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A review on the mechanical behaviour of aluminium matrix composites under high strain rate loading

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Abstract. AMCs (aluminium matrix composites) are commonly utilized in various structural applications as they possess high strength, low weight, and improved wear resistance properties in comparison to monolithic aluminium alloys. The properties of AMCs generally improve by adding reinforcements. These reinforcements can be ceramics like Alumina, Silicon carbide, or inorganic materials like fly ash. It was noticed that AMCs behave differently with a change in strain rate. Additionally, failure mechanisms under dynamic loading settings are discovered to be distinct from those under quasistatic or low strain rate loading conditions. The wide applications of AMCs rely both on their low strain rate behaviour and high strain rate characteristics. The emphasis of this study is to review the dynamic behaviour of AMCs where the strain rate varies from 100-10,000 s^{-1}. AMCs were discovered to be strain rate sensitive at increasing strain rates, where their strength and failure strain increases with the strain rate.
Keywords: aluminium matrix composites; metal matrix composites; high strain rate; dynamic behaviour; mechanical properties

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Introduction

Composite is a combination of any two of the material types (polymer, metal, or ceramic) that differ in chemical composition and phases [1,2]. A composite has two phases, the matrix phase, and the reinforcement phase. Reinforcement carries the load whereas the matrix phase helps in transferring and distributing the load to the reinforcement. The matrix phase is generally ductile in nature and it binds the fibres together whereas the reinforcement phase is hard and brittle [3]. The classification of composites can be seen in Fig. 1. In the metal matrix composites (MMCs), the matrix phase is necessarily a metal and the reinforcement can be a polymer, ceramic, or even metal [4]. Aluminium, copper, magnesium, and titanium are the most commonly used matrix material in MMC. In this review paper, the focus is on the aluminium matrix composites (AMCs) where different aluminium alloys are used as matrix materials such as Al6061, Al5083, Al7075, A356, A359, etc. The reinforcement material in AMCs can either be in the form of particles (nano or micron size) or fibres (continuous or discontinuous type) [5,6]. The ceramic type reinforcements are mostly used [7,8] like silicon carbide (SiC), tungsten carbide (WC), alumina (Al_2O_3), titanium diboride (TiB_2), zirconia (ZrO_2), etc. Amongst various ceramic reinforcements, Al_2O_3 and SiC are largely used reinforcement materials types due to their easy availability and cheapness. Organic materials like fly ash, rice husk, etc. [9,10] can also be used as reinforcement materials. The first development of MMCs with ceramic reinforcements was in the early 1960s with Aluminium metal as matrix and graphite particles as reinforcement material [11]. Nowadays, the focus is more on hybrid composites [12,13], where two or more materials are used as reinforcements. The MMCs can be fabricated using

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either liquid state, solid-state, or in-situ fabrication techniques (refer to Fig. 2). The universally used techniques for synthesizing of MMCs in the liquid state are stir casting and squeeze casting whereas powder metallurgy is preferred among various solid-state techniques [14].

