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High Strain Rate Mechanical Characterization of Rutile Particle Reinforced Aluminium Composites Using Split Hopkinson Pressure Bar

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Abstract
The present paper presents the results of high strain rate mechanical characterization of aluminium alloy LM-13 reinforced with rutile particles with concentration of 5% and 15% by weight. The samples were prepared by stir casting route. Quasi-static compressive tests were carried out using Universal Testing Machine at strain rate of $10^{-3}s^{-1}$. Dynamic compressive tests were carried out using Split Hopkinson Pressure Bar (SHPB) at strain rate of 10^3s^{-1}. Pulse shaping technique has been utilized to attain dynamic equilibrium in the specimens for SHPB tests. 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. Negative strain rate sensitivity at 5% rutile reinforcement is attributed to Portevin–Le Chatelier effect which takes place due to the diffusion of solute Mg atoms at dislocation sites which tend to resist dislocation motion. But the diffusion of Mg atoms becomes much more difficult even at low strain rates as the rutile concentration is increased to 15% and thus material shows positive strain rate sensitivity, which is very essential material property for defense applications.

Keywords
Split Hopkinson Pressure Bar, Negative Strain Rate Sensitivity, Portevin–Le Chatelier Effect, Aluminium Rutile Composite

I. Introduction
The design of almost all the engineering structures are based on mechanical properties determined from quasi-static uniaxial stress experiments. These structures are generally subjected to quasi-static loads and are designed to remain in the elastic region only [1]. But in defence and aerospace applications such as body armour, vehicle armour, aircrafts, space vehicles, missile and gas turbine engines, the structures are generally exposed to large deformations and dynamic loading conditions. Material response under these dynamic loading conditions differs considerably from quasi-static loading conditions [2]. The constitutive behaviour of the material needs to consider the effect of large strains and high strain rates [3].

Aluminium alloys and composites have gained a lot of interest in aerospace, defence and automotive applications due to their low density, high strength, high corrosion resistance and high thermal conductivity. Aluminium Matrix Composites (AMCs) belongs to the class of light weight and high performance aluminium centric material systems. In AMCs the commonly used particulate reinforcement is embedded in the aluminium matrix. Usually non-metallic and ceramic such as SiC, Al_2O_3, graphite, carbon boron etc. are used as a reinforcement to obtain the tailor made properties of the composites by varying the nature of the constituents, their shape, size and the volume fraction [4]. Addition of reinforcement drastically improves the mechanical [5] and thermal [6] properties of the material over a wide range of temperatures.

Now a days, use of minerals such as zircon [7], garnet [8], sillimanite [9] as a reinforcement are attracting many researchers because of its low cost, abundance availability at the sea coast as well as excellent mechanical and thermal properties [10]. The significant improvement in mechanical properties like hardness, tensile strength and compressive strength of the casted Al 6061-WC composite was observed at the cost of reduced ductility [11].

In the present study, rutile mineral particles of size 106 – 125 µm were used for the preparation of the aluminium LM-13 composites. Two different concentration of rutile particles, 5% and 15%, were used in the present study. The samples made out of the melt composite were subjected to quasi-static compressive loads machine at strain rate of $10^{-3}s^{-1}$ using universal testing and dynamic compressive loads at strain rate of $10^{+3}s^{-1}$ using split hopkinson pressure bar. Compression tests are employed in the present study as they are more useful and convenient method to characterize the material behaviour under large deformations as there is no restriction due to necking phenomenon which takes place in tensile tests. Moreover, true stress-true strain curves for compression are identical to tension for isotropic materials. Compression test specimens are simpler in shape, do not require threads or enlarged ends for gripping and use less material than tension-test specimens.

II. Material Details

A. Raw Materials
Al-Si alloy (LM13) of near eutectic compositions obtained in the form of ingots was used as a matrix material. LM13 alloy was chosen as matrix material due to its light weight with good corrosion résistance. Rutile has been used as reinforcement material because of high hardness, high modulus of elasticity with good thermal stability. Commercial grade LM13 alloy was purchased from M/s Earth Metals Private Limited, Mumbai (India) and rutile mineral was supplied by Indian Rare Earths Limited, Orissa, India. The chemical composition of the LM13 alloy and rutile is given in Table 1 and Table 2 respectively. Rutile particles were sieved in a range between 106-125µm by using sieving machine AS-200 supplied by Retsch, Germany.

