Hygrothermal effects on the dynamic compressive properties of graphite/epoxy composite material

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A B S T R A C T

The effects of temperature and moisture on the response of graphite/epoxy laminated composites to high
strain rate penetration loading using the Split Hopkinson Pressure Bar apparatus was investigated. The
results show that in the thickness direction loading under extreme temperature, moisture and combined
moisture and temperature conditions, the compressive strength, elastic modulus, and energy absorbed
decrease exponentially. Failure strain and displacement increase linearly with temperature and moisture
with particle velocity increasing linearly with temperature but independent of moisture content. The
combined effect of temperature and moisture on the damage process was more apparent than the effect
of temperature or moisture acting alone. At the same impact energy, the results show the failure prop-
erties to be sensitive to the strain rate, with energy absorbed increasing linearly with strain rate at
low temperature and remaining relatively constant at high temperature. The compressive yield strength
increases as the strain rate increases both at low and high temperatures while the ultimate strength
(maximum strength) decreases slightly with strain rate.

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1. Introduction

The temperature and moisture content of a material can determine its elasticity and the thermoplastic properties. An increase in temperature and moisture, which inherently increases the molecular movement of the material, can readily alter the shape and volume of the material. Such alteration is further complicated when the material is subjected to high strain rate loading conditions. Understanding the effects of moisture and temperature in the behavior of composite structures is necessary in aerospace, military and civilian applications because many composite structural parts and military installation encounter high and low temperature variations in the presence of moisture. Characteristic failure responses such as cracking, strength loss, and moisture swelling can be detrimental to the integrity of the design. Materials tend to become hard and brittle at low temperatures and many brittle materials tend to crack at such conditions due to rapid change in volume caused by differential temperature changes. Composite materials are generally known to have a lower compressive strength in fiber direction than in tension. As temperature is lowered, the hardness, yield strength, and modulus of elasticity increase while fracture toughness, thermal expansion coefficient and specific heat tend to decrease in general. Studies have shown that lowering the maximum attainable particle volume fraction will increase the stiffening and strengthening of composite materials if the particles have elongated shapes [1]. Graphite/epoxy composite materials have high stiffness and low thermal expansion over a wide temperature range. A decrease in temperature has been observed to initiate a crack in graphite/epoxy laminates due to increase in tensile stresses. On the other hand, an increase in temperature would lower the stress level causing the crack to close [2]. Dutta [3] has shown that a preexisting crack inactive at normal temperature can become self-propagating at low temperatures, and may cause structural failure. Thus, the effect of temperature in composite materials is important design parameters that need further investigation.

A composite material may gain about three percent in weight due to absorption of moisture when exposed to a humid environment [4]. It appears that moisture mainly degrades matrix-controlled properties and causes a time-shift in the viscoelastic response of polymer in a manner that is analogous to the influence of temperatures [5,6]. Recent studies by Hague and Hossain [7] on the effects of temperature and moisture on the high strain responses of woven composite at temperatures ranging from 23 °C to 204 °C revealed that when loaded in the thickness direction, compressive failure strength, strain, and dynamic modulus increase with strain rate. They observed that the maximum strain rate effect occurred at glass transition temperature of 121 °C. Hu
and Sun [8] showed that when a polymeric composite is above its glass transition temperature, the polymer can instantaneously reach thermodynamic equilibrium which can be considered as a measure of physical aging. Below this glass transition temperature, it was conceived that the polymer cycles through continuous changes in molecular and material properties as it progresses toward thermodynamic equilibrium [9].

The objective of the studies presented in this paper was to investigate the combined and individual effects of temperature and moisture on the dynamic failure responses of laminated graphite epoxy composites subjected to high strain rate loading for temperatures ranging from 80 to 160 °C at glass transition temperature. This paper makes some significant contribution to the current state of knowledge of hygro-thermal effects of composites by extending Hague and Hossain [7] work to cold temperature range at constant strain rate. The study also presents a destructive characterization of degradation of material property.

