Effects of temperature and loading speed on interface-dominated strength in fibre/polymer composites: An evaluation for in-situ environment

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Abstract

The present investigation intends to study the influence of crosshead velocity and in-situ environmental conditioning i.e. high temperature and cryogenic temperature on micromechanical performance of glass fiber/epoxy, carbon fiber/epoxy and Kevlar fiber/epoxy polymer composites. 3-point short beam shear tests were conducted on the conditioned specimens to evaluate the interfacial properties and failure modes which are related to mechanical properties of the composites. The effect of crosshead velocity (within the range 1-10^3 mm/min) on the interlaminar shear strength (ILSS) of all the three composite systems at different temperatures was studied. The glass transition temperature (T_g) of conditioned samples were measured by differential scanning calorimetry (DSC) in the temperature range of 25°C to 150°C temperature. At 1 mm/min loading rate, for both glass/epoxy and carbon/epoxy composites maximum increase in ILSS value was about 85.72% with respect to ambient, while for kevlar/epoxy composite 31.77% reduction in ILSS was observed at -100°C temperature.

Key words: Polymer composites, environmental conditioning, interfacial strength, interlaminar shear strength, fractography, in-situ testing

1. Introduction

In present century, fibre-polymer composites are the promising and reliable materials in different high performance and structural applications. Their superlative properties such as high specific strength and stiffness, high fatigue endurance, good corrosion and abrasion resistance, make them prime choice material in various industries such as aerospace, marine and automotive [1]. During their manufacturing and service periods the materials are exposed to various environments and loading conditions. The performance of these materials is governed by the response of their constituents i.e. fibre, matrix and the existing interface/interphase, in that particular environment. The sizing of fibres generally influences the chemistry and character of the interface/interphase and might generate structural gradient in the polymer matrix (Fig.1). Their susceptibilities to degradation are dependent on nature of environments and each of the constituent's responses differently and uniquely. Among the three constituents, the interface/interphase has very critical role to play on the performance and

reliability of fibre reinforced polymer (FRP) composites [2]. Under low temperature environment or cycling from room temperature to low temperature with applying loads microcracks may generate and propagate in the polymer matrix and/or at the fibre/matrix interface [3].Various structural damages such as fiber/matrix interfacial debonding and potholing or delamination result in degradation of mechanical properties of FRP composites [4]. Cryogenic conditioning stimulates the formation of rows of cups due to coalesce of transverse microcracks that originate longitudinal cracks along the fibre. Potholing or localized surface degradation, micro cracking and delamination, are some of the more dramatic phenomena that can occur as a result of cryogenic cycling. At elevated temperature differential thermal expansion of fibre and matrix may leads to the formation of microcracks at the fibre/polymer interface [5]. The fibre matrix interface also becomes susceptible to aggressive reactions under the exposure of high temperature environment, which can leads to degradation of both the fibres and the matrix.

Interlaminar shear strength is one of the most important mechanical properties of laminated composite which is also an indicative of fibre/matrix interfacial bond strength if all the other parameters are remains constant. Three point short beam shear test can be used to qualitatively evaluate apparent interlaminar shear strength of the laminated composites [6]. For short beam shear test, it is assumed that the specimen is subjected to pure shear loading but the effects of stress concentration cannot be eliminated completely. In a short-beam test, the low span-to-thickness ratio (typically, L/h=4 or 5) minimizes bending stresses, allowing through-thickness shear stresses to dominate, and promoting interlaminar shear failure at the neutral plane [7].For a valid short beam shear test the specimen should fail under delamination mode through mid-plane, but due to the effects of stress concentration and material constraints, the origin of delamination may shift from the mid-plane to either upper or lower interlaminar planes. Further the variation of loading rate makes the stress distribution more complex and the failure of the composite includes various damage modes separately and/or interactively. Since the fibres are usually much stronger than the matrix, one may postulate fibre/matrix debonding and matrix failure as the two primary mechanisms of failure initiation [8]. Delamination and matrix cracks are intrinsically associated in the composite materials primarily under bending loads. Further, the interaction between these two damage modes constitutes a complex damage mechanism that has not been addressed at a realistic level [9]. One of the most frequent damage mechanisms is the delamination between the adjacent plies of the laminate. Many FRP composite components have tapered thickness, curved shapes, and plies with different orientations, which will also make the delamination grow with a mode mix that depends on the extent of the crack. Thus, delaminations generally grow in mixed-mode [10]. The toughest challenge faced by material scientists is to assess and ascertain its behavioural log in a range of loading rates. The heterogeneity and responses of multiple distinct phases to varying loading conditions are most often complex and far away from comprehensive conclusion. The less substantial durability data related to the loading rate sensitivity of FRPs in conjunction with environmental exposures has created more confusion in using high factors of safety, and thus led to increased cost and weight of the composites [11, 12]. The endurance on durability and tailorability is most often underrated. Continuous crack growth usually occurs at low temperature and high strain rates, which promotes the brittle failure of the polymeric composite materials.

