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Effect of loading speed on deformation of composite materials: a critical review

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Abstract

Composite materials possess multiphase and by virtue of this has varied applications in the field of automotives, aerospace and defence industries. These applications demand high impact loading at many instances, so the evaluation of the effect of impact loading on composite materials are important. Under high strain loading the composites mainly exhibit matrix properties but the variation arises when the amount of reinforcement is considered. The response of composite materials to high strain loading for dilute concentration of reinforcement differs than that of highly populated reinforcement material. The loading speed refers to the crosshead velocity which has direct proportionality with strain rate. Loading speed is a experimental parameter which can be altered to study the crashworthiness of a material. This review report contains a brief review of literature on the effect of loading speed on the deformation history of polymer, metal and ceramic matrix composites.

Keywords: Composite: Crosshead Velocity: Loading speed: Strain rate

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1. Introduction

Since the composite materials are utilized instead of traditional materials in high speed structural applications, it has become important to study their dynamic behaviour in addition to static behaviour [1]. Also, since the mechanical properties of composites vary significantly with strain rate, it might be too conservative to design dynamically loaded structures using static properties [2]. Polymers are generally regarded as viscoelastic materials since their mechanical properties are sensitive to the rate at which they are loaded [3]. Thermoplastic composites which find many applications in automobile parts such as front-end chassis frames, underbody closures, spare wheel wells, bumpers and side impact beams are subjected to high strain-rate loading during a crash. Polymer matrix composites are widely used in aerospace structures. These structures are subjected to dynamic loading under service conditions such as high velocity impacts from hailstones or other kind of debris [4,5]. Sea mines during detonation can emit underwater shock waves, that can impart severe impact loading to a naval ship structures generally made up of glass reinforced polymeric composites (GRP)[6,7]. So for the effective use of these materials, their response under different strain rates should be clearly understood [8]. Most of the high strain-rate characterization studies are focused towards the thermosetting composites such as epoxy and polyester matrices which are reinforced mainly with carbon and glass fibers [9]. Uniaxial compression tests are widely performed for high strain rate studies of polymeric composites. In a few cases uniaxial tensile test methods are also described where considerable increase in stiffness and strength with strain rate has been reported. Also, most high rate studies are conducted under a one-dimensional state of stress i.e., uniaxial compression, uniaxial tension, or shear. Off-axis loading or confined testing are used to study the effects of biaxial states of stress [10]. Numerical simulations are also now extensively used in vehicle design and crashworthiness assessment [5].

Most of the researches presently are concentrated on the behaviour of the PMCs at high strain rate even though for comparison purposes some tests are still conducted at low strain rates [11]. Lot of complexities and difficulties are present in the experimental high strain rate testing of composites. Success with the high strain rate testing of polymer composites depends mainly on the ability to isolate the inherent inertial disturbances attributed to the test system [12]. For testing composites at intermediate strain rate levels, ranging from 50 s^{-1} to 150 s^{-1}, hydraulic driven and/or drop weight impact test systems are widely used. Split Hopkinson Pressure Bar (SHPB) is generally used for the testing of composite materials at strain rates higher than 200–300 s^{-1}[13,14].

Variation of failure modes is caused due to change in the loading rate. Non-ductile mode of failure is generally favoured during high strain rate deformation while, low strain rate deformation induces more ductile failure [15]. The fiber/matrix interface mechanical properties of PMCs are sensitive to loading rate [16]. The behaviour of the resin controls the overall strain rate sensitivity of a laminated composites [17,18]. The studies on the effect of loading rate on hybrid composites are also now becoming popular. Hybrid composites have better response to different loading conditions than traditional composites since they are made up of more than one reinforcement material [19]. The shear modulus and strength of polymeric composites are also sensitive to loading rate [20]. Since the ceramic matrix composites (CMCs) undergo negligible amount of deformation with increasing strain rates, research on their loading rate sensitivity is very scarce.

Different loading rates are quite probable in several applications of metal matrix composites (MMCs) to evaluate their crashworthiness [16]. High impact loading conditions are withstood at instances such as MMC armours, collision of cars and impact of foreign objects on aerospace structures. MMCs respond differently to high strain rate loading conditions as compared to monotonic or quasistatic loading [21]. As loading rate is directly proportional to strain rate, we can assume the changes in behaviour of material to possess similarity in both the cases. As strain rate is increased from quasi-static to dynamic, the temperature conditions gradually change from isothermal to fully adiabatic. There is thermo-mechanical coupling in the adiabatic stress-strain curves i.e the effects of strain hardening, strain/rate strengthening and thermal softening caused by the adiabatic temperature increase couple together. The dislocation density is an internal state variable which is a function of plastic deformation [22]. The heterogeneous microstructure of composites necessitates the evaluation of mechanical strength at different loading conditions. Residual stresses also play a vital role in the effect of loading speed on composites. Loading rate sensitivity of metal matrix composites is a function of loading rate sensitivity of the matrix as well as the status and stability between particles and matrix [23].