2. Theoretical considerations

2.1. Strain-strain rate and stress measurements

The basic assumptions and validity of Split Hopkinson Pressure Bar (SHPB) in the study of the dynamic behavior of materials are well documented and summarized in Hashin [1] including minimum dispersion, elastic conditions of the bars, homogeneous state of stress in the plate material, and non-dimensional uniaxial stress. For the P-SHPB, it is further assumed that sample strain is much greater than the total strain of the bar and the specimen fixture. In the previous paper by Nwosu [10], these assumptions were carefully investigated and repeated for the present set up and found to be satisfied.

A simplified schematic of the wave propagation is shown in Fig. 1. Dynamic loading of composite plates is provided by the longitudinal impact load $F_0$ of the striker bar resulting in a uniaxial stress $\sigma$ pulse generated at the incident bar as:

$$\sigma(t) = F_0 \frac{A_b}{A_c} = (\rho c_0) v(t)$$

where $c_0 = dx/dt$ is the velocity of the wave pulse in the bar, $v(t)$ is the particle velocity, and $\rho$ is the density of the striker bar material. Accurate measurements of the wave pulse in dynamic impact studies are important since the wave train is considered as the propagation of the disturbance or vibration of the particles.

Accurate measurements of the wave pulse in dynamic impact studies are important since the wave train is considered as the propagation of the disturbance or vibration of the particles. With a specimen of the cross sectional area, $A_c$, placed in a specimen fixture and sandwiched between the incident (input) and transmitter (output) bars of the cross section area, $A_b$, equilibrium at each interface (input bar/penetrator, penetrator-head/specimen, specimen fixture, and fixture/output bar) encountered is satisfied by the continuities of forces and velocities at the interface. The incident, reflected and transmitted strain waves are known from strain-gauge measurements on the input and output bars [10,11]. The input and output bars interface displacements are denoted as:

$$u_i(x, t) = u_i(x, t) + u_r(x, t) = f(x - ct) + g(x + ct)$$

$$\varepsilon(t) = \frac{\partial f(x, t)}{\partial x} + \frac{\partial g(x, t)}{\partial x} = \varepsilon_i(t) + \varepsilon_r(t)$$

$$v(t) = \dot{u}(t) = \frac{\partial f(x, t)}{\partial t} + \frac{\partial g(x, t)}{\partial t} = -v_i(t) + v_r(t)$$

Load on the interface, $P_1 = A_b \rho_0 (\varepsilon_i(t) + \varepsilon_r(t))$

The displacement in incident bar–specimen interface:

$$u_i(x, t) = \int_0^t (-v_i(t) + v_r(t)) dt$$

Similarly, on the displacement of the transmitter bar is:

$$u_r(x, t) = u_r(x, t) = h(x + ct)$$

$$\varepsilon_i(t) = \frac{\partial h(x, t)}{\partial x} = e_i(t)$$

$$v_i(t) = \dot{u}(t) = \frac{\partial h(x, t)}{\partial t} = v_i(t)$$

Load on the interface, $P_2 = A_b \rho_0 e_i$

The displacement of the transmitted bar–specimen interface is $v_f(t)$

Table 1: Properties of [(IM7/8551-7) graphite/epoxy composites.]

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Temp. (25 °C)</th>
<th>Temp. (82 °C)</th>
<th>Temp. (121 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal compressive strength (Dry)</td>
<td>1.62 GPa (235 ksi)</td>
<td>1.38 GPa (200 ksi)</td>
<td>1.28 GPa (185 ksi)</td>
</tr>
<tr>
<td>Longitudinal compressive strength (Wet)</td>
<td>–</td>
<td>1.10 GPa (160 ksi)</td>
<td>–</td>
</tr>
<tr>
<td>Longitudinal compressive modulus (Dry)</td>
<td>148 GPa (21.5 msi)</td>
<td>145 GPa (21.0 msi)</td>
<td>152 GPa (22.1 msi)</td>
</tr>
<tr>
<td>Longitudinal compressive modulus (Wet)</td>
<td>–</td>
<td>143 GPa (20.7 msi)</td>
<td>–</td>
</tr>
<tr>
<td>Fiber volume fraction</td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>1272 kg/m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass transition temp. (Dry)</td>
<td>157 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass transition temp. (Wet)</td>
<td>116 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lay-up stacking sequence:</td>
<td>[±45/0/90]s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Schematics illustration of wave propagation.
For a uniform stress through a thin specimen the loads on the interfaces are assumed equal ($P_1 = P_2$, and $\epsilon_r + \epsilon_t = \epsilon_t$) and the sample stress, strain, and strain rate, can respectively be defined as:

\[
\sigma_s(t) = \frac{P_1 + P_2}{2A_s} \approx \frac{A_b}{A_s} E_0 \epsilon_t(t)
\]

\[
\epsilon_s(t) = \frac{u_2 - u_1}{L_e} \approx -\frac{2c_0}{L_e} \int_{t_0}^t \epsilon_r(t) dt
\]

\[
\dot{\epsilon}_s(t) = -\frac{2c_0}{L_e} \epsilon_r(t)
\]

