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A microstructural study of Gr/Ep composite material subjected to impact

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Abstract

Fracture morphology and texture were observed on the impact generated graphite/epoxy composite fragments. The work identifies and explains changes in the surface texture of the fragments generated at different impact velocities (122 to 610 m/s, 400 to 2000 ft/s) and over a wide range of specimen temperatures (−54 to 24°C, −64 to 75°F). The composite panels were impacted by spherical steel projectiles, and the entire spall was carefully collected after the impact. The spall was differentiated according to different sizes and shapes. A few fragments representing each shape and size were selected to analyze the surface morphology using scanning electron microscopy (SEM). Change in the surface texture was observed according to the different sizes and shapes, and the change in size and shape of the fragments was credited to the change in impact force. The results following from the close and intense observation of several SEM fractographs revealed that the surface texture of the fragments is strongly dependent on the type of forces acting at the point of impact resulting in four different modes of failure: delamination, transverse matrix cracking, fiber fracture and fiber-matrix interface debonding. Published by Elsevier Science Ltd.

1. Introduction

This paper deals with the microstructural analysis of the fracture surface of carbon composites subjected to the ballistic impact force and represents an extension of the work reported earlier by Dutta and his colleagues [1–3]. The damage sustained by a fiber composite material during impact may include fiber breakage, matrix cracking, delamination and plastic deformation. In high velocity impact problems, i.e., at velocities above V_{50} level (which means that the probability of perforation is 0.5 or above) the energy transferred from the moving projectile to the composite target plate is expended in four primary modes of fracture [4]: delamination, transverse matrix cracking, fiber fracture and fiber-matrix interface debonding. The fracture surface is likely to show the telltale signs of all these failure modes. But before discussing that, we will briefly review the failure and fracture characteristics of the laminates under impact.

Sun and Yang [5] found that factors that affect the extent of damage are the impactor's mass and velocity, the plate's stiffness and Hertzian contact behavior. Sierakowski and Chaturvedi [6] noted that delamination is the dominant fracture mode in graphite/epoxy system. Foos [7] also confirmed that the delamination is the primary source of energy absorption. Sjoblom et al. [8] found that bending during the impact caused compression failures on the impacted surface and tensile failures on the rear side of the laminate. Bowles [9] believed that most matrix cracking and delamination

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were a result of shear stresses, and tensile stresses were responsible for the propagation of delamination. But several investigators suggest that the tensile wave is the main factor that initiates and propagates delamination. According to Yarve [10], during the impact phenomenon, after the initial contact, a compressive wave propagates toward the rear surface and eventually reflects in the form of tensile wave that initiates delamination. This reflecting tensile stress wave is more widespread and significant than shear stresses acting through the thickness. Czarnecki [11] also found that compressive stress wave had sufficient amplitude such that, with reflection from rear surface, delamination would easily occur. Stress wave events proved to have greater significance earlier in the impact sequence than flexural events. Czarnecki also observed an increase in the energy absorption, delamination area, and damage volume until the V_{50} velocity was reached. Above the V_{50} velocity the damage volume decreased sharply and quickly attained a constant.