The relationship between loading rate and strain rate is as follows

Strain rate, $\dot{\varepsilon} = \frac{d\varepsilon}{dt}$ (1)

Cross head velocity, $v = \frac{dL}{dt}$ (2)

Engineering / Conventional strain rate, $\dot{e} = \frac{de}{dt}$

$$= \frac{d[\frac{(L-L_0)}{L_0}]}{dt}$$

$$= \frac{1}{L_0}\frac{dL}{dt}$$

$$\dot{e} = \frac{v}{L_0} \quad (3)$$

Hence, $\dot{e} \propto v$

Where L_o is the original length and L is the length after time t [24]

In this paper, a brief review on the literature of loading rate sensitivity of composites has been done over the last past decade with classification done according to the basis of type of loading to which they are subjected.

2. Effect of loading rate on deformation of polymer matrix composites

(a)Tensile loading

The strain rate sensitivity of polymer matrix composites under tensile loading has been discussed in this section. The inertia and the strain rate sensitivity of the epoxy matrix affect the strain rate sensitivity of the woven composite [25]. The tensile behaviour of a polypropylene thermoplastic composite reinforced with woven fabric commingled E-glass was investigated over a strain-rate range of 10^{-4} to 70 s^{-1} and it was observed that on increasing the strain rate above $36s^{-1}$, the elastic modulus, ultimate strength, and strain to failure of the composite were enhanced significantly. The increase in tensile modulus of the composite with increasing strain rate can be attributed to the viscoelastic effects of the polymeric matrix and the woven structure and geometry of the composite material accounts for the increase in strength with strain rate. Compared to satin-weave, unidirectional, and multi- directional composites, higher strain rate sensitivity was depicted by plain-weave composites than due to the enhanced interaction between the matrix and fibers in them [26]. A glass fiber reinforced ethylene-propylene copolymer matrix composite subjected to tensile testing at high strain rates up to 200 s^{-1} showed localized deformation in the interface zone around fibers when observed through SEM. This local deformation zone can delay the damage initiation through interfacial crack propagation in the matix by acting like a dissipation zone with increase in strain rate. Also an extensive increase of the damage stress, strain and Young’s modulus has also been noticed. The interaction between local and the global viscous behaviour of the matrix and fiber–matrix interface debonding dictates the effect of strain rate on the composite behaviour [27].

Substantial increase in the tensile strength, stiffness and ductility during high speed loading was observed for functionalized silica nanoparticle reinforced polyamide composite when compared with low speed loading. The strong and tough interphase formed due to the covalent binding of the polymer matrix with the silica nanoparticle accounts for this increase in mechanical properties. The propagation of micro-cracks and even pin cracks during high strain-rate loading can be inhibited by the presence of these covalently-bonded nanoparticles. This inturn results in more energy dissipation making the material strong and tough simultaneously [28]. When tested in tension over a range of strain rates between quasi-static and 87.4 s^{-1}, the behaviour of CFRP was found to be strain rate- dependent with a considerable change in the failure patterns. This enhancement in tensile property can be attributed to the combined effect of many factors such as the strain rate dependency of CFRP fibers, its woven structure and the viscoelastic nature of the polymer matrix. At high strain rate, there was also enhancement in the absorbed energy of the composite which helps in extending the service life of composite structures [29].

The transverse tensile strength of carbon/epoxy composite varied linearly with the logarithm of strain rate when tested over a wide range of strain rates from from10^{-4} to over 400 s^{-1} [30]. An increase in tensile strength by about 75–93% was observed for a typical plain weave fabric E-glass/epoxy composite along the thickness direction [31]. Significant increase in tensile strength, modulus and strain to failure was observed for unidirectional glass fiber reinforced polymeric composites with increasing strain rates. Also changes in failure modes were seen when loading was changed from quasi-static to high dynamic loading [32]. The longitudinal strength of E-glass/epoxy composite was found to be more rate sensitive than its longitudinal stiffness [33]. In the case of carbon/epoxy laminate damage localisation was observed during rapid tensile testing at high strain rates [34].

(b) Compressive loading

The strain rate sensitivity of polymer matrix composites under compressive loading has been discussed in this section. Considerable increase in the dynamic strength and stiffness with strain rates were reported when carbon/epoxy laminated composites were tested under high strain rate compression using a modified split Hopkins pressure bar setup. The dynamic values obtained were high compared to the static values. The strains were higher for static loaded samples since they have more amount of time for deformation to take place [35].