$L_e$ is the effective length between the bar ends taken to be equal to the length of the specimen when the specimen strain is much greater than the strain in the bar fixture and penetrator head.

2.2. Energy measurements

Assuming that the energy delivered by the incident bar and penetrator is equal to the total expendable energy for the penetration process, the energy transferred by the propagating compressive wave to the composite plate is derived as:

\[
E_p = \int_0^t F_i(t) du_n \equiv E_A
\]
where \( F_i(t) \) is the net compressive loading force and the net plate displacement \( \Delta u_n \) is simplified to become

\[
du_n(t) = \frac{c_0}{E_0} \int_0^t \left[ \frac{\sigma_i(t)}{C_0} - \sigma_r(t) \right] dt
\]  

(8)

\( E_p \) can be obtained as the integrated area of the force–displacement curve over the duration of the wave. Substituting \( du_n \) expression from Eq. (8) into (7), the net energy to be expended for the damage generation process plus energy losses to the fixture is expressed as:

\[
E_A = \left( \frac{A_0}{E_0} \right) \int_0^t \left[ \sigma_i(t)^2 - \sigma_r(t)^2 - \sigma_(t)^2 \right] dt
\]

Thus, Eq. (9) gives the total energy absorption curve decomposed into energy absorbed by the plate (\( \Delta E_{abs} \)) and the elastic strain energy (\( \Delta E_s \)). The numerical integration is carried out with time shifted to zero and all three waves beginning at the same time and for the same time duration, \( t \). This is justified by placing the strain gages at mid-point of the incident and transmitted bars at the same distance from the specimen.

The validity of the proposed P-SHPB method can be justified since only the strain measurements on the input and output bars and the geometry of the bars and specimen are required for the determination of particle velocities, displacements and energy absorption. The drawback in the continuity assumption, however, is that energy losses to the specimen fixture and the penetrator head could reduce the relative strain reaching the gage at the mid-point of the output bar. This will result in Eq. (9) over-estimating the energy measurement. An experimentally determined correction factor that accounts for the total energy loss to the penetrator and fixture are usually applied to minimize the error due to the losses. Although the error could reduce the accuracy of P-SHPB method for absolute measurements of materials properties, P-SHPB remain a reliable tool for better understanding of penetration/perforation mechanics and dynamic failure behaviors of composite materials subjected to high strain rate loading.
2.3. Moisture and temperature variation in absorption in composite

The equation associated with moisture diffusion through a material in the thickness direction \( z \) as described in Fick’s equation is written as:

\[
D_z \frac{\partial^2 c}{\partial z^2} = \frac{\partial c}{\partial t},
\]

Subject to the boundary conditions:

\[
c = c_0 \quad \text{for} \quad 0 < z < h \quad \text{at} \quad t = 0
\]
\[
c = c_\infty \quad \text{for} \quad 0 < z = 0 \quad \text{and} \quad \text{h at} \quad t > 0
\]

where \( c \) represents the moisture content as a fraction of dry mass of the composite, \( h \) is the thickness of the composite, and \( D_z \) is the diffusion coefficient. For a sufficiently long time, the composite will reach a final equilibrium concentration, \( c_\infty \). Hence, from Eq. (10) subject to the boundary conditions of Eq. (11) as discussed in detail in [12,13], yield the solution defined as:

\[
\bar{c} = \frac{1}{h} \int_0^h c \, dz
\]

where

\[
\bar{c} = c_0 \quad \text{at} \quad t = 0
\]
\[
\bar{c} = c_\infty \quad \text{at} \quad t = \infty
\]