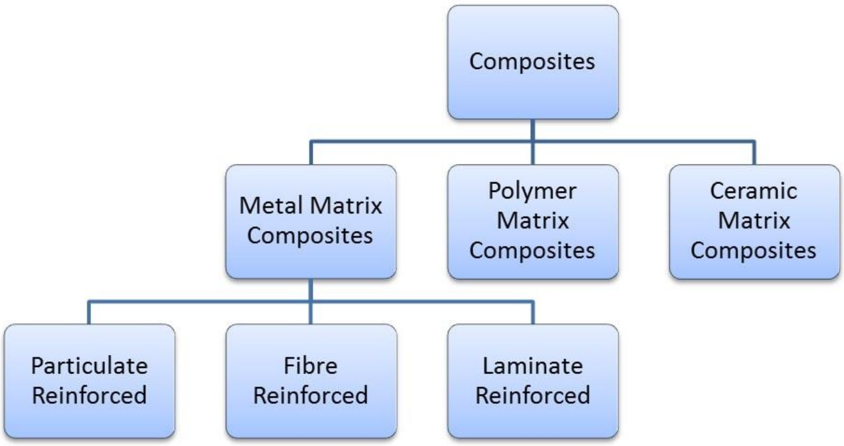

Fig. 1. Classification of composites

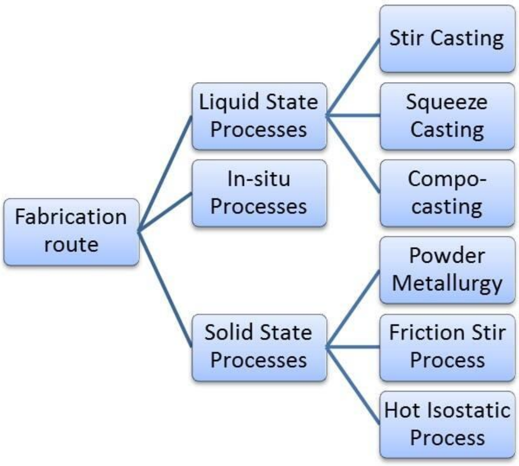

Fig. 2. Different types of fabrication routes for MMCs

AMCs are typically used in marine, aerospace, and automotive industries owing to their low weight, good load-bearing capacity, better wear resistance, and corrosion resistance as compared to monolithic metals [15–17]. Due to lower thermal strain, the wires of conductor cables in power transmission towers are made of MMCs instead of monolithic metals like steel, aluminium, and copper [18–20].

The AMCs used in engineering and structural designs such as aerospace, automotive and marine vehicles are susceptible to dynamic loads such as sudden impact due to foreign objects (animals, birds, marine life-forms, etc.) or high-speed collision due to human error while navigating such vehicles [21]. Even armour shields used for the protection of vehicles or any human are made of AMCs. Such shields must possess good anti-penetrative properties as they are prone to ballistic incidents. Such dynamic loading may lead to localized deformation of AMCs.

This review study concentrates on the mechanical behaviour of the AMCs under the dynamic loading.

Effects of reinforcement material on the properties of AMCs

With the introduction of reinforcements, there will be few changes in the mechanical, physical, and tribological properties of the AMCs compared to that of monolithic metals or their alloys. Some changes are beneficial and some are unwanted. The mechanical properties can be divided into two parts based on the strain rate – (a) low strain rate (LSR) properties due to static loading, and (b) high strain rate (HSR) properties due to dynamic loading.

LSR mechanical properties and tribological behaviour of AMCs. In static loading conditions, the strain rates for the mechanical tests are usually less than 10^{-3} s^{-1} [22]. Mechanical properties like tensile strength, compressive strength, and hardness usually improve with the addition of reinforcement particles into the base matrix as these particles act as barriers to the dislocation movement (Orowan strengthening) which increases the value of stress required for the same amount of plastic deformation [23–26]. Whereas properties like ductility and percentage elongation are negatively affected as the wt. % of reinforcement is increased which may be due to the grain refinement of particles [27–29]. The wear resistance of AMCs was also observed to increase with reinforcement content because the addition of strong ceramic particles minimizes material loss during wear tests [30]. The fracture toughness and creep properties may also improve with the addition of reinforcement [31,32].

HSR mechanical properties of AMCs. Under dynamic loading circumstances, strain rates typically range from 10^2 to 10^4 s^{-1} or even above [33]. For HSR tests, the split Hopkinson pressure bar (SHPB) test (also referred to as the kolsky bar test) is employed [34]. In the SHPB test, the test sample is pressed between an incidence bar and a transmission bar (Fig. 3).

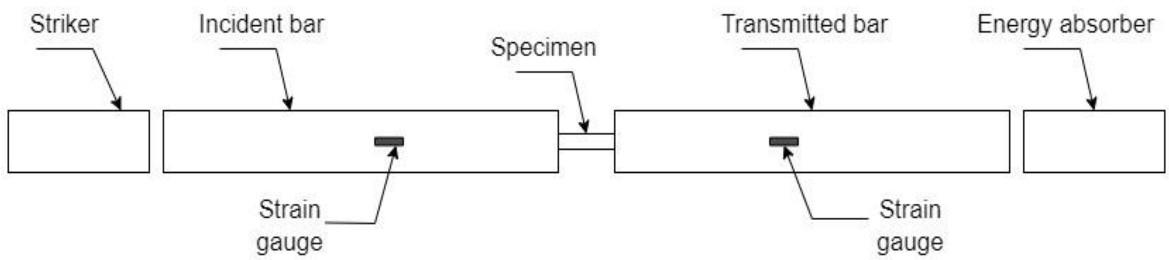

Fig. 3. Schematic of SHPB test apparatus. Redrawn from [35]