The fractographic features from impact and its relation to the failure are of interest. Very little information on the genesis of the special fractographic features like hacklemark formation is available in literature, except that a large number of researchers have observed their presence related with brittle failure [12,13]. Purslow [14] showed that in static failure, the presence of the relative stiff fibers increases the influence of shear stresses on the resin, and hacklemark development under such conditions is suppressed, but cleavage and hackle formation are common under high strain rate loading (impact). Lau et al. [15] studied the microstructure of a commercial glass fiber composite specimens failed at different test temperatures. He explained the formation of hackle-like pattern using a simple model as shown in Fig. 1. The sequence of delamination crack propagation resulting in hackles is as follows: (a) applied specimen force, P, initiates cracking adjacent to a fiber, (b) as the crack propagates, tensile stress S_2 forms at the unbound fiber matrix interface due to vertical bending of the constituents, (c) secondary cracks S_3 initiated by S_2, then propagate from the primary crack at approximately 45° (associated with maximum shear) so as to partially relieve the surface tensile stresses, S_2, and (d) this procedure is repeated over and over, creating a family of cracks. Ultimately, a complete fracture of the composite results, exposing platelets that produce a hackle-like pattern. The increased fracture surface of the hackle pattern morphology means more surface energy dissipation and therefore an increase of the interlaminar fracture toughness. Fractographic study of the graphite/epoxy fatigue specimens by Morris and Hetter [16] reveals that the formation of hackles or striations may be limited and will not occur in Gr/Ep fatigue specimens in which the applied stress has exceeded 70% of the ultimate compressive strength, whereas striation or hackle-like surface texture is observed when the failure is ultimately by tension.

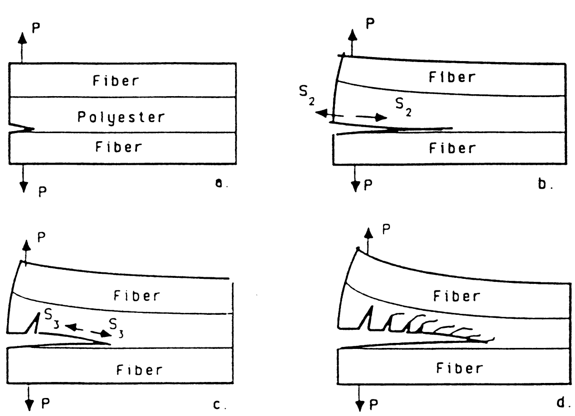


Fig. 1. Formation of hackle-like pattern in polyester matrix glass composite (after Ref. [15]).

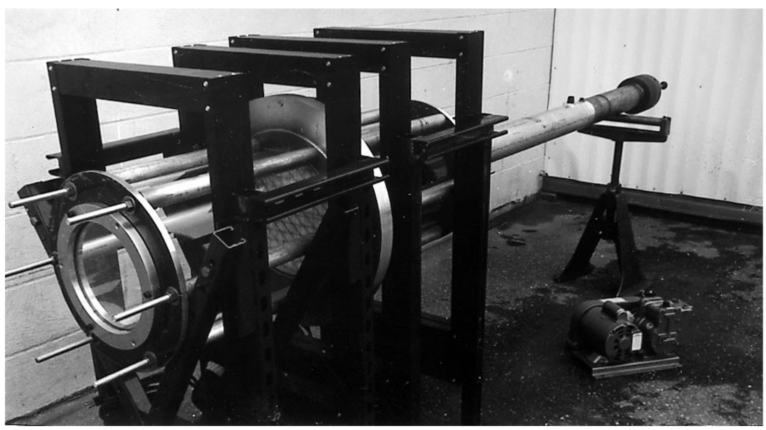
Wang and Socie [17] examined the hacklemarks of the fracture surface formed as a result of delamination that is caused due to the tearing fracture associated with interlaminar shear stresses. They concluded that the surface of the debonded fibers depicting clean surface matrix residues is related to the weak interfacial bonding. Most of the fractured surfaces of the unidirectional composites showed a clean and smooth matrix surface, indicating the absence of interlaminar shear forces. Usually cross-ply specimens showed a hackle-type pattern on the failed surfaces, as the interlaminar stress is expected to be higher for these laminates than for unidirectional composites. Whitney and Browning [18] also found that in short beam shear tests on unidirectional composites, complex failure modes in the presence of extremely high combined stress gradients caused the hackles. Dutta et al. [1] observed hackle type texture on the impact generated fragments. They discussed about the frequency and spacing between the hackles in detail. They found that the hacklemarks present a periodic formation of sigmoidally shaped ridges and troughs running roughly parallel to the fiber direction and located in the matrix between them. The spatial periodicity is manifested in a direction parallel to the fibers. The second observation is that the wavelength of these hackles appears to increase as the distance between the neighboring fibers increases. The wavelength of the hacklemarks is of the order of inter fiber distance. They also observed that ridges appear to be slanted at an angle to the fiber axis. Dutta et al. offered an explanation that the hackles result from intense resonant vibrations of the matrix contained between the two adjacent fibers. They anticipated an increase in spatial frequency with increase in impact velocity, and the amount of material missing from the region occupied by hackles should increase with the increase in the intensity of the applied (impact) stress. It is stated that the hacklemark wavelength is a function of the inter fiber space occupied by matrix, and its characteristic length is associated with the rate of impact event.