Substituting Eq. (12) into (13) and using (14) for a sufficiently long time, the Eq. (12) can be approximated as in [13], and therefore

\[
\eta = \frac{\bar{c} - c_0}{c_\infty - c_0} = 1 - \frac{8}{\pi^2} \sum_{j=0}^{\infty} \frac{1}{2j+1} \exp \left[ -\frac{\pi^2 D_z t}{h^2} \right]
\]

For a short time and for an initial moisture content, \( c_0 = 0 \)

\[
\bar{c}(t) = 4c_\infty \left[ \frac{D_z}{\pi h^2} \right]^{1/2} \sqrt{t}
\]

The coefficient of diffusion, \( D_z \), can be estimated from the slope of the linear portion of \( c(t) \) versus \( t^{1/2} \) curve from Eq. (15) given as:

\[
\alpha = 4c_\infty \left[ \frac{D_z}{\pi h^2} \right]^{1/2}
\]

from which \( D_z \) can be determined as:

\[
D_z = \pi \left[ \frac{zh^2}{4c_\infty^{1/2}} \right]^{2}
\]
3. Experimental considerations

3.1. Materials

The target laminates are (IM7/8551-7) graphite/epoxy composites consisting of IM7 graphite fiber with Hercules toughened resin matrices with the properties shown in Table 1 [21].

Fig. 2 shows the experimental set up for penetration/perforation split Hopkinson Pressure Bar. The motivation is a continuation of investigation that began at Cold Region Research and Engineering Laboratory using CRREL environmental chamber for cold temperatures only [11]. The specimen and the mating ends of the Hopkinson bar are enclosed in a specially designed cooling chamber made of aluminum with foam lining inside to keep the chamber cool with less minimum leaks. Cooling is done by circulating nitrogen gas into the chamber.

3.2. System calibration

The purpose of the system calibration is to obtain a relationship between the compressed pressure applied to the system and the striker velocity delivered to the incident bar and the energy transferred to the incident bar using infrared photo gate detectors just before the impact.

A photo gate detector and a flag with the length of 0.023 m were used to measure the duration of the blocking time in photo gate detectors. The time measured in photo gate detectors is divided to the length of the flags to determine the velocity. The photo gate detector was positioned to the end of the impact bar to measure the impact velocity \( V_i \) just before impact. In order to measure the impact bar velocity, the flag was attached to the end of the striker rod. Once the pressure is applied, the rod with the flag moves toward the incident bar blocking the infrared beam in photo gate detectors just before the impact. The blocking time is obtained from a software program connected to the photo gate detectors (Data Studio). Then the blocking time is divided to the length of the flag to determine the impact bar velocity just before the impact. The impact energy transferred to the system is equal to the kinetic energy of the impact bar and can be expressed by

\[ E_i = \frac{1}{2} m_i V_i^2 \]  

where \( m_i \) is the mass of the striker bar. Finally, calibration curve can be obtained plotting striker velocity versus applied pressure and corresponding energy versus applied pressure data. Fig. 3b gives the calibration curves showing there is a nonlinear relationship between the striker velocity and applied pressure.

An alternative but approximate technique was adopted in the presented case. This involved cooling or warming up the specimen in a separate cooling or oven chamber. Once the required temperature is obtained, it was set stable for at least 15 min before conducting the experiment. The sample was held in-between the horizontal pressure bars (the incident and transmitter bars) while in penetration experiments, the sample was simply...
supported inside the sample holder. Thermocouples were used to monitor the specimen’s temperature. The difficulty is in transferring the specimen from chamber to the perforation fixture. To account for the change in the specimen ambient temperature during exposure to outside temperature, the exposure time and warm up rate were measured to generate a calibration curve shown in Fig. 3.

**Fig. 3.** Summary normalized plot of amplitude reflected and transmitted stress wave to at varying (a) temperatures, (b) moistures, and (c) combined moisture for 32-ply dry specimen at 110 J striker bar impact energy.

Fig. 3 shows the warming up curve for the specimen cooled in dry ice and allowed to warm up as function of exposure time and the moisture absorption curve as functions of square root of moisture absorption time. The temperature curve shows that the sample remained at dry ice temperature of $-80^\circ C$ for about 90 s before starting to warm up. Therefore, exposure time of more than 90 s is assumed to be too long for the experiments.