An elastic wave is generated when the striker bar collided with the incident bar with some velocity. This elastic wave passes through the interface between the incidence bar and the sample, where a portion of it is transferred to the transmission bar and the remainder is reflected back to the incident bar [36]. The reflected and transmitted wave values can be monitored using strain gauges installed at the incidence and transmission bars [37]. Stress (σ), strain rate ($\dot{\varepsilon}$), and strain (ε) can be calculated from reflected and transmitted waves [38] using the given Eqs. (1) – (3):

$$\sigma_S(t) = \frac{A_O E_O}{A_S} \varepsilon_T(t), \quad (1)$$

$$\dot{\varepsilon}_S(t) = \frac{2C_O}{L_S} \varepsilon_R(t), \quad (2)$$

$$\varepsilon(t) = \int_0^{\tau} \dot{\varepsilon}_S(t)\, dt, \quad (3)$$

where *A*, *E*, and *L* are cross-sectional area, elastic modulus, and length respectively, *s* and *o* represent specimen and bar, ε_T is the transmitted wave signal and ε_R is the reflected wave signal, and C_O is wave speed in the incident bar which is given by Eq. (4):

$$C_O = \sqrt{\frac{E}{\rho}}. \quad (4)$$

There are mainly three types of HSR mechanical tests upon which the previous researchers had worked, namely HSR compressive, HSR tensile, and HSR torsional test or HSR shear test. In this study, the behaviour of AMCs under these dynamic tests and their failure mechanism is summarized by reviewing past research.

Behaviour of AMCs under HSR tensile test. Perng et al. [39] observed the HSR tensile behaviour of Al_2O_3 reinforced AMC. The HSR tensile specimens were prepared in accordance with the ASTM E8 standard. It was found that composites were highly sensitive to strain rate (about 10^{-3}, 1, 140, and 400 s^{-1}) when compared to the base metal. UTS (ultimate tensile strength) of both composite and base metal were increased with the increase in the strain rate. When tested at room temperature, UTS of Al/15 %Al_2O_3 was increased from 366.53 to 468.06 MPa; and UTS for base metal Al6061-T6 was increased from 322.68 to 397.15 MPa. It was hypothesized that the decrease in dislocation velocity increased the strain rate sensitivity (SRS). The reinforcement particles acted as a barrier to dislocation motion thereby reducing dislocation velocity.

Chichili and Ramesh [40] studied the dynamic behaviour of Al/Al_2O_3 composite and also monolithic alloy under HSR tensile test by varying the strain rates over a range of 185 to 750 s^{-1}. The failure strain was observed to be increased with an increase in strain rate which suggested high values of dynamic fracture toughness compared to that of quasistatic one. There was no significant strain hardening under the dynamic tensile test. The composite test samples showed brittle fracture when viewed macroscopically but the occurrence of dimples on the broken surface of specimens indicated ductile fracture of the matrix at the microscopic level. The failure mechanism for the monolithic alloy was found to be ductile fracture with necking.

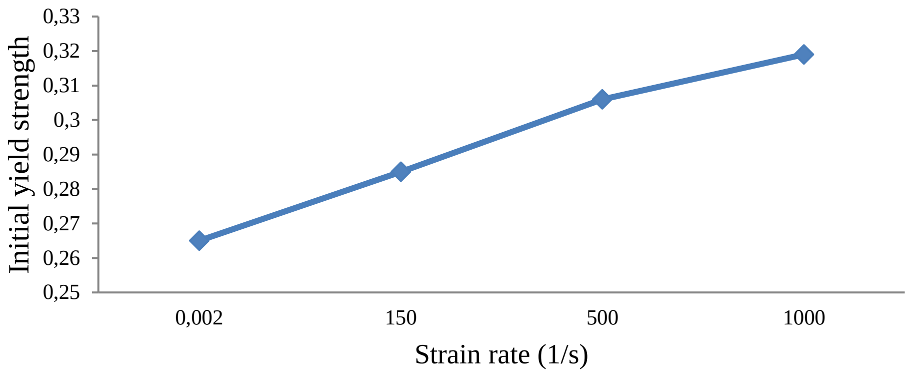

Fig. 4. Relationship between Initial yield strength and strain rate under HSR tensile test. Based on [41]