Acoustic emission analysis was used by Woo et al. [36] to study the failure and damage development in Kevlar-woven composite specimens during dynamic compressive loading. There was considerable increase in the toughness and peak stress values of the composite with increasing strain rate during high-strain-rate loading. But the strain at peak stress was found to be decreasing.

In a woven carbon/ epoxy laminate composites studied under dynamic compression loading, a variation in the failure strength was observed with different fiber woven directions. There was also gradual variation in the stress-strain curves, maximum compressive stress and strain with the strain rate. Shear mode of failure was observed for the specimens under out-of – plane loading. This shear mode of failure was independent of the loading states and strain rates applied. Another interesting observation was that, the occurrence of delamination was seen only at high strain rates under in-plane dynamic loading. But, in the case of in-plane quasi-static loading, both delamination and shear deformation were observed. During in-plane compression loading, the dynamic strength limit was observed to be less than that of quasi-static strength limit whereas for out-of-plane compression loading, the dynamic strength limit is higher than that of the quasi- static strength limit. Three failure zones are present during in-plane quasi-static compression loading which includes: two delamination zones, undeformed zone at the center and two shearing deformation zones. Shearing bands are present at the edges of the central un-deformed zone and shearing deformation zone [37]

Enhancement in compressive strength at high strain rate loading was depicted by woven fabric E-glass/epoxy laminated composite which was fabricated using resin film infusion technique. The compressive strength increased with increasing strain rate but, the rate of increase becomes diminished on further loading [38]. Compressive stress-strain behaviour of a (±45°) symmetric E-glass/polyester composite at different strain rates were investigated along three perpendicular directions and were found strain rate sensitive. With increasing strain rates, enhancement in modulus and strength of the composite was observed. The properties in-plane direction was more strain rate sensitive than that in through-thickness direction. Axial splitting followed by formation of 45^0 inclined crack surface was the failure mode taking place in the in-plane direction. Similar failure modes were exhibited during quasi-static and high strain rate loading [39]

A better balance between weight and impact resistance makes particulate filled polymer composites an alternative for many structural applications. The static and dynamic compression properties of polypropylene/silica composites at different strain rates were studied using a split Hopkinson pressure bar apparatus and a universal testing machine. It was found that the particle size influenced the strain rate sensitivity of the composite. For a smaller particle size, lower strain rate sensitivity was recorded. Also the yield strength, the ultimate strength, and the stiffness of the composite were found to be strain rate sensitive [40]. The dynamic compressive properties of a laminated graphite/epoxy composite was investigated at high strain rate loading for temperatures ranging from 80°C to 160°C and at glass transition temperature. It was observed that the compressive yield strength of the composite increased with the strain rate at both low and high temperatures while the ultimate strength decreased slightly with strain rate. The failure properties were also observed to be strain rate sensitive at the same impact energy. Linear relationship was observed between energy absorbed and strain rate at low temperature. At high temperature the energy absorbed remained relatively constant [41]. Investigation on the quasi-static and high strain rate compression behaviour of an E-Glass fiber woven fabric reinforced Polyester matrix composites showed an increase in both failure strength and elastic modulus with strain rate in both in-plane directions and transverse direction [42]. Higher strength was shown by glass fiber polymer composites embedded with tetra-needle-like zinc oxide (ZnO) nanowhiskers with increasing strain rates in both the thickness and in-plane directions. The amount of ZnO nanowhiskers in the resin affected the compressive properties of the composite significantly. The three-dimensional structures of ZnO nanowhiskers and the corresponding stress transfer behaviour can be used to explain this high strength exhibited by the composite during dynamic compressive loading. The peak strain and compressive strength in the in-plane direction are found to be lower than those in the normal direction [43].

Increase in transverse compression modulus of elasticity, yield strength and failure strength by 12, 83 and 45% was observed in a unidirectional carbon-epoxy material subjected to transverse compression and in-plane shear loading using a split-hopkinson pressure bar. Compressive failure strain in the transverse direction was found to be strain rate insensitive for the strain rates considered. Increase in in-plane shear modulus of elasticity, yield strength and failure strength by 25, 88 and 42%, respectively was also observed. Excellent strength predictions for both quasi-static and dynamic loading are given by puck failure criterion for matrix compressive failure [44]. Naik et al. studied the behaviour of typical polymer matrix composites under high strain rate compressive loading along thickness direction using a compressive split Hopkinson pressure bar apparatus. Emphasis was given to condition where no specimen failure occurs during loading. Strain rate sensitivity was exhibited by the composite during this case also. Here initially the specimens are subjected to compressive strain and then tensile strain during the later part of loading. The tensile strain induced was observed to be greater than that of the induced compressive strain [45].