**Fig. 8.** Summary normalized plot of amplitude reflected and transmitted stress wave to at varying (a) temperatures, (b) moistures, and (c) combined moisture for 32-ply dry specimen at 110 J striker bar impact energy.

**Fig. 9.** Variation of stress–strain curves with changes in (a) low temperature and (b) high temperature for 32-ply graphite/epoxy at 110 J striker bar impact energy.
Fig. 10. Variation of stress–strain curves with changes in (a) moisture and (b) combined temperature and moisture for 32-ply graphite/epoxy at 110 J striker bar impact energy.

Fig. 11. Effects of (a) Cold temperature and (b) high temperature on ultimate strength/strain for 32-ply graphite/epoxy at 110 J impact.

Fig. 12. Variations of compressive strength and yield strength with (a) cold temperature and (b) high temperature for 32-ply graphite/epoxy at 110 J striker bar impact energy.
at dry–ice temperatures. The exact temperature at the time of impact could be determined from the rate curve (curve rate) by recording the time of exposure.

The perforation tests were carried out in the thickness direction at 110 J striker bar impact energy in the temperature ranging from –80 °C to 160 °C to investigate the effect of extreme temperature on the composite failure response under dynamic compressive loading conditions.

For the effect of moisture, samples of 32-ply dry graphite/epoxy ([±45/0/90]4s) laminates were submerged and weighted down in water from 1 h to 72 h at room temperature. The dry weights (before and after) were measured to estimate the moisture content as the total mass of the absorbed moisture divided by the dry weight of the sample. At the end of each soaking period, perforation test was performed at 110 J strikers bar impact energy at 24 °C room temperature.

Application of Eq. (16) is shown in Fig. 4 with the plot of moisture content, which is a function of square root of moisture absorption time. The moisture absorption curve show that, the composite moisture diffusion started approaching equilibrium after about 24 h of soaking time.

For the combined effects of temperature and moisture (hygro-thermal effect), 32-ply original dry graphite/epoxy ([±45/0/90]4s) was soaked for 24 h in water and then subjected to variable temperature between –24 and 25 °C.

4. Experimental results and discussions
4.1. Variations of stress waveforms

The effects of temperature on the stress waveforms are shown in Figs. 5–7. As depicted in Fig. 5, the stress waveform appears more distorted after one full wavelength of the wave at high temperature than at low temperature. The waveforms at cold temperatures (–80 °C, –60 °C) show slight distortion of the reflected wave compared to the same at room (24 °C) temperature. As the temperature increases from –80 °C to 160 °C in Fig. 5, the distortion of the stress waveform increases. The observed distortion is mainly due to the degradation of the material properties by temperature both at low and high temperatures. Fig. 6 also shows the increasing distortion of the waveform as moisture content increases as clearly demonstrated by Fig. 6c, which shows greater degradation than the eave form for the dry specimen (Fig. 6a). Corresponding effect of moisture content in Fig. 7 also shows slight distortion of the waveform at increasing moisture content compared to the composite laminate at zero moisture content indicative of increased degradation of the specimen as the temperature decreases from room temperature to –24 °C. The results clearly show that moisture content has similar effect on the graphite/epoxy composite as that of temperature variations with the effects more pronounced at elevated temperature and high moisture content.
The above observations are made clearer in Fig. 8 by normalizing the wave amplitudes relative to amplitude at room temperature or zero moisture content. It is clear that the amplitude of the reflected and transmitted waves is a function of temperature, moisture and hydrothermal variations, which is at lower range ($R_r$ and $R_t < 1.0$) than when it is in dry and room temperature conditions. The hydrothermal effect shown in Fig. 6 depicts the combined effect of temperature and moistures. The composite with 0.37% moisture content was subjected to temperature variations ranging from $-24$ to $24\,^\circ C$. It can again be seen that the stress waveform at 0.37% moisture content is more distorted than the waveform at $24\,^\circ C$, and all three waveforms at hydrothermal conditions are more degraded with reduced reflected wave amplitude than the dry specimen at room temperature. The ratio of the amplitude of reflected wave at increasing temperature to the amplitude at room temperature increases only slightly with increase in temperature. In contrast, the amplitude of transmitted wave relative to the amplitude of transmitted wave at room temperature increases to maximum at room temperature before decreasing to a minimum at glass transition temperature between $120\,^\circ C$ and $160\,^\circ C$.