Wang et al. [41] investigated the tensile dynamic behaviour of AMC with 10 % SiC particles as reinforcement with varying strain rates (0.002, 150, 500, and 1000 s^{-1}). The composite was revealed to be rate responsive as specimen yield stress increased with strain rate (refer to Fig. 4). Li et al. [42] monitored the deformation of A359/SiC composites under a dynamic tensile test using Laser Occlusive Radius Detector for measuring the local strain of specimens. For this investigation, the strain rates were 10^{-3} and 250 s^{-1}. The rate dependency of the composite was observed with a change in yield stress by varying strain rates. The dynamic failure strain was found to be less than the quasistatic strain. This was due to the fact the strain measured was local strain whereas the previous studies measured overall strain for the specimens. The failure of the composite was mainly due to matrix failure. Reddy [43] discovered that the yield stress of Al6061/SiC composites dropped with increasing temperature but increased with increasing strain rate.

Wang et al. [44] performed HSR tensile tests on Al/CNT composites with a strain rate of about 2000 s^{-1}. The composites were manufactured with CNT particles having two different aspect ratios (AR25 and AR55). The stress-strain diagram revealed that the flow stresses were higher for AMCs with a lower aspect ratio (AR25) under both quasistatic and dynamic test conditions (refer to Fig. 5). Large values of failure strain suggest increased strain rate sensitivities within AMCs. The SEM micrographs of fractured surfaces revealed finer and shallower dimples for AMCs tested at

2000 s^{-1} compared to quasi-statically tested AMCs. Table 1 summarizes the variations in tensile characteristics of various AMCs with strain rate.

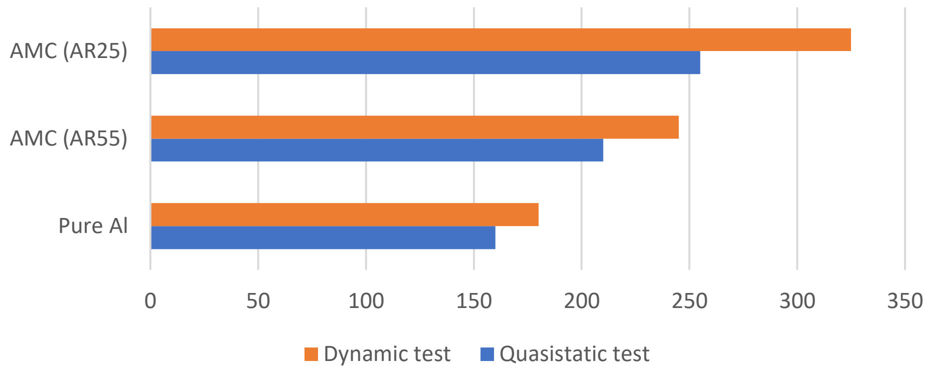

Fig. 5. Flow stress under Quasistatic and HSR Tensile test conditions. Based on [44]

Table 1. Tensile properties of various AMCs at varying strain rates

AMCs	Strain rate, s^{-1}	Tensile strength, MPa	Strain, %
Al6061-T6/15 % Al_2O_3 [39]	10^{-3}	366.53	5.1
	416.93	468.06	5.59
Al6061-T6/20 % Al_2O_3 [40]	10^{-3}	380	2.4
	750	390	6.75
Al/SiC [41]	0.002	265	5
	1000	319	7.5
A359/20 % SiC [42]	10^{-3}	160	1.2
	250	180	1.08

Behaviour of AMCs under HSR torsion test. There are very few past studies on the dynamic behaviour of AMCs under the HSR torsion or shear test. Those investigations are summarized in this section. Shear property is vital for composites with fibrous reinforcements [45]. Marchand et al. [46] used the HSR torsional test to investigate the dynamic behaviour of AMCs reinforced with SiC whiskers. The specimens were made in the shape of a thin-walled tube with flanges (refer to Fig. 6). The strain rates of 10^{-4}, 900, 1300, 1600, and 3500 s^{-1} were considered for the observation. Fracture toughness was found to be improved when loaded dynamically. The shear ductility of AMCs was also found to be increased from 29 % at a 10^{-4} s^{-1} strain rate to 40 % at a strain rate of 3500 s^{-1}, but there were no significant changes in UTS of composites with a change in strain rate.