A modified instrumented falling weight drop tower was used for characterizing the high strain rate behaviour of commingled E- glass/polypropylene woven fabric composite at different strain rates. Enhancement in tensile and compression modulus and strength were observed with increasing strain rate whereas the shear modulus and strength decreased with increasing strain rate. The matrix viscoelasticity and fiber–matrix interfacial properties were found to significantly influence the high strain rate behaviour of the composites. The time dependent nature of damage accumulation and the woven reinforcement architecture also affects the strain rate behaviour of the composites upto a certain extent [46]. A servo-hydraulic testing apparatus was used to characterize the compressive properties of unidirectional glass–fiber reinforced polymeric composites at varying strain rates. When the strain rate was increased, enhancement in compressive strength and modulus were observed. But, the compressive strain to failure was found to be insensitive to strain rate. Also the absorbed energy also increased with strain rate which would be beneficial in applications where the composite structures would be subjected to dynamic loading conditions. Also, changes in failure modes with increased strain rate were confirmed from the visual examination of the failed specimens. This can be attributed to the transition to an increase in energy, from low-to-high strain rates [47].

High strain rate compressive properties of typical plain weave E-glass/epoxy and plain weave carbon/epoxy were determined along all the principal directions and it was found that compressive strength is greater at high strain rate loading when compared with that at quasi-static loading. Along the thickness direction, compressive strength increased with increasing strain rate. No significant effect of strain rate on compressive properties was observed for the composites when loaded along the warp and fill directions. Compressive modulus was observed to be lower along thickness direction when compared with those along warp and fill directions [48]. A hybrid composite fabricated using satin weave carbon and plain weave E-glass with epoxy resin was tested under compressive loading to study the effect of high strain rate behaviour in the warp, fill and thickness direction. Both the ultimate strain and compressive strength was increased with increasing strain rate whereas no significant change in compressive modulus was observed. The hybrid composite exhibited higher compressive strength when compared with satin weave carbon/epoxy composite [49].

E-glass fibers were impregnated with a low viscosity epoxy resin through infusion process and tested under compressive dynamic loading to study the effect of fiber orientation and strain rate. A strong sensitivity to fiber orientation was showcased by the material which was confirmed from the stress strain curves at the same impact pressure. Failure of the specimen by fiber kinking was observed at low strain rates whereas delamination and interfacial separation was seen in high strain rate failure regime [50]. A method was developed by Gillespie et al. for the determination of the interlaminar shear strength and friction function as a function of strain rate by testing out-of-plane off-axis plain weave S2-glass/SC79 polymer matrix composites under both quasi-static and high strain rate loadings. Results from the off-axis compression test method shows good agreement with that of quasi-static-v notch shear test results [51]. Effect of loading rate in a glass fiber reinforced polymer composite was studied using a servo-hydraulic test machine. When loaded in the in- plane direction, similar variation in compressive strength and elastic modulus with strain rate was observed. The in-plane elastic modulus and strength first increased with strain rate and then decreased markedly at higher strain rates. Fracture toughness of the woven GRP composite also exhibited loading rate sensitivity whereas the failure strain at peak stress was found to be insensitive to strain rate [52].

(c) Flexural loading

The strain rate sensitivity of polymer matrix composites under flexural loading has been discussed in this section. Interlaminar shear strength (ILSS) which measures the in-situ shear strength of the matrix layer between the plies is a matrix dominated property which can be determined using short beam test under three point bending. For low values of cross head speed, there is significant variation in the interlaminar shear strength of FRP composites. But, the variation is not so prominent for high cross head speeds. The type and amount of constituents present in the composite affects the variation of inter laminar shear strength. The poissons's ratio of laminated FRP composites is not sensitive to strain rate. This is due to the presence of fibers in it. The inter laminar shear strength can be calculated using the formula as per ASTM D 2344 – 84,

$$S = (0.75P_b)/ (bd) \qquad (4)$$

Here, P_b = Breaking load in kg, b = Width in mm, d = Thickness in mm.

Very high strain rate sensitivity is observed for epoxy and polyester resins. The interlaminar shear strength increases with fiber weight fracton irrespective of the loading speed employed [53].