B. Development of Particle Reinforced Aluminium Matrix Composite
Stir casting route is used for the development of the composite. This process involves the mixing of the particles into aluminium melt with the help of the stirrer and then allows the material to solidify in the mould at the normal environmental conditions. In this technique, the required quantity of LM13 alloy was taken in the graphite crucible and was melted at 800 °C in the electric

furnace. Three blades with graphite impeller inclined at angle of 45° were used for stirring. During melting, the impeller was kept at a distance of 2/3 in the melt, so that during stirring melt should not be thrown upward which will increase the porosity of the composite. Rutile particles were preheated at a temperature of 300°C to remove the moisture. These powders were charged to the melt from the side of the vortex created during rotation with the help of the funnel at the rate of 12-15 gm/min. During charging of rutile particles the melt temperature and impeller speed was maintained constantly. The stirring was continued for 5 minutes even after the addition of the particle to ensure the homogenous distribution of the particulate in the melt. The melt was transferred to the metal mould of cast iron of dimension 12×12×4 cm^3 and then allowed to solidify at room temperature. Two different concentration of rutile particles, 5% and 15%, were used in the present study. Fig. 1 shows the optical micrographs of the LM-13 aluminium alloy with 0%, 5% and 15% rutile particle concentrations. The LM13 base alloy with no rutile reinforcement, as shown in Fig. 1(a), consists of a eutectic mixture of α-Al and Si. Fig. 1(b) and (c) shows that 5% and 15% rutile particles are fairly distributed in the composite. The homogeneous distribution of particles is achieved by the constant stirring action of the impeller which provides the normal shear strain and delays the particle settling tendency during stirring. Specimens in the form of discs of 10mm diameter and 5mm thickness, as shown in fig. 2, were machined from these material blocks.

III. Experimental Procedure

Two types of mechanical tests were carried out on specimens under compressive loading: quasi-static and dynamic. Quasi-static tests were carried out on a Universal Testing Machine (UTM) and dynamic tests were carried out using Split Hopkinson Pressure Bar (SHPB).

A. Universal Testing Machine (UTM)

Quasi-static tests have been conducted at Terminal Ballistics Research Laboratory (TBRL), Chandigarh using a 100 kN Universal Testing Machine (Make Lloyd LR 100K), which is shown in fig. 3. The cross-head speed of the machine was kept constant at 1mm/min for all the tests, which corresponds to strain rate of 10^{-3} s^{-1}. Lubricant (molybdenum disulfide) was applied on both ends of the specimen to reduce friction between specimen and testing machine. When a cylindrical specimen is compressed, poisson expansion occurs. If this expansion is restrained by friction at the loading faces of the specimen, non-uniform states of stress and strain occur as the specimen acquires a barrel shape. The results of experiment become invalid under this non-uniform deformation.

B. Split Hopkinson Pressure Bar (SHPB)

Hopkinson Bar is named after B Hopkinson [12] who, in 1914, developed pressure bar technique to experimentally determine the pressure produced by an explosive. In 1949, Kolsky [13] used the pressure bar technique in determining the dynamic compression stress-strain behavior of different materials by splitting the Hopkinson bar in two parts. A schematic diagram of classical SHPB is shown in fig. 4. In the present study, SHPB facility available at Terminal Ballistic Research Laboratory (TBRL) Chandigarh is used and is shown in fig. 5. A detailed discussion on the history and recent developments has been given in [14].

The compression Hopkinson bar test apparatus at TBRL Chandigarh consists of two elastic pressure bars between which the rectangular specimen is sandwiched. The bars used are constructed from high strength maraging steel having yield strength ~ 1750 MPa. The yield strength of the bar material determines the maximum stress attainable within the deforming specimen given that the bars remain within elastic limit. The diameter of striker, incident and transmitter bars is 20 mm while length of the incident and transmitter bars is 2000 mm each. The bars are instrumented with strain gauges for stress wave measurements.

A projectile or striker bar of same diameter as the input bar is propelled towards the incident bar using compressed gas launcher. The length of the striker bar can be varied from 100mm to 900mm. Upon impact a longitudinal elastic compressive wave is generated within the incident bar designated as $\varepsilon_i(t)$.