The rapid advancement of these fibre-polymer composites outstripped the understanding of appropriate failure analysis techniques. Researchers have investigated the interlaminar shear strength response of fibre-polymer composites at different environmental conditionings. Interlaminar shear strength of unidirectional graphite composites were decreased by 30 % under the exposure of elevated temperature [13]. Investigations on CFRP and GFRP sheets, which are exposed to 600 °C reported, that the residual tensile strength and stiffness severely degraded when the composite is exposed to a temperature, higher than the decomposition temperature of polymer resin and further increase in environmental temperature would not lead any further reduction in the aforesaid properties [14,15]. Effect of thermal environment on the residual mechanical performance of graphite-fabric epoxy composite was evaluated for constant 170°C temperature for 120, 240 and 626 h prior to flexural testing [16]. Unidirectional CFRP composite that had been aged at -196 ˚C for 555 h with half of the failure load undergone about 20% degradation in tensile strength compared to that at room temperature [17]. Some studies on strain rate sensitivity of glass/epoxy, carbon/epoxy, and kevlar/epoxy composite systems have been shown that the mechanical behaviour of these systems is strain rate sensitive [18-23]. Shokrieh et al. studied the in-plane shear failure properties of unidirectional glass/epoxy composites at various stroke rates from 0.0216 to 1270 mm/s [24]. The dynamic shear strength response showed an increase of approximately 37% over the measured quasi-static value. Al-Salehi et al. obtained the lamina in-plane shear properties at various rates of strain on glass/epoxy and Kevlar/epoxy filament wound tubes with winding angles ±55° and ±65°, under internal hoop loading [25]. The results obtained from ±55° specimens indicated that with increasing strain rate from 1 to $400s^{-1}$, the shear strength is increased by 70% for glass/epoxy, and 115% for Kevlar/epoxy materials. There is significant amount of literature available on the effects of temperature on mechanical properties of FRP composites but according to author's knowledge scarcely information regarding the effects of temperatures on interfacial behavior (ILSS) in polymeric composites at different loading rates and temperature has been published to date.

The aim of the present study is to provide in-depth analysis of interlaminar shear test and failure mechanisms of glass fibre/epoxy, carbon fibre/epoxy and Kevlar fibre/epoxy composites under different temperatures and crosshead velocity. Different high and low temperature conditioning were performed using Instron with environmental chamber providing additional information regarding in-situ failure of laminate composites. Following the test, the fracture surfaces of the samples were scanned under SEM to understand the dominating failure modes. Microstructural assessments can also reveal the response of each constituent viz. fibre, matrix resin and the interface/interphase; under temperature and mechanical loading. This paper comprehensively presents the mechanical behaviour and structural changes in fibrous polymeric composite systems during the mechanical loading under high and low temperature service environment.

2. Materials and Experimental Methods

2.1 Materials

Present investigation includes three types of woven fabric reinforcement in epoxy resin i.e. glass fibres, carbon fibres and, kevlar fibres. The epoxy resin used is diglycidyl ether of Bisphenol A

(DGEBA) and the hardener is Triethylene tetra amine (TETA) supplied by Atul Industries Ltd, Gujarat, India under the trade name Lapox, L-12 and K-6 respectively. Some properties of these reinforcements and epoxy resin used in the study are provided in the table-1. The volume fraction of fibres is 60%. The ratio of epoxy and hardener is taken as10:1. The laminated composites has been prepared by hand lay-up method with 16 layers of woven fabric cloth of reinforcement and then placed in a hot press. Then the curing of the laminate has been carried out at 60°C temperature and 20 kg/cm^2 pressure for 20 minutes. The laminates were then removed from the press and kept at room temperature for 24 hours. The test specimens have been cut from the laminates using diamond tipped cutter as per standard.

2.2 Experimental methods

2.2.1 Short-beam shear test

The Short-beam shear tests are frequently applied to polymeric composite materials to evaluate the apparent interlaminar shear strength of the composite system. A testing machine with controllable crosshead speed is used in conjunction with a three-point loading fixture. The shear stress induced in a beam subjected to a bending load, is directly proportional to the magnitude of the applied load and independent of the span length. Thus the support span of the short beam shear specimen is kept short so that an inter-laminar shear failure occurs before a bending failure. This test method is defined by ASTM: D2344-13, which specifies a span length to specimen thickness ratio of five for low stiffness composites and four for higher stiffness composite. The SBS tests have been conducted as per ASTM: D2344-13 with an Instron-5967 testing machine with span to thickness ratio 5 for glass fibre/epoxy and 4 for carbon fibre/epoxy and Kevlar fibre/epoxy composite systems.

Fig 2 (a) represents the schematic view of 3-point short beam shear test (b) glass fibre/epoxy specimen failure during shear test and (c) represents the Instron testing machine with furnace and Dewar. 3-point short-beam shear tests were performed on a 30KN capacity Instron testing machine. The specimens were tested at room temperature, high temperature and low temperature. The shear testing at -50˚C and -100˚C temperature was conducted with specimens by spraying of liquid nitrogen in an environmental chamber where temperature was controlled by temperature controller, liquid nitrogen flow from dewar by controlling the pressure, whereas for high temperature (+50˚C and +100˚C) specimen heated by environmental chamber by heating option. The in-situ tests have been performed on the samples at different temperatures viz; +50° C, +100° C, -50° C and, -100° C inside the environmental chamber of Instron-5967 with 10 minutes holding time to evaluate the inter-laminar shear strength (ILSS). The tests were performed with six crosshead speeds viz; 1, 100,200, 500,700 and 1000 mm/min. For each point of testing 5 to 6 specimens were tested and the average value was taken. The ILSS is calculated from the following expression of equation (1).