The effect of loading speed on the environmentally conditioned glass fiber reinforced epoxy resin matrix composite is being studied here. With more conditioning time, there is less influence of strain rate on the composite. The ILSS values are decreased due to their exposure in moisture environment. More reduction in ILSS is observed at low cross head speeds compared to high rates of loading for same time of exposure. This is because at lower cross head speeds, more time is available for the absorbed moisture to pass through the cracked channel which facilitates enhanced moisture/matrix interaction and further deterioration. The failure modes exhibited by the FRP composites are influenced by the changes in the loading rate. Various complex combinations of energy absorbing mechanisms such as delamination by shear mode, matrix cracking as a result of transverse shear and translaminar fracture due to fiber rupture and/or by kinking constitutes the failure mechanisms in laminated composites under high loading speeds. The variations in cross head speeds during flexural testing can alter the ILSS values of hygrothermally conditioned specimens which contain same quantity of absorbed moisture. This effect is also observed if the absorbed moisture is freezed inside the composite at sub-zero temperature. But during this freezing treatment, residual stresses may develop which can degrade the ILSS value of the composite. This effect is more evident at lower loading speeds. A lower cross head speed can result in a lower value of ILSS. A higher failure strain or ductility of the resin matrix may be a possible explanation for this behaviour. The behaviour of the resin matrix has a prominent influence in controlling the strain rate sensitivity of PMCs [54].

In free thaw testing of composites, after subjecting the specimen to a cryogenic temperature for a certain duration in a freezing chamber, it is taken out and allowed to thaw at ambient condition for certain duration and then flexural testing is performed on it. The ILSS values of freeze thaw tested composites are then compared with that of cryogenically conditioned and then immediately tested specimens and also with untreated specimens. Cryogenically tested composites exhibited higher shear strength values than other two. Higher ILSS values are observed at low cross head speeds which can be attributed to the cryogenic hardening taking place in the polymer matrix phase. At higher cross head speeds, ILSS values are found to decrease sharply. This is due to the damage of matrix by cryogenic microcracking. So the loading rate of the composite is strongly evident at lower rates of loading [55].

Eyring theory of viscosity can be used to explain the effect of strain rate on most polymers. In this theory it has been assumed that the motion of a chain molecule over the potential energy barriers constitutes the deformation of a polymer. The yield stress of hygrothermally shocked glass/epoxy and glass/polyester laminates were found to vary linearly with the logarithm of strain rate. Only less time is available for the polymer matrix to localize at higher loading rates [56]. Flexural testing was done on E-glass fibers reinforced epoxy composites at a range of 0.5 mm/min to 500 mm/min crosshead speed to evaluate the sensitivity of mechanical behaviour during loading at ambient and sub-ambient (-80˚C temperature). The composite strength at high strain rates was limited by the ductility of the epoxy matrix resin. Mixed fracture modes are exhibited by the composite at higher crosshead speeds. The interlaminar strength at higher loading rate is minimized by thermal stress-induced cracks. These cracks are formed since the relaxation process at the crack tip is being minimized by the higher crosshead speeds during testing. Cryogenic hardening takes place at lower range of crosshead speed which results in higher ILSS values [57].

Flexural testing was done on E-glass/epoxy composite exposed to −40˚C, −60˚C, and −80˚C temperatures at different crosshead speeds. The loading rate sensitivity of the composite was found to be inconsistent which can be attributed due to low-temperature hardening, matrix cracking, misfit strain due to differential thermal coefficient of the constituent phases and also by enhanced mechanical keying factor by compressive residual stresses at low temperatures. The flexural strength and stiffness of E-glass/epoxy composite are rate sensitive at lower range of strain rate. Higher ILSS values at higher loading rate for all conditioning temperatures can be attributed to better adhesion at the interface. The change in failure mode from fiber brittle failure to brittle failure with considerable matrix damage was observed as the crosshead velocity increases which bring about a resulting increase in energy absorption. Loading rate sensitivity seems to be controlled by the area of interfaces and the percentage of polymer matrix phase present in composites [58]. At low rates of loading there is significant variation of inter laminar shear strength of laminates of FRP composites, but at high loading speeds, the variation is not so prominent [59]. The UV-treated Jute/glass hybrid reinforced epoxy composite showed better yield properties at higher loading rate. Fiber fracture was the prevalent failure mode in the case of UV treated samples whereas fiber pull-out failure mechanism occurred in the untreated samples [60]. The behaviour of the resin controls the strain rate sensitivity of the carbon/epoxy composites when tested at liquid nitrogen temperature. The matrix is unable to transfer the load effectively to the fibers at high crosshead speeds due to lack of time. So at high strain rates, loading resembles like an impact load and it will lead to crack propagation along the matrix without blunting phenomena at the crack tip [61].

At lower ranges of cross head speed the loading rate sensitivity of fibrous composite materials are strongly evident [62]. At low temperatures after initial increase in the fracture strain of glass/epoxy composites, it later decreased with loading speed as the matrix became brittle. Then at very high crosshead speeds, the fracture strain was observed to increase again due to adiabatic heating [63]. The failure mechanisms in FRP composites changes from fiber fracture to matrix cracking with change in loading rate from static to dynamic [64]. High failure strain at low strain rates can cause lower value of ILSS [65]. Cryogenic hardening of the matrix and mechanical keying factor due to compressive residual stresses causes increased breaking load values for cryogenic conditioned laminates than the untreated laminates at all loading rates [66]. Fiber fracture, matrix cracking, fiber pull-out and delamination are the main damage mechanisms appearing in FRP composites at different loading rates [67].