Upon reaching the bar-specimen interface, a part of the pulse, designated as $\varepsilon_r(t)$ is reflected back in the incident bar and the remaining of the stress pulse passes through the specimen and upon reaching the transmitter bar is termed as transmitted wave, $\varepsilon_t(t)$. These wave signals are recorded by the strain gauges and the stress and strain in the specimen is calculated from the transmitted and reflected wave signals using the following formulae:

$$\sigma = \frac{AE\varepsilon_t}{A_s} \quad \text{and} \quad \varepsilon = \frac{2C_0}{l_s}\int \varepsilon_r dt$$

where 'A' and 'E' are the cross-sectional area and Young's Modulus of the bar respectively. Co is the elastic wave speed in the bar. 'A_s' and 'l_s' are the cross-sectional area and length of the specimen respectively.

1. Pulse Shaping

The incident pulse generated by impact of striker bar with input bar is of rectangular shape as shown in fig. 6(a). This pulse gives a very sharp and impulsive loading to the specimen as the slope of this pulse is very high. Due to this impulsive loading, the specimen doesn't remain in equilibrium because the stress wave has not reached the other end of the specimen. Fig. 6(b) shows the force-time histories at the two ends of specimen without pulse shaping. It can be observed from fig. 6(b) that the specimen is not in equilibrium for about 100 micro-seconds. This means that around one-third of the data recorded cannot be used in analysis since the basic assumption in the theory of SHPB is not met.

Pulse shaping technique [15] has been used to increase the rise time of the incident pulse as shown in fig. 7(a). This is done by placing 1 mm thick copper disk of 12 mm diameter on the impact end of the incident bar. This also helps in filtering out the undesired oscillations in the incident signal. The force histories as shown in fig. 7(b) show that the specimen is in equilibrium right from beginning of the test duration with pulse shaping. Pulse shaping is done for all the experimental results reported in this paper and force-time histories are analyzed to verify the equilibrium in the specimen.

IV. Results and Discussions

The stress-strain curves obtained from the universal testing machine and split Hopkinson pressure bar are engineering stress-strain curves, which are calculated using original cross-sectional area of the specimen before the commencement of the test. This data is not valid for large plastic deformations since area of the specimen increases significantly in comparison to the initial area of the specimen in a compression test. True stress-strain curves give a more accurate description of the material behaviour in such cases [16]. True stress and true strain are calculated based on the instantaneous area of the specimen during the test. Since it is difficult to measure the instantaneous area of the specimen during the test, true stress and true strain values have been deduced from engineering stress and engineering strain values using the following formulae assuming volume does not change during the plastic deformation:

$$\sigma_t = \sigma_e(1+\varepsilon_e) \text{ and } \varepsilon_t = \ln(1+\varepsilon_e)$$

where σ_t, ε_t, σ_e, and ε_e are true stress, true strain, engineering stress and engineering strain respectively.

The true stress-strain curves for rutile-aluminium composites with 5% and 15% rutile concentration under low strain rate (quasi-static) and high strain rate (dynamic) loading conditions are shown in figs. 7 and 8. The strain rate in UTM and SHPB tests was maintained at $10^{-3}s^{-1}$ $10^{+3}s^{-1}$ respectively. In other words, rate of loading in SHPB tests is one million times faster than UTM tests.

It can be observed from fig. 8(a) that strength of aluminium composite with 5% rutile concentration is decreasing at high strain rate as the stress-strain curve from SHPB test is lying below the UTM test. This means that the material is showing negative strain rate sensitivity when the rutile concentration is 5%. But the trend changes and material starts showing positive strain rate sensitivity when the rutile concentration is increased to 15% as is evident from fig. 8(b).

Normally, almost all materials exhibit positive strain rate sensitivity i.e. the strength increase at higher strain rates. This is attributed to the fact that dislocations do not get enough time for their movement at higher strain rates and this results in strain rate hardening. Twining, which requires higher stresses as compared to dislocations, is also observed for many materials at high strain rates [17].

Negative strain rate sensitivity has been reported by some researchers for Al-Mg alloys [18-20]. They have attributed this behaviour to Portevin–Le Chatelier effect which takes place due to the diffusion of solute Mg atoms at the site of dislocations.