The variations of the longitudinal compressive elastic properties are also shown in Figs. 11–14. The ultimate strength of the composite increase as the temperature increases from $-80\,^\circ C$ to room temperature (Fig. 11a) but decreases as temperature reaches elevated temperatures (Fig. 11b). The longitudinal compressive modulus and yield strength on the other hand are significantly affected by temperature variation as shown in Fig. 12 especially at high temperatures. In contrast, the ultimate strain only increases slightly with temperature variation at both extremes. It was originally hypothesized that stiffness matrixes would increase at lower temperatures, causing the Young's modulus to decrease. However, previous studies by Dutta et al. [14,15] have shown that the laminate's stiffness could slightly increase initially but will tend to degrade upon further cooling. It is conceivable that further cooling will increase the thermal mismatch between the fibers and matrix resulting in an increase in the thermoelastic residual stress. When such residual stress exceeds the matrix strength, debonding and transverse micro cracks will develop in the matrix. The result of such micro cracks is the reduction of the laminate's stiffness. Thus, under extreme condition of low and high temperatures, it is possible that the graphite/epoxy composite properties could cycle between minimum and maximum strength depending on the thermal mismatch between the fiber and the matrix. The cycle could also be caused by the debonding and subsequent hardening of the matrix.

4.3. The variations of the longitudinal compressive elastic properties

The variations of the compressive elastic properties of the composite are also shown in Figs. 11–14. The ultimate strength of the composite increase as the temperature increases from $-80\,^\circ C$ to room temperature (Fig. 11a) but decreases as temperature reaches elevated temperatures (Fig. 11b). The longitudinal compressive modulus and yield strength on the other hand are significantly affected by temperature variation as shown in Fig. 12 especially at high temperatures. In contrast, the ultimate strain only increases slightly with temperature variation at both extremes. It was originally hypothesized that stiffness matrixes would increase at lower temperatures, causing the Young's modulus to decrease. However, previous studies by Dutta et al. [14,15] have shown that the laminate's stiffness could slightly increase initially but will tend to degrade upon further cooling. It is conceivable that further cooling will increase the thermal mismatch between the fibers and matrix resulting in an increase in the thermoelastic residual stress. When such residual stress exceeds the matrix strength, debonding and transverse micro cracks will develop in the matrix. The result of such micro cracks is the reduction of the laminate's stiffness. Thus, under extreme condition of low and high temperatures, it is possible that the graphite/epoxy composite properties could cycle between minimum and maximum strength depending on the thermal mismatch between the fiber and the matrix. The cycle could also be caused by the debonding and subsequent hardening of the matrix.

**Fig. 15.** Degradation of compressive elastic modulus with temperature.

\[
\sigma(e, T) = \sigma_0 + K(T) \varepsilon^n
\]
\[
\sigma(e, c) = \sigma_0 + K(c) \varepsilon^m
\]
Thus, the combined effect of temperature and moisture on the velocity both remain constant with temperature. The plate at composite.

and other temperature depended on phase changes of the composite.

Fig. 13 demonstrates the effect of moisture content on the compressive properties. While the elastic modulus and yield strength decrease with moisture content, the composite ultimate strength and strain remain relatively independent of moisture content. This as expected for matrix dominated property such as compressive modulus and strength since water has the tendency to weaken the bonds and therefore degrade the strength. The elastic modulus decrease linearly as the specimen become more saturated with water while the failure strength remains constant as the sample saturates.

For the combined effects of temperature and moisture, the composite plates were soaked in water for 24 h after which they were cooled to −24 °C and 10 °C. Each sample was then tested at 110 J striker bar impact energy. Fig. 14a and b shows that elastic modulus and ultimate strain decreases with moderate increase in temperature from −24 to 24 °C while the ultimate and yield strengths are not drastically affected. The failure strain and particle velocity both remain constant with temperature. The plate at −24 °C (cold) sample shows slightly higher yield than sample at 24 °C. The damage here appears to be dominated by elastic failure. Thus, the combined effect of temperature and moisture on the damage process is more significant than the effect of moisture or temperature acting alone. Thus, environmental factors such as temperature and moisture could change the failure characteristics of composite materials.