2. Experiments

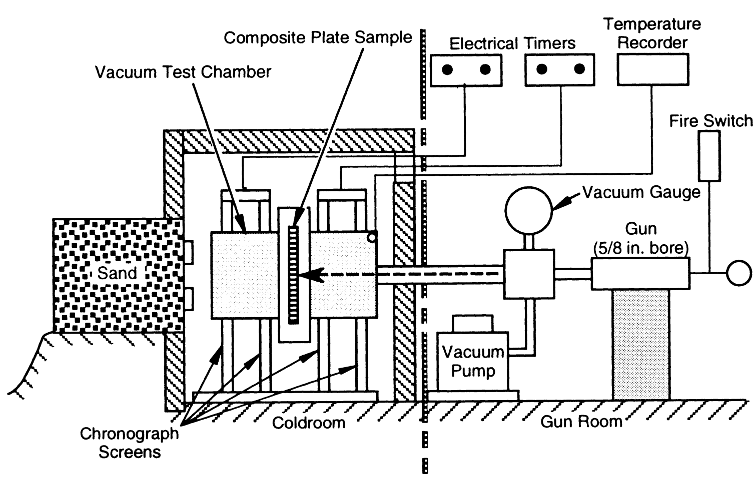
The experiments involving different types of lay-ups of Graphite/Epoxy composite panels were conducted at two different laboratories: (1) US Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH, and (2) Air Force Research Laboratory, Wright-Patterson Air Force Base (WPAFB), Dayton, OH.

At the Cold Regions Research and Engineering Laboratory (CRREL), unidirectional, AS4-3501-6 graphite/epoxy panels of $[0]_{16}$ and $[0/90]_{8s}$ 32-ply laminates, and 6061-T6 aluminum plates were used as targets to ballistically impact 14.23 mm (0.5625 in) hardened steel spheres by a 15.87 mm (0.625 in) bore powder gun at velocities varying from 152.4 m/s (500 ft/s) to 426.7m/s (1400 ft/s). Five different test temperatures ((24°C, 75°F), (−18°C, 0°F), (−29°C, −20°F), (−40°C, −40°F), (−54°C, −65°F)) of the target were used. At Wright-Patterson Air Force Base (WPAFB), the only variable was impact velocity, and it involved $(0°/22.5°/45°/67.5°/90°/-67.5°/-45°/-22.5°)_{2s}$ 32-ply AS4/3501-6 graphite/epoxy panels. The velocities ranged from 122 m/s (400 ft/s) to 610 m/s (2000 ft/s).

The photograph of the experimental setup used at CRREL is shown in Fig. 2(a) and a schematic in Fig. 2(b). The test setup has been described in detail by Dutta et al. [1] in 1996. It mainly consists of a powder gun, which was used to fire solid 14.23 mm (0.5625



(a)



(b)

Fig. 2. (a) Photograph of the experimental set up for impact at CRREL. (b) Schematic of the experimental set up for impact at CRREL.

in.) hardened steel spherical projectiles weighing 11.88 g. Shotgun shells are used as cartridges in the gun, which includes a primer and a suitable sabot. Primer is basically used to ignite the gunpowder, which gives thrust to accelerate the projectile, and sabot is used to hold and guide the projectile leaving the shotgun shell. 'Red Dot' gunpowder is used as the igniting powder in the cartridge. The impact velocities are controlled by varying the amount of gunpowder used, which is measured in grains.