The LM-13 aluminium alloy used in the present study also contains 1% Mg and these solute Mg atoms can diffuse at a speed greater than the speed of dislocations at low strain rates and make a cluster around the dislocations and thus tend to resist dislocation motion. But at high strain rates, these Mg atoms do not get sufficient time to make a cluster around the dislocations and thus are not able to restrict the dislocation motion. This reduces the stress required for plastic deformation and hence the material shows negative strain rate sensitivity as shown in fig. 8(a).

But the diffusion of Mg atoms becomes much more difficult even at low strain rates as the rutile concentration is increased to 15%. Therefore, material displays positive strain rate sensitivity as shown in fig. 8(b). This makes aluminium composite with rutile concentration of 15% more suitable for defence applications where strain rates are generally very high (10^3 to $10^4 s^{-1}$). The positive strain rate sensitivity is one of the most important mechanical properties which enable the material to perform better at higher strain rates in defence and aerospace applications.

V. Conclusion

The effect of strain rate on the constitutive behavior of aluminium alloy LM-13 reinforced with rutile particles has been analyzed under uniaxial compressive loading conditions. The following conclusions can be made from the present study:

1. The material shows negative strain rate sensitivity when the rutile concentration is 5%. This is due to the diffusion of Mg atoms at dislocation sites.
2. The material shows positive strain rate sensitivity when the rutile concentration is 15%. This is because diffusion of Mg atoms get restricted due to the presence of large number of rutile particles
3. Aluminium composite with rutile concentration of 15% is more suitable for defence applications where strain rates are generally very high (10^3 to $10^4 s^{-1}$). The positive strain rate sensitivity is one of the most important mechanical properties which enables the material to perform better at higher strain rates.

References

[1] Callister, W.D., Rethwisch, D.G.,"Materials Science and Engineering: An Introduction". John Wiley & Sons, 2010.

[2] Meyers, M.A., "Dynamic Behaviour of Materials. John Wiley & Sons", 1994.

[3] Zukas, J.A., Hohler, V., Jameson, R.L., Mader, C.L., Nicholas, T., Rajendran, A.M., "High velocity impact dynamics". John Wiley & Sons; 1990.

[4] Surappa, M.K., "Aluminium matrix composites: Challenges and opportunities". Sadhana, Vol. 28, No. 1-2, 2003, pp: 319-334.

[5] Singh, P.R., Pandey, O.P., "Study of wear behavior of zircon sand-reinforced LM13 alloy composites at elevated temperatures". Journal of Materials Engineering and Performance, Vol. 22, No. 6, 2013, pp: 1765-1775.

[6] Rajaram, G., Kumaran, S., Rao, T.S., "High temperature tensile and wear behaviour of aluminum silicon alloy." Materials Science and Engineering A, Vol. 528, No. 1, 2010, pp: 247-253.

[7] Kumar, S., Panwar, R.S., Pandey, O. P., "Effect of dual reinforced ceramic particles on high temperature tribological properties of aluminum composites." Ceramics International, Vol. 39, No. 6, 2013, pp: 6333-6342.

[8] Sharma, S.C., "The sliding wear behavior of Al6061–garnet particulate composites". Wear, Vol. 249, No. 12, 2001, pp: 1036-1045.

[9] Singh, M., Mondal, D.P., Jha A.K., Das, S., Yegneswaran, A.H., „Preparation and properties of cast aluminium alloy–sillimanite particle composite." Composites Part A: Applied Science and Manufacturing, Vol. 32, No. 6, 2001, pp: 787-795.

[10] Pathak, J.P., Singh, J.K., Mohan, S., "Synthesis and characterisation of aluminium-silicon-silicon carbide composite." Indian Journal of Engineering and Materials Sciences, Vol. 13, No.3, 2006 pp: 238.

[11] Swamy, A., Ramesha, A., Kumar, G., Prakash, J., „Effect of particulate reinforcements on the mechanical properties of Al6061-WC and Al6061-Gr MMCs." Journal of Minerals and Materials Characterization and Engineering, Vol. 10, No. 12, 2011, pp: 1141.