The results show that the degradation of matrix stiffness and strength properties effectively prominent at both temperature extremes. The matrix dominated properties of longitudinal compressive strength decreases by 9% as opposed to cold temperature at 32%, which decrease at high temperature while the ultimate strength increased by 12% at low temperature and decrease 10% at high temperature. Similarly, the ultimate strain increased by 22% at high temperature. The observed behavior is probably due to higher stiffness and brittle properties at low temperatures which indicates that the strength of the composite is significantly degraded by warm temperature than by the cold temperature. The ultimate compressive strength for the dry specimen is significantly higher than that of the wet sample.

Fig. 15 shows the degradation of the elastic properties by temperature. The slope of the straight line portion is determined as $1.476 \times 10^{-5} \text{ s}^{1/2}$ from Table 4 and using Eq. (14), the diffusion coefficient was determined as $2.0 \times 10^{-8} \text{ mm}^2/\text{s}$ which is in close agreement with published result of $2.62 \times 10^{-8} \text{ mm}^2/\text{s}$ [14] for graphite/epoxy laminate.

4.4. Variation of energy absorption and dynamic properties

The effect of temperature on energy absorption-time history of composite plate penetrated at 110 J striker bar impact energy is investigated at temperature range from −80 °C to 160 °C are illustrated in Figs. 16 and 17. Energy absorbed increase linearly during the initial loading of the specimen up its peak before decreasing due to strain energy released in delamination. Comparison of Figs. 16 with Fig. 17 clearly shows that moisture content effect has a significant consequence on energy absorption than temperature effect. As temperature decreases (Fig. 16a) or increases (Fig. 16b) without any moisture, the residual energy absorption decreases showing that thermal contraction (compression) due to temperature decrease has the same effect in reducing the energy absorption due to thermal expansion (tension) from the temperature increase. Similarly, as moisture increases, Fig. 17 shows that energy absorption also decreases. However, comparison of Fig. 16a and b and Fig. 17a reveals that moisture does not only decrease the residual energy, Fig. 19 shows that it also significantly decreases the peak energy available for the penetration/perforation event. This means that the presence of moisture weakens the compressive strength of a fiber-epoxy based composite material by lowering the absorbed energy needed to initiate and propagate damage on the material. The most detrimental effect is the combined effect of lowering the temperature when moisture is already present in the composite. A residual energy at room temperature (24) without moisture was 6.5 J (Fig. 16) compared to 3.5 J and 2.0 J at −24 °C and 24 °C (Fig. 17b) with 0.37% moisture content, respectively. Both the peak energy and residual energies are affected by the moisture content.

The summary result in Fig. 18 shows that although the particle velocity generated in the damage process remain unchanged at both low and high temperatures, the peak energy and displacement (laminated deformation) increase with increase in temperature. The total strain energy released and hence the residual energy of the composite in the damage process increases with increase in temperature. Earlier results in the range of −60 °C to 24 °C show that energy absorbed increases with increase in temperature [16]. In contrast, Fig. 19 shows a significant decrease in energy absorbed with increasing moisture content. For the combined effect of temperature and moisture shown in Fig. 20, peak energy absorbed and residual energy both decrease with
temperature. It is not clear why the particle velocity remains independent of temperature and moisture. It appears that the cold temperature "freezes" the particles from motion while they continue to absorb energy. This may explain the reason for increased brittle behavior of the sample at cold temperature. The compressive stress–strain curve showing an increase in yield stress as the
Fig. 20. Combined temperature and moisture effect on peak energy absorbed, particle velocity and displacement for 32-ply graphite/epoxy at 110 J.

Fig. 21. Strain rate-time history for the same 110 J impact energy at (a) low temperature, (b) high temperature, and (c) moisture absorption.
temperature is decreased suggests that the effect of temperature could be to “harden” the material by “freezing” the particle motion and increasing the energy absorption.