(d) Shear and impact loading

The strain rate sensitivity of polymer matrix composites under shear and impact loading has been discussed in this section. The impact tests were performed under varying strain rates ranging from 1096 to 4017s^{-1}on a multi-walled carbon nanotubes–polycarbonate composites (MWCNT–PC) fabricated using a two-step method of solvent casting followed by compression molding. The concentration of CNTs in polycarbonate matrix had a significant influence on the stress-strain behaviour of the composite at various strain rates. The impact absorption energy was increased by about 10-20% compared to pure polycarbonate material when the strain rate is increased. Resilience of composite was reduced with increase in concentration of CNT at higher strains [68]. Split Hopkinson pressure bar apparatus was used to determine the in-plane shear properties of a typical plain weave E-glass/epoxy composite under high strain rate loading by means of 45° off-axis tension and compression tests. In-plane shear strength was increased at high strain rate loading when compared to that at quasi-static loading. There was also increase in the in-plane shear strength and off-axis strengths with increasing strain rate. The trend of variation of IPS strength as a function of shear strain rate is nearly identical. For compression and tension tests, identical trend of variation of in-plane shear strength as a function of shear strain rate was obtained [69].

The quasi-static and dynamic fracture behaviour of particulate polymer composites using both nano and micro sized fillers were studied by Jajam et al. [70] under various loading rates. Loading-rate sensitivity was depicted by the fracture behaviour of both the fillers. Under dynamic loading conditions, nano filler reinforced composites exhibited lower crack initiation toughness compared with that of the micro filler ones. The behaviour was opposite in case of quasi-static loading. The behaviour of carbon/epoxy composite material under various biaxial states of stress combining transverse compression and shear was reported for a wide range of strain rates. Both the variation in moduli and strength of the composite was linear with the logarithm of strain rate. The ratio of transverse to in-plane shear modulus remained independent of strain rate. Linear variation with logarithm of strain rate was also exhibited by the transverse tensile and compressive strengths and the in-plane shear strength for the entire strain rate range [71]. A digital speckle correlation method was used by Lee et al. to study the effect of strain rate on the quasi-static and dynamic fracture behaviour of graphite/epoxy composites. The time-resolved full-field in-plane surface displacements during the quasi-static and impact loading of the specimens can be obtained by using the 2D digital image correlation (DIC) method. It was observed that the fracture behaviour is loading rate sensitive and the fracture surface morphology depicted bridging of crack faces by unbroken fibers during quasi-static loading. But no detectable fiber bridges were observed in dynamic loading conditions [72].

Digital image correlation method was also used to obtain the in-plane shear strain field of a unidirectional carbon-epoxy composite and the dynamic tests were conducted on a split-hopkinson pressure bar to study the effect of strain rates. The in-plane shear modulus was found to be strain rate sensitive and it increased with increasing strain rate. Due to the dependency of the apparent failure strength and strain on the ratio of biaxial loading, determination of effect of strain rate on the in-plane shear failure is difficult [73]. The shear modulus and strength were observed to be decreasing with increasing strain rate for a commingled E-glass/polypropylene woven fabric composite tested over a strain rate range of 10^{-3} to 10^{2} s^{-1}. The woven reinforcement architecture of the composite along with matrix viscoelasticity and interfacial properties plays an important role in determining the high strain rate behaviour of the composite [74].

Shokrieh et al. [75] studied the in-plane shear behaviour of unidirectional glass fiber-reinforced epoxy composite under quasi-static and intermediate strain rate loading conditions using a servo-hydraulic testing apparatus. The shear properties were found to be quite sensitive to strain rate. Failure shear strength was observed to be increasing with strain rate under dynamic loading whereas the shear modulus decreased with increase in strain rate. The shear modulus and strength were seen to decrease with increasing strain rate in the case of a commingled E- glass/polypropylene woven fabric composite over a strain rate range of 10^{-3}–10^{2} s^{-1}. The matrix viscoelasticity, fiber–matrix interfacial properties, the composite woven reinforcement architecture and the time dependent nature of damage accumulation prediminantly influences the strain rate effects [76].