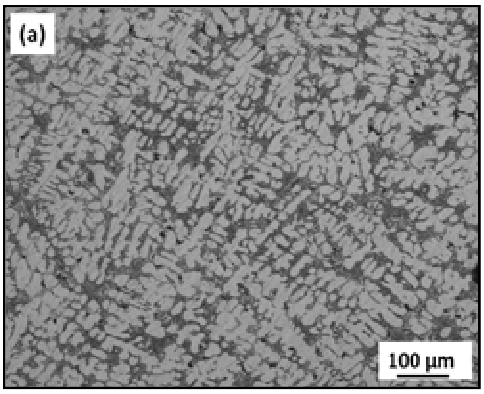
[12] Hopkinson, B., „A method of measuring the pressure produced in the detonation of high explosives or by the impact of bullets." Proceedings of the Royal Society of London, Vol. 89, No. 612, 1914, pp: 411-413.

[13] Kolsky, H.,"An investigation of the mechanical properties of materials at very high rates of loading", Proceedings of the Physical Society, 62.11 (1949): 676.

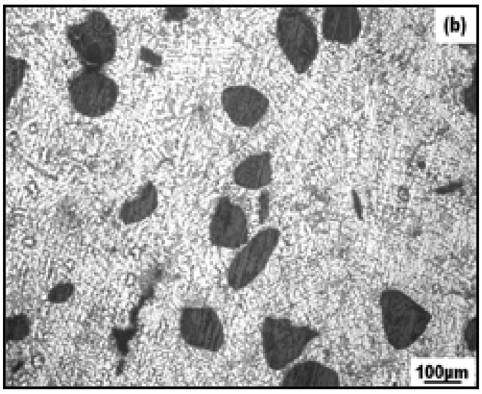
[14] Gama, B.A., Lopatnikov, S.L., Gillespie, J.W., "Hopkinson bar experimental technique: A critical review." Applied Mechanics Reviews, Vol. 57, No. 4, 2004, pp: 223-250.

[15] Frew, D.J., Forrestal, M.J., Chen, W., „Pulse shaping

techniques for testing elastic-plastic materials with a split Hopkinson pressure bar." Experimental mechanics, Vol. 45, No. 2, 2005, pp: 186-195.
[16] Dieter, G.E., Mechanical Metallurgy, McGraw-Hill, 1976.
[17] Blazynski, T.Z., Material at High Strain Rates, Springer Science & Business Media, 1987
[18] Kabirian, F., Khan, A.S., Pandey, A., „Negative to positive strain rate sensitivity in 5xxx series aluminum alloys: Experiment and constitutive modeling." International Journal of Plasticity, Vol. 55, 2014, pp: 232-246.
[19] Picu, R.C., "A mechanism for the negative strain-rate sensitivity of dilute solid solutions." Acta materialia, Vol. 52, No. 12, 2004, pp: 3447-3458.
[20] Rusinek, A., Rodríguez-Martínez, J.A., „Thermo-viscoplastic constitutive relation for aluminium alloys, modeling of negative strain rate sensitivity and viscous drag effects." Materials & Design, Vol. 30, No. 10, 2009, pp: 4377-4390.



(a)



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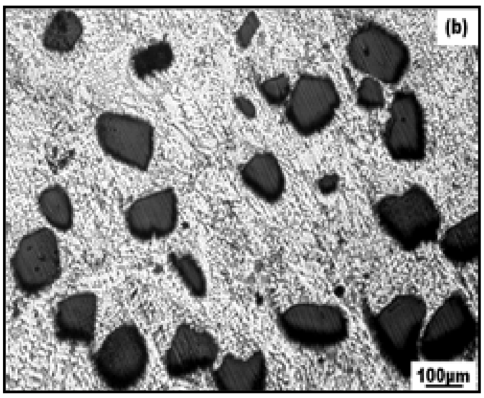


(c)

Fig. 1: Optical Micrographs of (a) 0%, (b) 5% and (c) 15% Rutile Particles Composite

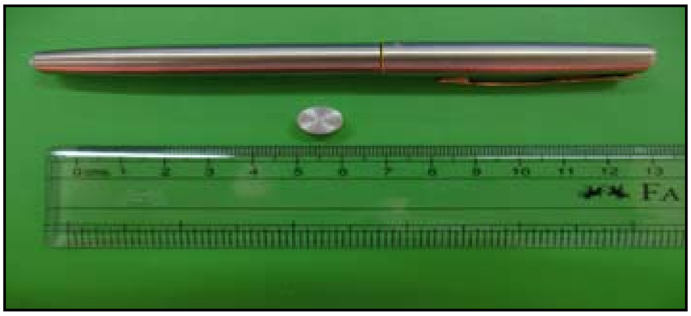


Fig. 2: Aluminium-Rutile Composite Specimen Used in Mechanical Tests

Fig. 3: Universal Testing Machine used for Quasi-Static Tests.

