive model of the Al MMC reinforced by a silicon carbide. They carried out experimental investigation of Al based MMCs reinforced by silicon carbide of volume fraction equal to 0%, 10%, 20% and 30% to capture the stress-strain curves over wide range of strain, strain rate. In this paper the experimental results were compared with data calculated by means of the analytical model. Images from the optical microscope investigations were studied and they observed the damage of reinforcement gains in the prestrained material. It was assumed that softening effects of specimen due to reinforcement particle damage are proportional to strain and reinforcement volume fraction.

Compressive behavior of high particle content B4C/Al composite at elevated temperature was studied by Xian-feng Li and et al. [13]. Compressive properties of the aluminum matrix composite reinforced with 55% B4C particles were characterized using Gleeble 3500 thermal-mechanical testing machine. He experimentally obtained the compressive stress-strain curves at the temperature ranging from 298 to 773 K and strain rate ranging from 1×10⁻⁸ to 5 s⁻¹. He observed that the ultimate compressive strength, whatever the strain rate is, decreases when the temperature of the specimen increases from 293 to 773 K. He also found that the flow stress of the composite increases as the strain rate increases from 1×10⁻³ to 5 s⁻¹. He concluded that the composite fails from the creep phenomenon to multiple micro-cracking with the increase of the strain rate.

IV. Conclusion and Recommendations for Future Work

The current Literature review reveals that, extensive work has been done to find out the mechanical behavior of Al based MMC materials over wide range of strain rates by changing the fraction of volume of reinforcement. In all literature review it is observed that, the flow stress-strain behavior of the Al based MMC is found to be dependent on both strain rate and fiber volume fraction. In future there is need to manufacture Al based Particulate MMC material reinforced with Fly Ash of different volume fraction and to evaluate the dynamic mechanical behavior of Al-fly Ash MMC under high strain rate using SHPB technique.

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