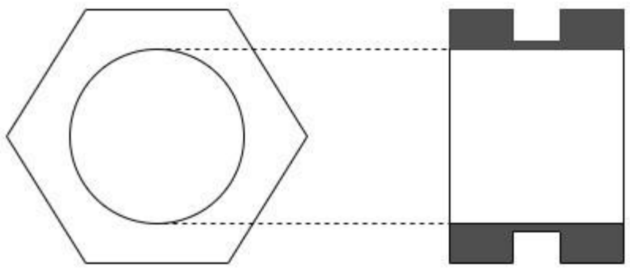

Fig. 6. Schematic of Torsional test specimen. Redrawn from [47]

Yadav et al. [48] observed that Al/Al_2O_3 composites were more sensitive to high strain rate (above 1000 s^{-1}) compared to the monolithic metal when samples were tested using HSR compression and HSR torsional tests. This change in SRS of composites was attributed to 1) hindrance to the dislocation motion, at a high strain rate, due to adding of reinforcement and 2) increase in the dislocation density as a result of the creation of dislocations due to varied strains. The increase in the values of flow stresses at HSR was credited to the restrained plastic flow due to reinforcements. Li et al. [49] investigated the dynamic torsional behaviour of newly developed specimens, made out of A359/SiC MMC and base alloy, which helped in reducing the cost of machining and also resulted in simpler machining of the specimen. The failure strain and yield stress in shear of the base alloy were increased with an increase in the shear strain rate from 260 to 1420 s^{-1} (refer to Fig. 7). The increase in shear yield stress and failure shear strain was also observed for the composite sample. It was found that the base alloy and composite were more ductile in shear than in tension.

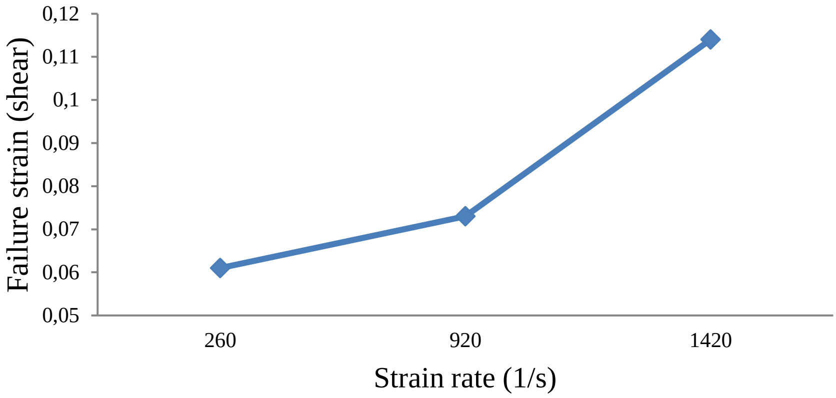

Fig. 7. Failure stress (shear) vs strain rate. Based on [49]

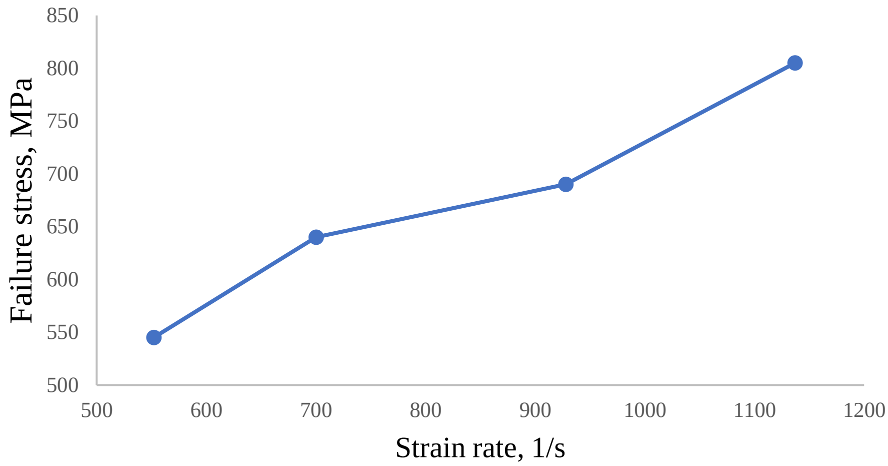

Fig. 8. Failure stress values of AMC composite with 10 wt. % Al_2O_3 under HSR torsional test. Based on [50]