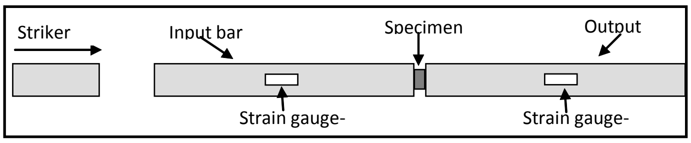
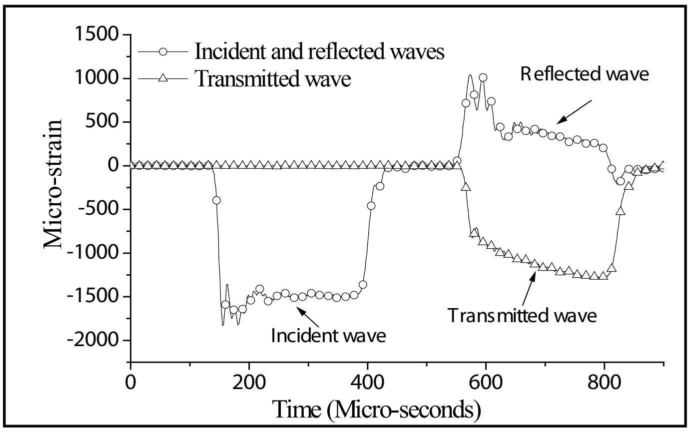


Fig. 4: Schematic Diagram of Split Hopkinson Pressure Bar

Fig. 5: Split Hopkinson Pressure Bar Used for Present Study



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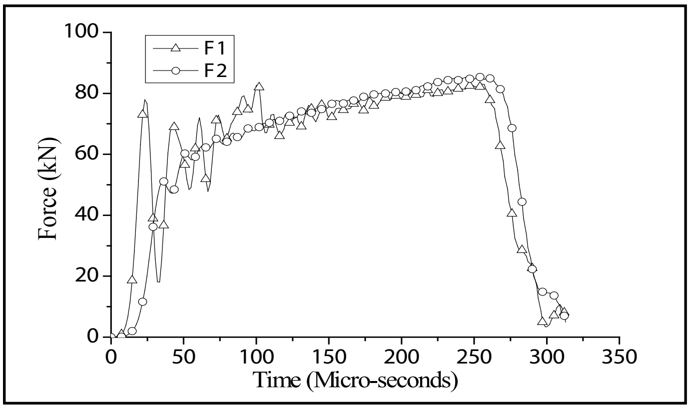
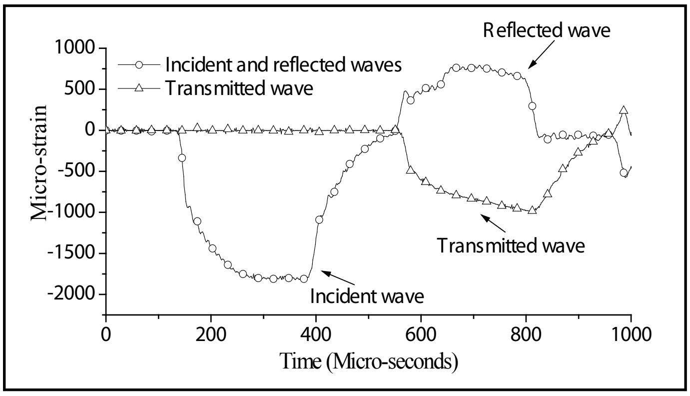


(b)

Fig. 6: (a) Recorded Wave Signals and (b) Force-Time Histories Without Pulse Shaping.