$$ILSS = 0.75*F/bt \qquad (1)$$

Where, F=maximum load, b=width of specimen and, t=thickness of specimen

2.2.2 Scanning electron microscope (SEM)

The scanning electron microscope (SEM) has been a well-accepted tool for many years in evaluation of fracture surfaces. To study the different failure mechanisms of the tested samples micrographs of the failure samples was carried out using a JEOL-JSM 6480 LV SEM at 20 KV. For better identification of failure modes the fracture surfaces are tilt around 15˚-20˚. Prior to SEM, the top surface of the specimens were coated with platinum using a sputter coater. The coating is used to make the surface conductive for scanning and prevents the accumulation of static electric charge for clear images during the microscopy.

2.2.3 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry measurements were made using a DSC 821 (Mettler-Toledo Instruments, India) with intra cooler, using STAR software. The temperature calibration and the determination of the time constant of the instrument were performed by standards of In and Zn, and the heat flow calibration by In. The underlying heating rate of 10˚Cmin-1 was used. The samples were referenced with an empty pan with a 50 mL/min nitrogen stream. The samples were heated to well above their bulk T_g for at least 5 min, cooled to well below the Tg and then heated (usually at 1°C/min) with a modulation rate of 1°C/min. The reported T_g was taken as the maximum of the derivative of the heat capacity curves.

3. Results and Discussion

3.1 Glass fibre /epoxy composites

3.1.1 Interlaminar behavior

The variation of ILSS for glass/epoxy composite system in-situ conditioned at +50° C, +100° C, -50° C and -100° C temperatures, and tested at 1, 100, 200, 500, 700, and 1000 mm/min loading rates, is shown in Fig 3. It is clearly evident from the figure that the above-ambient and sub-ambient temperature exposure alters the ILSS values and further at each temperature the ILSS is loading rate sensitive phenomenon, and the results are listed in Table 1. The ILSS values at -100º C temperatures are better as compared to other conditioning temperatures but as the loading rate increased the ILSS decreased. The maximum ILSS for glass/epoxy composite is about 38.37 MPa, obtained at -100° C temperature and 1 mm/min loading speed, with an increase of 85.72% than the ILSS value (20.66 MPa) obtained at ambient temperature at 1 mm/min as shown in Fig.3. Greater value of shear strength at low loading speed can be attributed to longer relaxation time resulting in improved interfacial integrity of the composite material. Higher crosshead speed during testing minimizes the relaxation process at the crack tip. This could be the reason for reduced ILSS values at higher crosshead speed. At -50° C temperature, initially the ILSS decreases from 1 mm/min to 200 mm/min and then increased with further increase in loading rate. The slight fall in the value at 200 mm/min conditioning could be related to the lower degree of cryogenic compressive

stresses at fibre/matrix interface. At +50º C and +100º C temperatures the ILSS increased with increasing loading rate. The reason may be the induced thermal stresses in the matrix region. Thermal stress induced micro-cracks in the polymer matrix and/or, at the fibre/matrix interface may possibly grow without blunting at a steady state. Some microcracks turn to potential cracks at low loading rates and cause significant reduction in interlaminar shear strength of the composite system while as the loading rate increases the time available to propagate the microcracks is less. This can be attributed to higher ILSS at higher loading rates at these above-ambient temperatures. The effects of microcracks and fibre breakage can nucleate the other form of damage such as delamination hence degradation in the thermomechanical properties of the composite occurred [26]. This interfacial separation caused by the delamination may lead to premature buckling of the laminates at high temperature. The life-limiting failure process (delamination) induces stiffness loss, local stress concentration and local instability in the laminate. Further the effect of temperature on the ILSS is shown in Fig.4 at 1mm/min crosshead velocity; percentage change in the ILSS values under the exposure of different temperature is also shown in table-2.

3.1.2 Failure fractography

To better comprehend the interfacial behavior and failure mechanisms of above ambient and sub ambient conditioned glass fibre/epoxy composites, the fracture surfaces after short beam shear tests have been examined by scanning electron microscopy (SEM). SEM micrographs of fracture surfaces are shown in Fig 5. The fracture surface of matrix at -100° C (Fig. 5 A, A') includes extensive riverline markings and fibre imprints. The convergence of pairs of planes from the tributaries of the rivers into one crack, form a trace markings known as river lines. Therefore the direction of crack growth is the direction in which riverlines converge. As multiple crack initiation and growth of riverlines shown in Fig 5 A. In Fig. 5A' fibre imprint refers to fibre matrix debonding. Here we also observed delamination failure modes on the laminate. At -50° C a significant difference in interfacial microstructure is observed which is shown in Fig. 5B, B'. The appearance of the cusps at relatively high magnification; cusps size is similar to that of the fibre spacing. However, the size of cusps is larger than particularly those which develop with in resin rich regions. These failures do not display a complete fibre matrix debonding from the fibre surface [27]. At high temperature, the resin exhibits greater plasticity, and cusps resulting from the microcracks are thicker and undergone greater deformation than at room temperature as shown in fig.5C, C' and Fig.5D, D'. The increase in cusps thickness implies fewer microcracks formed because of the increased plasticity.