Table 2. Torsional characteristics of AMCs over different strain rates

AMCs	Strain rate, s^{-1}	Shear strength, MPa	Shear strain, %
Al2124-T6/SiC whiskers [46]	10^{-4}	390	29
	3500	375	40
Al6061-T6/20%Al_2O_3 [48]	6.2×10^4	385	
	1.7×10^5	465	
A359/20%SiC [49]	260	165	6.1
	1420	175	11.4
Al6061-T6/20%Al_2O_3 [50]	687	680	19
	1008	820	28

Odeshi et al. [50] studied the dynamic shear and compression behaviour of $Al6061/Al_2O_3$ composite with strain rates varying up to about 1200 s^{-1}. The strain rate caused a rise in shear failure stress and failure strain (refer to Fig. 8). It was also observed that the AMCs were more susceptible to shear failure than failure due to compressive loading. Nucleation of micro voids and particle fracture were the reason for shear failure as observed from the SEM micrograph of fractured surfaces. Table 2 highlights the variations in torsional characteristics among different AMCs with strain rates.

Behaviour of AMCs under HSR compression test. Li and Ramesh [21] analyzed the dynamic compression behaviour of AMC with help of numerical modelling. The effect of shape, aspect ratio, and volume fraction of reinforcement particles on AMC under dynamic loading was investigated. With the increase in volume fraction of reinforcement, the strength increased even at high strain rates. Yield stresses of AMC at high strain rates were higher for cylindrical-shaped reinforcement particles as compared to spherical-shaped particles. Thus, SRS is higher for AMC at high volume fractions and also for cylindrical-shaped particles. Lee et al. [51] examined the HSR compressive properties of AMCs reinforced with 10 vol. % carbon fibres (C_f). The strain rates of 1300, 2300 and 3300 s^{-1} were used for HSR tests. The composites were manufactured with both longitudinal and transverse fibre orientations. The HSR compressive strengths of composites with both fibre orientations at different strain rates and temperatures are mentioned in Table 3. The compressive strength increased with strain rate; however, it decreased as the temperature increased from 25 to 300 °C.

Table 3. HSR compressive strengths of Al7075-T6 based AMCs reinforced with C_f at different temperatures [51]

Test Sample	Strain rate, s^{-1}	Temperature, °C	Compressive strength, MPa
AMC with longitudinal fibre orientation	1300	25	654.3
		300	288.3
	3300	25	692.8
		300	277.1
AMC with transverse fibre orientation	1300	25	832.8
		300	332.0
	3300	25	899.4
		300	367.2

Guden and Hall [52] performed HSR compression tests for three different AMCs – (a) Al-1.25 % Cu alloy reinforced with 20 % Al_2O_3 short fibres, (b) Al2124-T6 reinforced with 25 % SiC whiskers (SiC_W), and (c) Al2024 reinforced with 15% SiC particles (SiC_P). The strain rate was varied from 10^{-3} to 3000 s^{-1}. Composites showed higher SRS which resulted in an increase in yield or flow stress at higher strain rates. Whisker reinforced AMCs were least sensitive to strain rate compared to fibre and particle reinforced AMCs. Lee et al. [53] explored the HSR compressive behaviour of the Al7075-T6 AMCs reinforced with varying grain sizes of SiC particles (10 and 20 μm). A strain rate of 2800 s^{-1} was used for compressive HSR tests of composites. The increase in yield stress was observed when AMCs were loaded under dynamic conditions. The compressive strength of AMCs with SiC particles of grain size 10 μm was higher than AMCs with particle size 20 μm. The strain percentage also increased with the increase in strain rate. A similar improvement in strain percentage with strain was observed by Li et al. [54] when Al2124/SiC composites were tested under dynamic compressive loading (refer to Fig. 9).