3. Effect of loading rate on deformation of metal matrix composites

(a) Tensile loading

The strain rate sensitivity of metal matrix composites under tensile loading has been discussed in this section. Adiabatic stress/strain curves at high strain rates can be obtained from compressive or tensile impact tests. Investigations show that Al/SiC_p composites are strain rate sensitive materials and exhibit high velocity ductility under tensile impact. Strain rate sensitivity of composites is a function of the loading speed. At high strain rates the stress/strain curves of Al/SiC are adiabatic in nature which shows thermomechnical coupling which results in higher stress exponent of Al/SiC under tensile impact than under static loading. Isothermal stress/strain curves have same strain hardening effect when thermo-mechanical effect is decoupled [22]. Uniaxial and equibiaxial tensile tests show increased flow stress with initial increasing strain rate. Stain rate sensitivity exponent of A606l/20SiCw composite was found to be independent of strain [77]. Tensile properties of alloy are dependent on strain rate [78]. Negative strain rate sensitivity was observed at lower strain under tensile stress. Flow stress depends on strain rate and temperature non-linearly. Work hardening is comparatively insensitive to temperature but is dependent on strain rate. Work hardening exponent of the composite is higher than that of the matrix at all strain rates. Deformation of particles is sensitive not only to strain rates but also to plastic strain levels [78,79]. Flow stress of W-Ni-Fe composite increases with strain rate but an increase in the test temperature has an opposite effect. Moreover work hardening decreases when both test temperature and strain rate increase. Linear dependence of flow stress on logarithm of strain rate suggests the deformation of W-Ni-Fe composite is predominated by thermal activation mechanism [80]. Lower strain rate sensitivity was depicted in a short alumina fiber reinforced aluminium alloy matrix composite tested in tension over the strain rates ranging from 10^{-3} to $10^{3}s^{-1}$. This can be attributed to the higher tendency of fiber damage and local stress concentration in the composite. When the temperature was increased during tensile testing, corresponding increase in the strain rate sensitivity was observed [81]. Study on high strain rate superplastic behaviour of metal matrix composites have shown that the maximum value of elongation was obtained at a temperature close to the onset temperature for melting of the metal matrix. So the liquid phase plays a prominent role in the high strain rate superplasticity of the metal matrix composite [82]. It is difficult to accurately predict the high strain rate mechanical properties of metal matrix composites as their response to multiaxial loading is very complex in nature since different internal damage modes are developed in them during tension, compression and torsion. The hardening due to strain rate increases with the volume fraction of the reinforcement. Higher flow stress can be obtained in a particle clustered composite due to the more severely strain hardened matrix. The geometry of the reinforcement also influences the strain rate behaviour of metal matrix composites. Cylindrical shaped particles are more suitable reinforcement than spherical shaped particles during high strain rates. Also higher aspect ratio particles functions as more effective reinforcements with increasing loading rates [83,84]. Flow stress and strain rate sensitivity was higher for metal matrix composites with smaller particle size. The rate of damage accumulation is also less for them. Particle cracking followed by the separation of broken-particle segments and matrix cavitation were the sources of damage accumulation. High superplasticity was exhibited by aluminium matrix composites when subjected to tensile loading at very high strain rates. The increase in flow stress with strain rate makes it possible to meet the critical stress criterion which enables the nucleation of supercritical sliding events [85].

(b) Compressive loading

The strain rate sensitivity of metal matrix composites under compressive loading has been discussed in this section. Strain rate sensitivity of composite is higher than that of matrix. It was further found that the composites' strain rate sensitivity increases with increasing strain whereas the matrix sensitivity was constant. Strain rate sensitivity of composite increases with reinforcement particle volume fraction due to increasing particle constraint [79,86].

Failure mechanism in the axial, unconstrained specimens at low strain rates was found to be initiated by microbuckling followed by brooming of fibers at the interface of test plate and sample whereas at high strain rates failure was same as that of quasistatic tests [87]. Dynamic compression of 2024Al/SiC composite containing high reinforcement content reveals large elongation at high strain rates. Heat generated during dynamic compression at high strain rates does not get dissipated through interface of matrix-reinforcement, hence local heating can lead to softening of low melting point alloy matrix. Softening of alloy matrix leads to lowering of strain hardening exponent. Increasing the particle content may lead to increase in strain rate sensitivity; hence the flow stress of composite rises with rise in reinforcement particle content. Under compressive stress MMCs with lower content of particles tend to distribute stress via matrix showing ductile failure of matrix, whereas in case of higher content of particles stress gets transmitted by particle-particle contact revealing brittle damage mechanism dominated by particle-particle networking [88].