At +50° C temperature the matrix region consist few large cusps whilst the matrix between packed fibres consist a large amount of small cusps (Fig.5 D, D'). At +100˚C, the SEM micrographs show significant loss of polymer matrix between the fibres which affects the overall integrity of the composite system. These matrix dominated damages result in lower ILSS of glass/epoxy at +100° C.

3.2 Carbon fibre /epoxy composites

3.2.1 Interlaminar behavior

The interlaminar shear behaviour of woven fabric carbon fibre/epoxy composite with loading rate at different temperature is shown in Fig.6

Interlaminar shear strength (ILSS) is one of the most important interfacial properties for composites. To better understand the interfacial strength between the carbon fibre/epoxy composites, three-point short beam shear test method was used to evaluate the interlaminar shear strength of the composites. It is readily observed that at -100˚C temperature the carbon fibre/epoxy composites possess better ILSS compared to other testing temperatures. At -100˚C temperature the variation of ILSS with loading rate is shown in fig.6. It can be seen from fig.6 that the as the rate of loading increases the ILSS of the composite also increases upto 500 mm/min but, after 500 mm/min shear values decreases because microcrack density has exceeded the critical crack density for delamination. The energy release rate monotonically decreases as the delamination failure grows [28]. Thus ILSS value decreases with increasing loading speed after 500mm/min. As shown in Fig.6 at -50˚C temperature lower shear values were observed as compared to that of ambient temperature due to thermal presstress on the matrix resin. Here matrix behaves as brittle in nature which reduces the effective strain to failure and it is the source of matrix cracking [29]. But at 200mm/min the shear value decreases with loading rate. From the relaxation behavior the thermal presstress would vanish after sufficient period of time. But with increasing loading speed the shear value shows no significant changes due to some microcracks behaves less dangerous since their stress concentrations are small. The laminates failed by very little delamination or no delamination because of low crack densities. However at high temperature +50˚C and +100˚C there is a significant change in ILSS values with loading speed. These results are probably due to the shear band propagation in matrix resin at high temperature. Here crack propagation in matrix resin prone to by crack jumping (unstable or stick-slip) mode at slow loading rate. Yield stresses decreases with decreasing strain rates and increasing temperature, stick-slip crack growth may be attributed to plastic deformation at the crack tip prior to crack initiation [30]. Thus stress intensity factor is dependent on temperature and time. The size of the crack jump increases as the temperature approaches to glass transition temperature of the resin matrix. Thus shear value increases with increasing loading speed. But the ILSS value decreases with other testing conditions. At the vicinity of a glass transition temperature (T_g) viscoelastic processes decreases the modulus owing to unfreezing of molecular motion. At decreasing temperature due to thermal contraction a tighter packing and thus higher bond strength exist. As carbon fibre exhibit good interaction to matrix, they constitute good adhesion between fibre/matrix interface regions. When the force rises to a significant fraction of the force required to break a strong bond and threatens to break the backbone of the molecule, a domain unfolds. Thus, it could avoid the breaking of a strong bond in the backbone [31]. Hence ILSS value increases with increasing loading speed. Matrix ductility increases the critical loads for delamination onset and delamination resistance in the composite laminates. At this temperature it is very difficult to find the delamination failure mode. Further the effect of temperature on the ILSS is shown in fig.7. The results shown were obtained at 1 mm/min crosshead velocity. Percentage

change in the ILSS values under the exposure of different temperature is also shown in table-3 for carbon/epoxy composite system.

3.2.2 Failure fractography

The fracture surfaces for the carbon fibre/epoxy composites at different temperature have been studied by the SEM and the results are shown in Fig.8. As the shear load increases the cusps steps become deeper following shallow cusps on the surface at -100˚C temperature as shown in Fig.8 A, A'. This failure mode begins to dominant these cusps become more erect and closely spaced. At -50˚C temperature fibre dominated fracture surface was observed in Fig.8 B, B'. Here the tilt cusps can be used to deduce the crack growth direction. A plastic deformation zone ahead of the crack tip may be formed by this matrix deformation and matrix microcracking. This deteriorates integrity of the material and can results in low strength at high loading rate. Fig.8 C, C' shows the fracture surface of carbon fibre/epoxy composites at ambient temperature. These micrographs report good fibre/matrix strength and cohesive fracture in the matrix. Microscopically carbon fibre shows crenulations and radial pattern appears on the fibre ends [28]. At high temperatures matrix dominant failure modes were observed as shown in Fig.8. Matrix yielding in Fig.8 D, D' and extensive loss of matrix at +100° C can be observed in Fig.8 E, E'. Presence of these damage modes result in deterioration in the structural integrity of the composite system in high temperature environment.