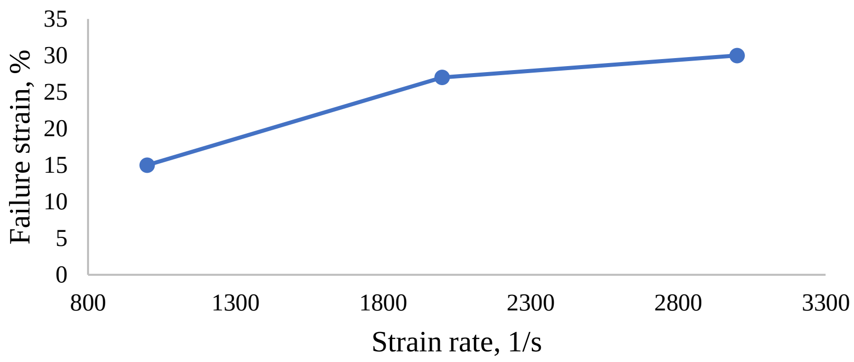

Fig. 9. Relation between strain and strain rate for AMC under HSR compression test. Based [54]

Tan et al. [55] tested the SRS of Al2024 composite reinforced with 50 % SiC particles. The quasistatic (0.001 s^{-1}) and dynamic compression tests (1250 to 2500 s^{-1}) were performed at 3 and 5 % strain for the study. There was an increase in flow stress when the strain rate was increased up to 2000 s^{-1}. The flow stress was increased by increasing the strain% from 3 to 5 % indicating strain hardening but the increase in flow stress by changing the strain rate was larger in magnitude. Thus, the hardening due to the change in strain rate is more significant than hardening due to the change in strain percentage. When the strain rate was increased from 2000 to 2500 s^{-1}, the value of flow stress dropped which was due to softening of the sample as a result of adiabatic heating during HSR compression. Zhu et al. [56] performed quasistatic (or LSR) and HSR compression tests on Al2024/60 %TiB_2 composite with strain rates of 0.0007, 1100, 1400, and 1850 s^{-1}. The flow stress values were increased by increasing the strain rate up to 1400 s^{-1}. At the strain rate of 1850 s^{-1}, there was a reduction in flow stress and an increase in elongation due to the thermal softening of the specimen during compression. For strain rates up to 1400 s^{-1}, there was brittle fracture of samples; but the failure mode for samples examined at a strain rate of 1850 s^{-1} was ductile fracture due to softening of the composite because of heating during HSR compression.

Similar findings were observed by Ye et al. [35] by testing SiC reinforced AMCs with SiC having average particle size (APS) of 10 and 50 μm under quasistatic compression test and dynamic compression test with strain rates spanning between 2200 and 5200 s^{-1}. Figures 10 and 11 demonstrate the increase in the value of flow or yield stress and fracture strain under compression with strain rate.

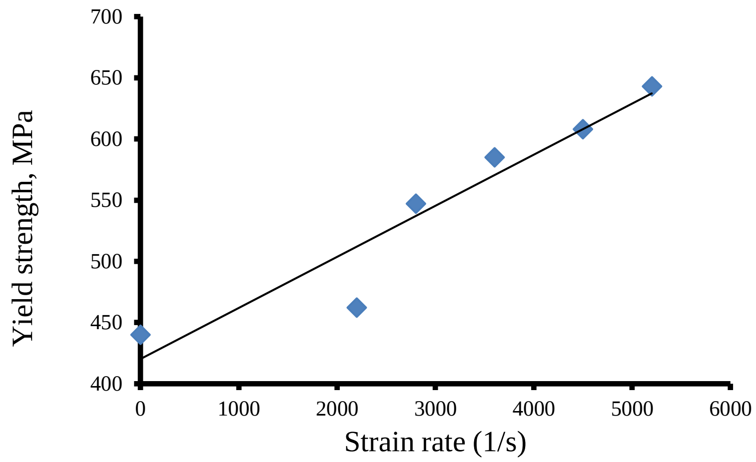

Fig. 10. Variation of Yield stress (compression) with strain rate for AMC reinforced with 10 μm SiC particles. Based on [35]