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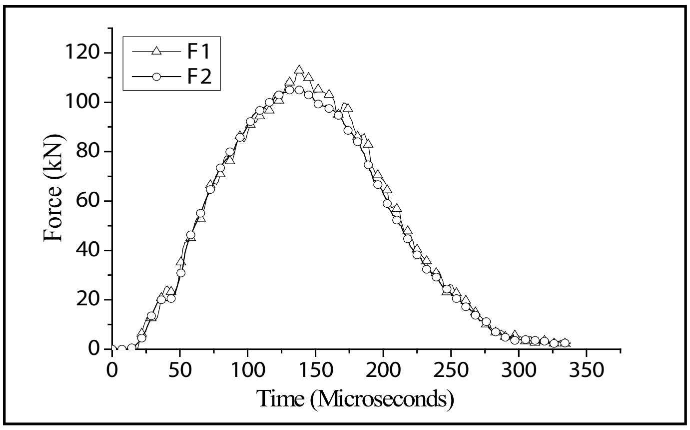
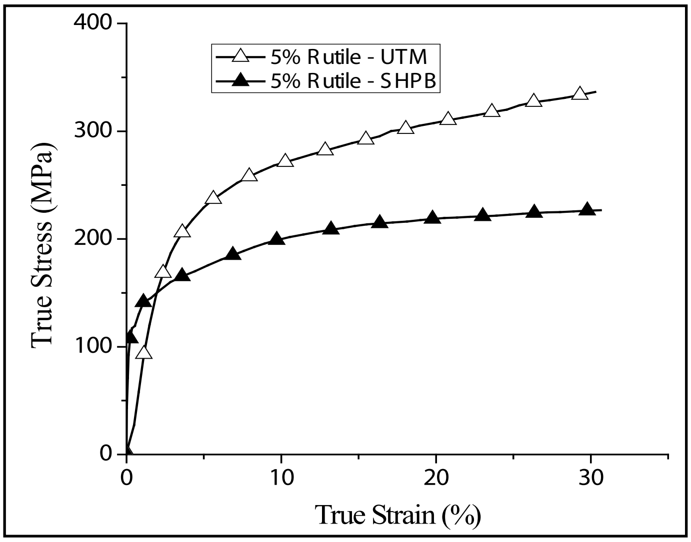


(b)

Fig. 7: (a) Recorded Wave Signals and (b) Force-Time Histories With Pulse Shaping.



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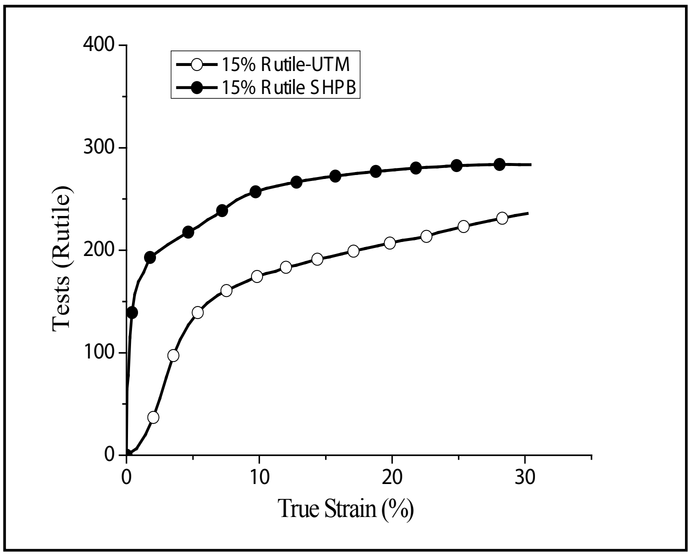

(b)

Fig. 8: True Stress Strain Curves Under Static and Dynamic Loading for (a) 5% Rutile and (b) 15% Rutile Particle Aluminium Composite

Table 1: Chemical Composition of the LM13 Alloy

Elements	Si	Fe	Cu	Mn	Mg	Zn	Ni	Al
Chemical Analysis (Wt %)	12.0	0.4	1.2	0.4	1.00	0.2	1.0	Bal.

Table 2: Chemical Composition of Rutile Mineral

Elements	TiO_2	ZrO_2	SiO_2	Fe_2O_3	P_2O_5
Wt % in Bulk	94.5	0.90	0.90	1.10	0.80