3.3 Kevlar fibre/epoxy composites

3.3.1 Interlaminar behavior

The effects of temperature on ILSS of Kevlar fibre/epoxy composites are shown in Fig.9. Here the specimens are subjected to insitu testing at high and low temperatures. It is readily observed that at ambient temperature the specimens possess better ILSS compared with other conditioning temperature. The variation of ILSS here is the net result of good adhesion at interface by physical and mechanical bonding at the interface. The ILSS value increases with increasing loading rate but reduction of ILSS value occurred may be due to less post curing effect. The thermal conditioning is likely to change the chemistry at the fibre/matrix interface. The unique chemistry and morphology of Kevlar fibre is also manifested by the composite behaviour [32]. The bond between the fibre and the surrounding matrix can be weakened by exposure to active environments.

At high temperature residual stress effects are negligible, mechanisms such as fibre/matrix debonding and matrix ductility become important. As the temperature increases the substantial segments of polymer chains have enough energy to surmount local barriers which hinders molecular motions and begins to move. Here deformation refers to change in shape without change in volume. A ductile tearing mode of failure may result when large-scale shear yielding occurs at a crack tip. Still at high temperature (close to glass transition temperature) molecular motion is so extreme that even chain entanglements are no longer effective in restricting molecular segmental flow [33]. This change in flow behavior of polymer is due to decrease of the degree of chain interpenetration. In addition to the enhanced flow, confinement effects on the chain conformation can perturb the interfacial

properties and ultimately the long term stability of the material [34]. So there is presence of weak interface at high temperature. The weak interface readily allows crack deflection. Here the composites can sustain a large deflection by permitting the absorption of more energy. At low temperature a noticeable improvement of shear value was observed compared to high temperature. The result may be attributed to the development of greater amount of shrinkage compressive stress. The fibre/matrix debonding is dominant for the low temperature conditioned Kevlar/epoxy composites. Further the effect of temperature on the ILSS is shown in Fig.10. The results shown were obtained at 1 mm/min crosshead velocity. Percentage change in the ILSS values under the exposure of different temperature is shown in table-4.

3.3.2 Failure fractography

The scanning photomicrograph Fig 11 A, A' shows the good adhesion between fibre and matrix in the unconditioned laminates. This strong interface may not permit a large deflection during fracture. The nature of this interface bond is not only significant for the strength and stiffness of the composites but it also controls the mechanism of damage and its propagation. In fig 11 B.B', the fibres show longitudinal splits which is known as fibrillation.

Further, identification of local crack growth directions by examining these fibres is almost impossible. For the specimen tested at ambient temperature, a fibre/matrix debonding microstructure is shown on the Fig.11 C, C'. These composites display a complex matrix debonding from the fibre surface. A considerable amount of surface debris which has been ground into the fracture surface is shown in Fig.11 D, D'. At +50˚C temperature the fractography shows fibre matrix debonding along with fibre fibrilliation. A resin rich region associated with undulation and interstitial sites exhibit riverlines which provide information about the local crack growth direction and scale of plastic deformation. Kevlar fibre, themselves fail in shear, leading to the formation of kink banding within the fibre. Fig.11 E, E' represents the matrix ductility failure with fibre failure of Kevlar fibre/epoxy composites at high temperature.

3.4 Thermal analysis

Glass transition temperature (T_g) of all the samples is evaluated and summarised in Fig 12. For glass/epoxy composite, the higher glass transition temperature is recorded for the samples exposed to -100°C temperature and the lower T_g value for +50°C temperature conditioned specimen (see Fig.12(a)). For carbon/epoxy composite specimens, exposure to +100°C temperature leads to significant increase in T_g as compared to ambient specimen (25°C temperature), while no significant change in T_g were observed for +50°C, -50°C, and -100°C temperature conditioned specimens (see Fig.12(b)). For Kevlar/epoxy composite, the higher glass transition temperature is observed for the samples exposed to +50°C temperature and the lower T_g value for the specimens tested at ambient temperature (see Fig.12(c)).

It is interesting to note that epoxy- based composites made with carbon fibre exhibit high glass transition temperature as compared to other epoxy based composites. The structure of the degraded material during conditioning of the carbon fibre is maintained by extensive inter-chain bonding

between the polymer chain through C=O and N=H groups [35]. Within the low temperature conditioning range the glass transition temperature for the carbon fibre composites were found to be lower than that of glass fibre and Kevlar fibre epoxy composites. This might be attributed to unstable wetting of carbon fibre by epoxy resin at low temperature.

4. Conclusions

The influence of sub-ambient and above-ambient temperature and loading rate on the interlaminar shear strength of glass fibre/epoxy, carbon fibre/epoxy and Kevlar fibre/epoxy composite laminates has been studied. Considering interlaminar shear strength and delamination behavior, the tested laminate characterized by SEM to reveal various failure modes. The present study may possibly reveal the following conclusions:

Delamination is the life limiting failure process in a composite material. It induces great loss of stiffness, local stress concentration, and buckling failure of composite material. At -100°C temperature glass fibre/epoxy laminates shows better ILSS value but decreases with increasing loading speed. At +50º C and +100º C temperatures the ILSS increased with increasing loading rate. It is readily observed that at -100˚C temperature the carbon fibre/epoxy composites possess better ILSS compared with that of the other testing temperature. But after 500 mm/min shear values decreases because microcrack density has exceeded the critical crack density for delamination.