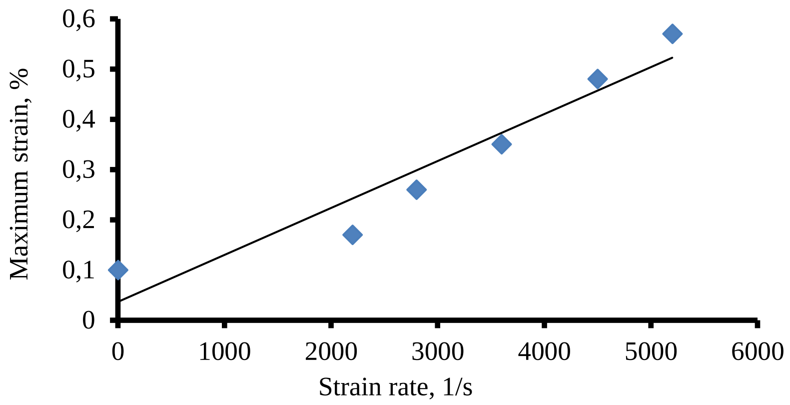

Fig. 11. Variation of fracture strain (compression) with strain rate for AMC reinforced with 10 µm SiC particles. Based on [35]

Changes in compressive strength and strain percent of numerous AMCs with the strain rate at room temperature are mentioned in Table 4.

Table 4. Compressive properties of AMCs at varying strain rates

AMCs	Strain rate, s^{-1}	Compressive strength, MPa	Total strain, %
Al2024/15 % SiC [52]	4.2×10^{-4}	380	16
	2200	420	28
Al7075-T6/SiC (10 µm) [53]	0.001	886±68	6.4±0.8
	2800	1309±108	8.4±0.8
Al2124/SiC [54]	1000	543	15
	3000	569	30
Al2024/50 % SiC [55]	0.001	580	7.2
	2000	775	13
Al/Al_2O_3 (4.5 µm) [57]	10^{-4}	340	18
	1600	480	11.5
Al6092/30 % SiC [58]	1600	535	19
	4300	605	54

Table 5. Summary of HSR compression tests performed on AMCs

MMC composition	Strain rate	Findings
Al7075 AMC reinforced with laminated carbon fibre [34]	0.1 to 3300 s^{-1} at 25, 200 and 300 °C	1. Flow stress increased with strain rate but decreases with temperature. 2. High-temperature results in an increase in ductility.
A356/Al_2O_3 composite [36]	100 to 1200 s^{-1}	1. AMC was sensitive to reinforcement % and strain rate. 2. Strength of samples was increased at strain rates.
AMC reinforced with nano-particles of Al_2O_3 (2.5 to 12.5 wt. %) [38]	700, 1400, and 3000 s^{-1}	1. Threshold Stress and fracture strain increases with strain rate. 2. Energy absorption also increases at HSR with the maximum at 5 wt. % SiC. 3. SSR increases with strain rate and deformation strain.
Al6092/B_4C composite [59]	varied up to 10^4 s^{-1}	1. Strength of composites increased with strain rate above 1000 s^{-1}. 2. Strain hardening of AMCs reduced at high strain rates with an increase in reinforcement content.
Al/SiC with APS of 12 and 45 µm [60]	800 to 5200 s^{-1}	1. AMCs were sensitive to HSR. 2. Dynamic Strength increases with a decrease in APS. 3. SRS decreased with a decrease in APS. 4. Strain softening region was observed above 3400 s^{-1} due to thermal softening.
A356/SiC [61]	about 1200-1500 s^{-1}	Increased strength of composite at dynamic loading.

The strength and fracture strain of the composites under dynamic loading (HSR) were found to be more than the strength of composites when tested under static conditions (LSR). The composite with a smaller particle size had higher values of yield strength and energy absorption compared to a composite with a larger particle size.

A summary of the composition of AMCs, strain rates used in the HSR compression test, and the findings of a few other previous investigations can be found in Table 5.

Conclusions

The review paper has discussed the dynamic behaviour of AMCs under different HSR tests. The following conclusions are made from a review of the earlier investigations done on various AMCs under dynamic loading conditions:

1. The quasistatic mechanical properties like tensile strength, compressive strength, hardness, and fracture toughness are generally improved with the addition of reinforcement into the matrix of AMCs.
2. AMCs were discovered to be extremely sensitive to variations in strain rate.
3. At higher strain rate (HSR) values, flow stress or yield stress, energy absorption, and deformation strain are more sensitive and their values are increased at HSR.
4. The impact of strain rate hardening is greater than the impact of strain hardening in the increase of flow or yield stress of AMCs.
5. At very high strain rate values, some thermal softening phenomena were observed which caused a decrease in flow stress and an increase in elongation.
6. With the increase in temperature at HSR the values of flow stress decrease.
7. The particle size of reinforcement also affects HSR mechanical properties.

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