4.5. Effect of strain rate on specimen failure properties

The dependence of various properties and behavior of materials under dynamic loading is investigated in this section. Mechanical properties vary significantly with strain rate and it is a more critical parameter than the velocity of deformation for evaluation of dynamic failure processes. Fig. 21 shows the time history of strain rate for various temperatures at the same impact energy. Comparison of the results at low and high temperature at the same impact energy (Figs. 21 and 22b) shows that strain rate varies more significantly at low temperature than at high temperature. The strain rate varies with temperature. Fig. 22 shows a maximum at −80 °C and significant decrease as the specimen warms up to −40 °C. On the average, the strain increases slightly as the specimen warms up from −40 °C to 160 °C. Figs. 21c and 22b clearly show that moisture has negligible effect on the strain rate.

It could be seen from these results that the damage initiated during the loading and unloading stages accumulated in 175 microseconds within the region of a constant strain rate. The rate at which composite plate deform under dynamic loading condition of the incident stress wave is an important damage characterizing parameter since it determines the validity of the experimental data. A critical assumption of use of a Hopkinson bar test is for the stress wave to be uniform within the specimen. It has been discussed that strain rates may not be constant in a Hopkinson bar test [17]. The strain rate-time histories from the present investigation clearly proved this not to be the case. The strain rate-time history indicates the existence of strain plateau within the time of the completion of the penetration process. The specimen experiences the highest compressive stress within the first few seconds of interaction with the compressive incident wave and continues to deform even after this stress is unloaded. For all the temperatures investigated, the specimen rapidly reached a constant strain rate and particle velocity within the first few microseconds of the test and remained constant for more than 200 μs. Thus, there is more than enough time for the damage event to be completed and be
measured. The constant particle velocity or strain rate region clearly shows uniformity of the propagating wave, validating the assumption of uniform stress in the specimen.

Fig. 23 shows the effects of strain rates on peak values of energy absorbed by the specimen, particle velocity, and compressive strengths (ultimate and yield strengths). At its maximum strain rate at the same impact energy, the results shows that the failure properties appear to be sensitive to the strain rate. Fig. 23 clearly shows that the peak particle velocity and energy absorbed increase linearly with strain rate at low temperature (Fig. 23a) and remain relatively constant at high temperature (Fig. 23b). On the average, the compressive strength is also observed to be sensitive to strain rate; the yield strength increases as the strain rate increases both at low and high temperatures. In contrast, the ultimate strength (maximum strength) decreases slightly with strain rate.

A threshold strain rate is observed above which the specimen will begin to respond to the incident compressive stress. Fig. 21 shows that the damage begins to accumulate when the strain rate reaches the plateau region. This observation decomposes the strain rate into regions exhibiting elastic behavior and the plateau region or region of incipient plastic deformation above this value. This observation is in agreement with strain rate dependent theory originally proposed by Malvern [18]. The theory decomposes strain rates into an elastic and plastic portion and predicts that a material will reach a state of incipient plastic flow after certain amount of elastic strain has been attained. Subsequently, the specimen begins to retain or dissipate the incident energy for minor damage events such as delamination when the strain rate is above this value. The specimen deformation (measured by the particle displacement) and velocity increase linearly with strain rates. It appears from the current investigation that laminated composite specimen experience highest strain rate at low temperature or that cold temperature accelerates the rate at which composite materials fracture than high temperature. This is expected as materials become more brittle and easier to fracture at low temperature in contrast to more plastics or plastic behavior at higher temperature.

5. Conclusions

The effects of laminate orientation and temperature on the material properties of graphite/epoxy laminated composites using the Split Hopkinson Pressure Bar apparatus lead have shown that temperature has significant effect on the material properties of the graphite/epoxy laminates. The longitudinal Young’s modulus increases with decrease in temperature. The energy absorbed is found to decrease with decreases in temperature, and with further cooling, the energy absorbed increases simultaneously. It further demonstrates that energy absorbed and elastic modulus decrease linearly with increase in water absorption while no significant effect on the failure strength was observed. The results also highlights that the failure strain and displacement increases linearly with water absorption, while failure strength, particle velocity all remains independent of water absorption. Finally, the combined effect of temperature and moisture on the damage process was more evident than the effect of temperature or moisture acting alone.

At the same impact energy, the results show the failure properties to be sensitive to the strain rate; the peak particle velocity and energy absorbed increase linearly with strain rate at low temperature and remain relatively constant at high temperature; the yield strength increases as the strain rate increases both at low and high temperatures. In contrast, the ultimate strength (maximum strength) decreases slightly with strain rate.

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