Furthermore, for Kevlar fibre/epoxy composites at ambient temperature the specimen possess better ILSS compared with other conditioning temperature. The variation of ILSS here is the net result of good adhesion at interface by physical and mechanical bonding at the interface. Different failure modes such as different types of cusps on the matrix region, riverline marking, fibre/matrix interfacial debonding, plastic deformation of matrix and fibre fracture were observed for the composite specimens failed after the exposure to different above-ambient and sub-ambient temperature.

It is found that the type of fibres and matrix present in the composites influences the amount of heat required and the glass transition temperature. This brings out that the microstructure of the fibre/matrix within the composites found to be influencing the amount of thermal energy absorbed by the materials and consequently affect the mechanical properties.

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Figure Captions

Fig 1: Schematic representation of a fibre/matrix interface or interphase.

Fig 2: (a) Schematic representation of 3-point short beam shear test. (b) Experimental set up for 3-point short beam shear test (c) Instron machine used for the test.

Fig.3: Variation of ILSS with loading rate for glass/epoxy composite system at different temperatures.

Fig.4: Interlaminar shear strength of glass/epoxy composite at 1 mm/min for different temperature.

Fig 5: Scanning electron microscopy (SEM) images of the glass fibre/epoxy composites: (A, A') at -100˚C temperature (B, B') at -50˚C temperature (C,C') at ambient temperature (D,D') at +50˚C temperature (E,E') at +100˚C temperature

Fig.6: variation of interlaminar shear strength with different loading rates at different temperatures for carbon fibre/epoxy composite system.

Fig.7: Interlaminar shear strength of Carbon/epoxy composite at 1 mm/min for different temperature.

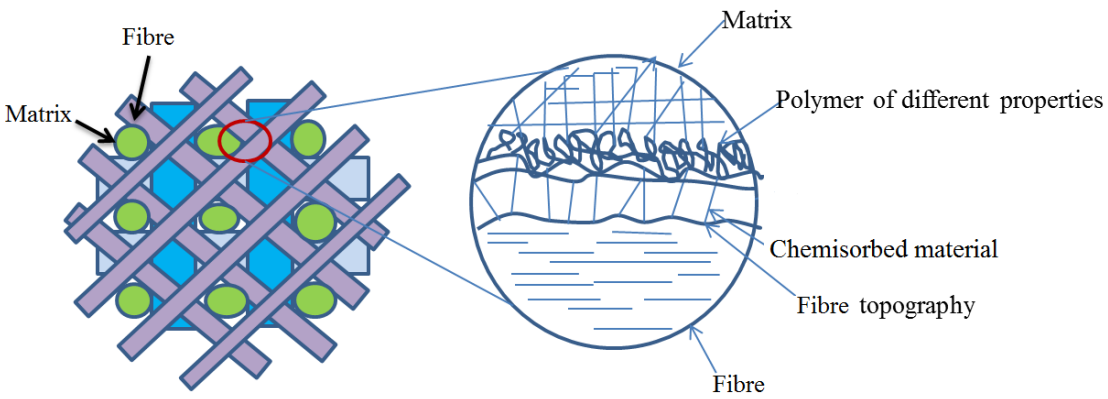
Fig 8: Scanning electron microscopy (SEM) images of the carbon fibre/epoxy composites: (A, A') at -100˚C temperature; (B, B') at -50˚C temperature; (C,C') at ambient temperature; (D,D') at +50˚C temperature; (E,E') at +100˚C temperature.

Fig.9: Variation of ILSS with loading rate for Kevlar/epoxy composite system at various temperatures and loading rates.

Fig.10: Interlaminar shear strength of Carbon/epoxy composite at 1 mm/min for different temperature.

Fig 11: Scanning electron microscopy (SEM) images of the Kevlar fibre/epoxy composites: (A, A') at -100˚C temperature (B, B') at -50˚C temperature (C,C') at ambient temperature (D,D') at +50˚C temperature (E,E') at +100˚C temperature

Fig 12: Comparison of glass transition temperatures of glass fibre/epoxy composites at different conditioning temperature. (a) Glass fibre/epoxy composites (b) Carbon fibre/epoxy composites (c) Kevlar fibre/epoxy composites



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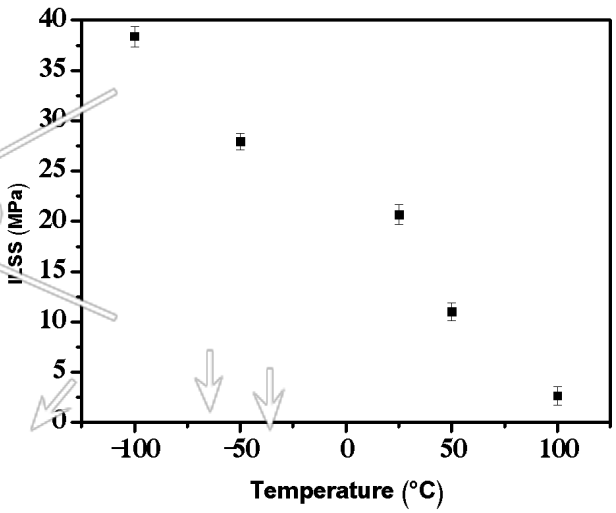