Composites display higher strength than monolithic alloys but almost the same strain hardening is observed at large strain showing that composites are more strain rate sensitive than alloys. Moreover the flow stress of composite increases with increase in strain rate [89]. During dynamic deformations the dislocation mobility changes substantially which are generated by misfit strains. It has been found that the plastic incompatibility between particles and matrix results in dislocations tangles around the particles eventually forming dislocation cells whose size is related to particle spacing. Dislocation cell sizes decrease with increasing strain rate. Higher strain rate results in high strength for Al alloy/C fiber composite also. The strain rate sensitivity is by virtue of the matrix and not the fibers [90]. Rise in strain rate sensitivity can be attributed to change in mobile dislocation density due to mismatch strain as well as increased resistance to dislocation motion imposed by reinforcement at high strain rates. Initial strain hardening and high strength at high strain rate for in-situ composite can be attributed to an increase in dislocation density in the matrix of the composite [91].

Mondal et al. [92] have established that SiC concentration does not affect the strain hardening exponent, proof stress, elastic limit and flow stress at room temperature. Increase-decrease tendency of compressive strength with strain rate was observed in the case of SiC particulate reinforced aluminium matrix composite which was studied at strain rates ranging from 10^{-3} to $2.5x10^{3}s^{-1}$ using a split Hopkinson pressure bar. At high strain rates, softening of the aluminium matrix takes place due to the heat generated during dynamic compression. This inturn facilitates better elongation of the composite at high strain rates [93]. The progressive particle fracturing during the compressive deformations can lead to lower strain hardening in the metal matrix composite when compared to the monolithic material [94]. Higher value of strain hardening can elevate the flow strength of the composite material [95]. Matrix cavitation was found in the hot deformation behaviour of spray formed SiC particulate reinforced aluminium matrix composites at high strain rates. This cavitation behaviour can be attributed to the increase in porosity after deformation [96]. The growth of cavity is essentially plastic-controlled. The amount of cavity under equibiaxial tension was found to be slightly larger than under uniaxial tension in the case of SiC whisker reinforced aluminium alloy at high strain rates [97].

(c) Transverse loading

Transverse strength is a matrix dominated property and is influenced by matrix yield strength and fiber volume fraction. With increase in strain rate the flexural strength also increases. Failure mechanism in this fracture mode is fiber bending, fiber cracking and shear failure along fiber length. Microbuckling of fibers takes place along the loading axis. The failure strain in transverse loading shows very little variation with increase in strain rate. Hence, it can be used as a failure criterion for dynamic loading conditions [87].

4. Effect of loading rate on deformation of ceramic matrix composites

Ceramic matrix composites are generally insensitive to loading rates. They show only negligible deformation with increasing loading rate. Lankford et al. [98] observed strain rate insensitivity in SiC whisker reinforced ceramic matrix composites. The tensile behaviour of cementitious composites reinforced using twisted steel fiber shows rate sensitivity while that using hooked fiber shows no rate sensitivity. Also both fiber volume fraction and matrix strength which influences the interface bond properties controls the rate sensitivity in twisted steel fiber reinforced cementitious composite [99].

5. Conclusions

A review on the effect of loading speed (strain rate) on the deformation behaviour of composite materials has been carried out and the following conclusions were made:

i. Polymer matrix composites show high degree of strain rate sensitivity than its metal and ceramic counterparts. The viscoelasticity of polymer matrix, fiber–matrix interfacial properties, composite woven reinforcement architecture and the time dependent nature of damage accumulation predominantly influences the strain rate effects in polymer matrix composites. Plain weave polymer composites have higher strain rate sensitivity than satin-weave, unidirectional and multidirectional composites due to better interaction between the matrix and fibers in them. The failure patterns of polymer composites also changes as the loading speed is increased. The failure mechanisms in FRP composites changes from fiber fracture to matrix cracking with change in loading rate from static to dynamic. Significant variation in interlaminar shear strength (ILSS) is predominant at lower cross head speeds than higher speeds. High failure strain at low strain rates can cause lower value of ILSS. Fiber fracture, matrix cracking, fiber pull-out and delamination are the main damage mechanisms appearing in FRP composites at different loading rates.

ii. Metal matrix composites shows prominent strain rate sensitivity when subjected to tensile, compressive and transverse loading. Both the flow stress and work hardening rate of metal matrix composites are dependent on strain rate. Rise in temperature during tensile testing can significantly enhance the strain rate sensitivity. Reinforcement geometry also influences the strain rate behaviour of metal matrix composites. Superplastic behaviour is exhibited by metal matrix composites during loading at very high strain rates. This is due to localized heat accumulation in the matrix which occurs due to the unavailability of sufficient time for the heat developed during dynamic compression to get dissipated through the matrix-reinforcement interface. Failure strain during transverse loading is less sensitive to strain rate when compared with tensile and compressive loading.

iii. Ceramic matrix composites are generally insensitive to loading speed as they only undergo negligible amount of deformation due to their low ductility.

Acknowledgement

The authors would like to express their sincere gratitude towards the department of metallurgical and materials engineering, NIT Rourkela for providing the necessary facilities and infrastructure for carrying out the research work.

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