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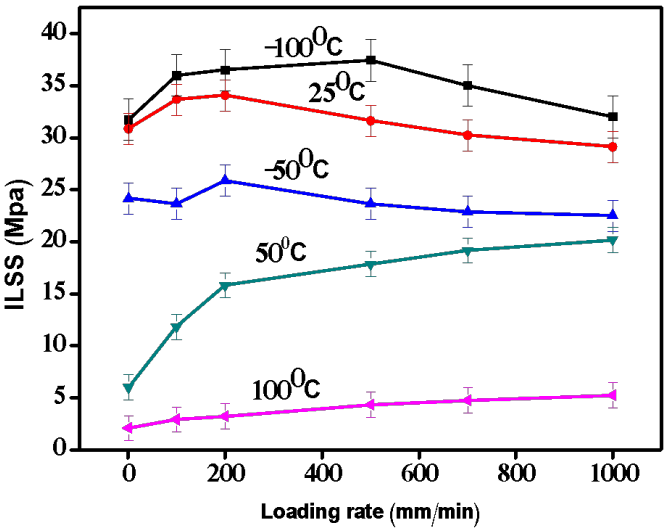


Fig.6: variation of interlaminar shear strength with different loading rates at different temperatures for carbon fibre/epoxy composite system.

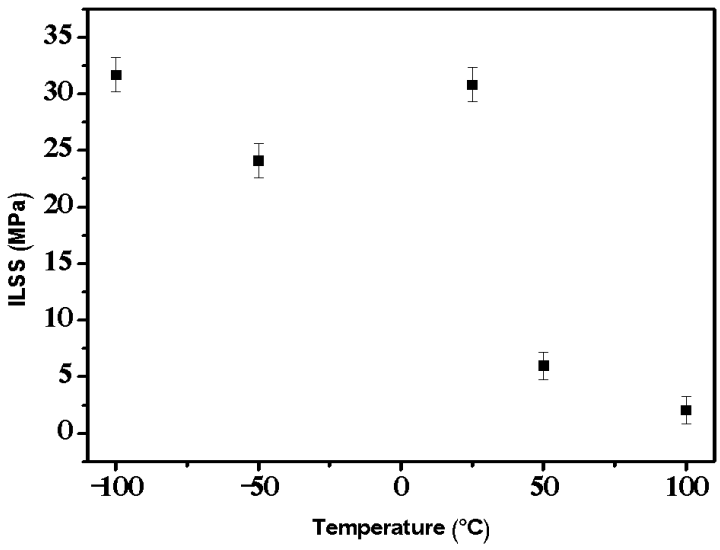
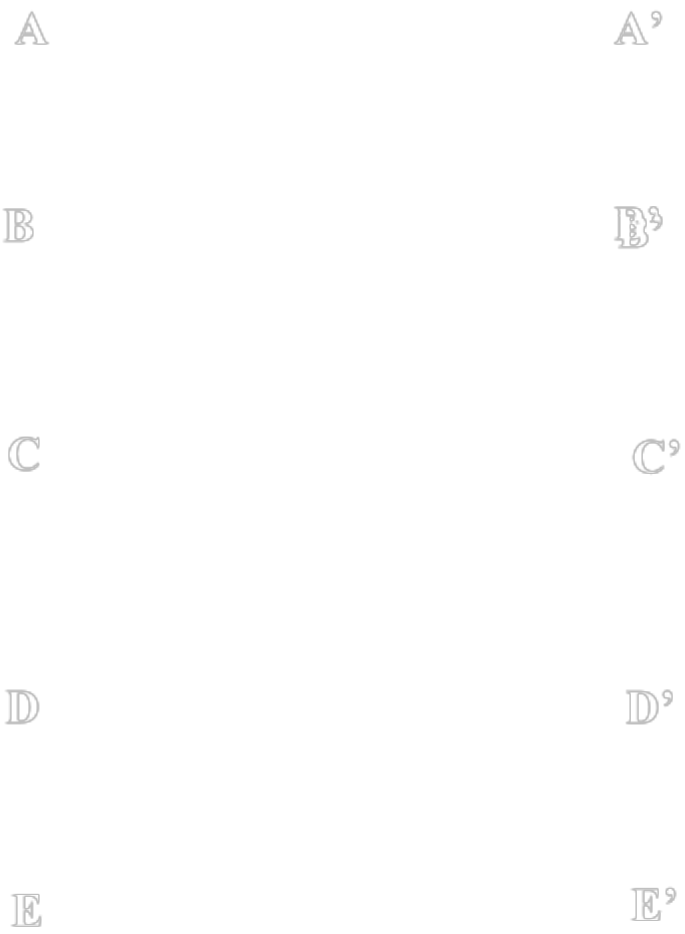


Fig.7: Interlaminar shear strength of Carbon/epoxy composite at 1 mm/min for different temperature.



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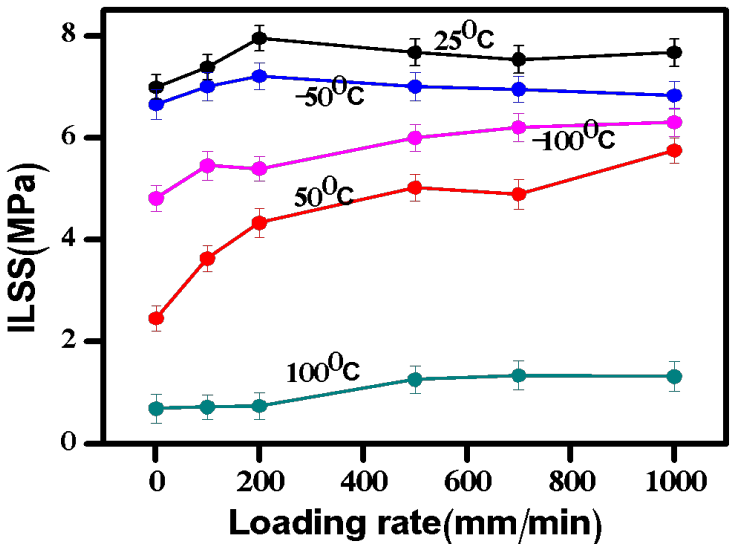

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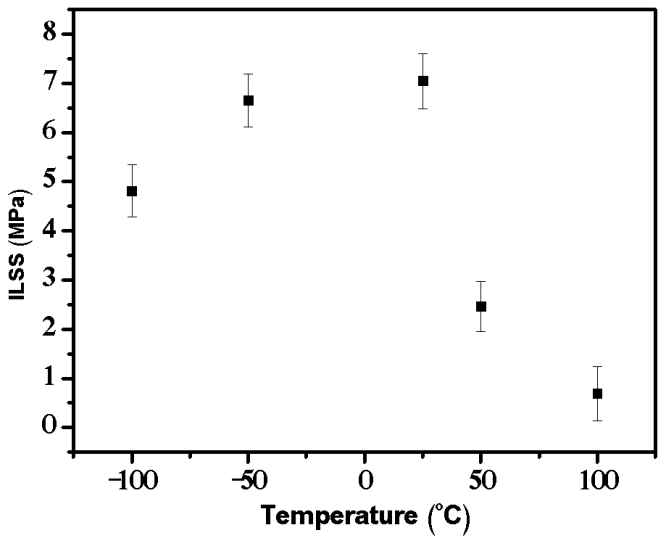

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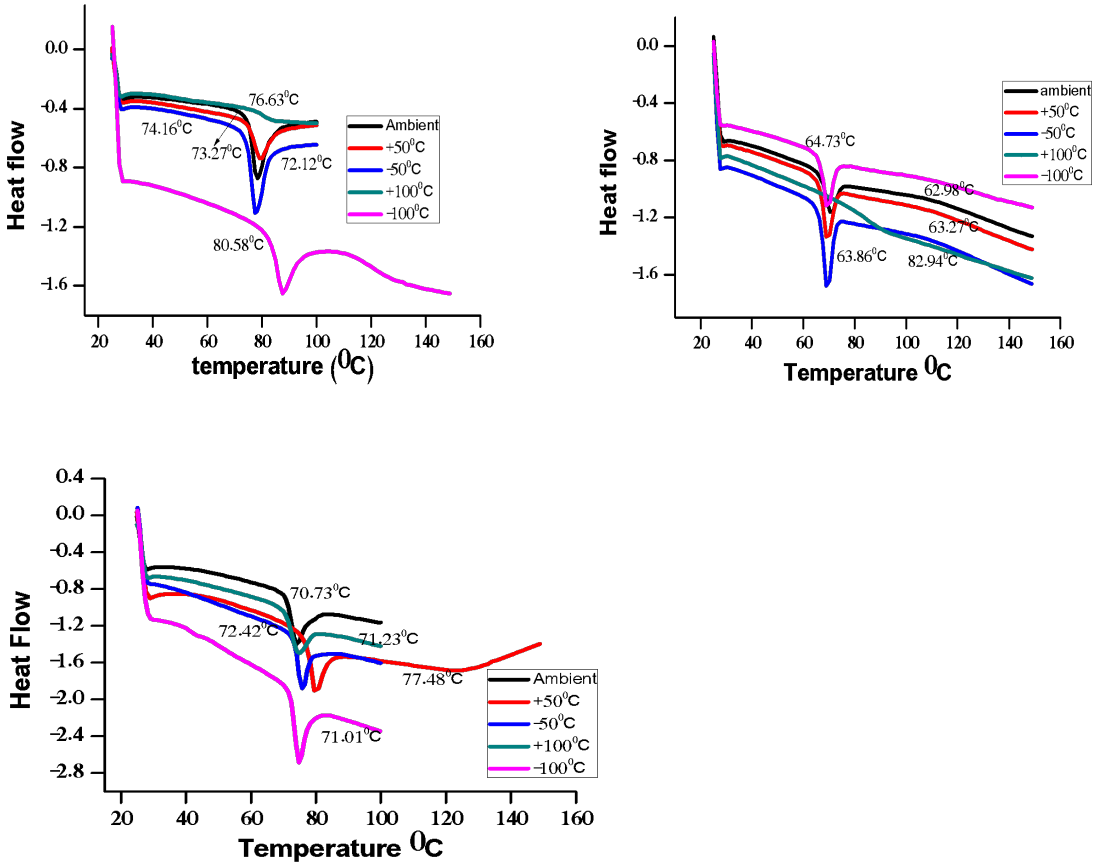

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