Three sets of highly sensitive chronograph light screens were used for velocity measurements. A set of light screens consists of two individual light screens separated by 30.5 cm (1 ft). Each set of light screens is connected to individual universal counter that clocks the time taken by the projectile to pass the light screen set. One set is placed in front of the gun barrel to record initial velocity, and one set is placed after the panel to record the exit velocity of the projectile. The third set at the end of the transparent Lucite chamber is used to double-check the exit velocity. The target plate is sandwiched between two Lucite chambers, which leaves the panel in a partially clamped boundary condition. Two Lucite chambers are used to collect the spall fragments on both the front and rear side of panel. Figure 3 shows the fragments collected from the rear side of a panel.

For the experiments involving low temperatures, two liquid nitrogen cylinders were used to reach the desired low temperature. The mechanism involves expansion of liquid nitrogen to gaseous form by dripping the liquid nitrogen from the full cylinder into the empty cylinder at a very slow rate. Thus expanded nitrogen gas is allowed to fill the two Lucite chambers until the target plate reaches the desired temperature. The temperatures are measured by digital thermometers with the help of two thermocouples placed one each at the front and rear side of the target plate. Equilibrium state of temperature is said to be reached within the panel when the two thermocouples read the same temperature.

Initial and residual weight of the panel were recorded for each test. After each test the weights of front and rear side spall fragments were recorded separately in all cases of composite panels. Fragments were collected carefully from the Lucite chambers, and were then stored in separate containers for further SEM observations. Care was taken to prevent dust in the glass chambers, which can contaminate the fragments, by cleaning them with ethyl alcohol before each test.

The test setup of the WPAFB is shown in Fig. 4. At WPAFB experiments mainly three velocity measurement devices were used: break wires, light screens and electromagnetic coils. Break wires are the thin (40 SWG) wires placed across the shotline and spaced at known distances. The time of each wire's breaking is assessed to the projectile and used to obtain a velocity. All the light screens and break wires were connected to a data acquisition system. An image analysis equipment was used to calculate the projected area of complex shapes such as shear plugs, fragments of different sizes and shapes, and delamination areas within the composite laminate.

3. Results and discussion

An analysis was performed to establish the relationship between energy absorption and different modes of

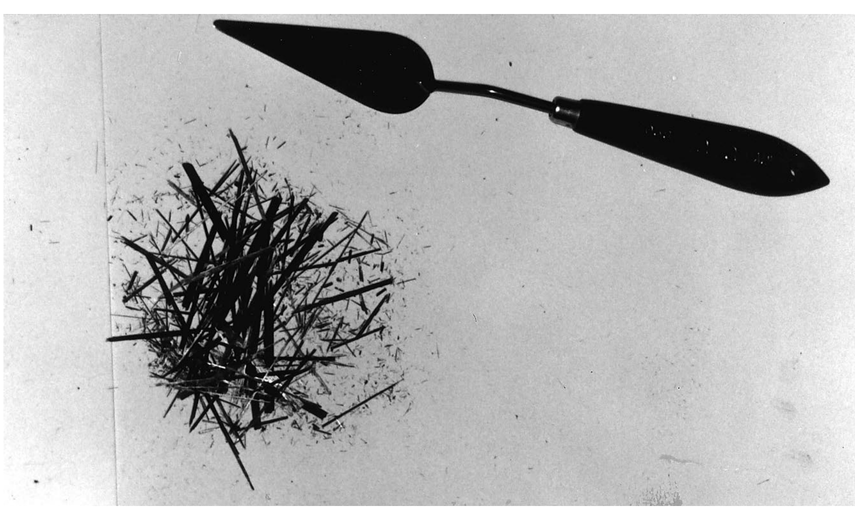


Fig. 3. Fragments collected from the rear side of a panel after impact.

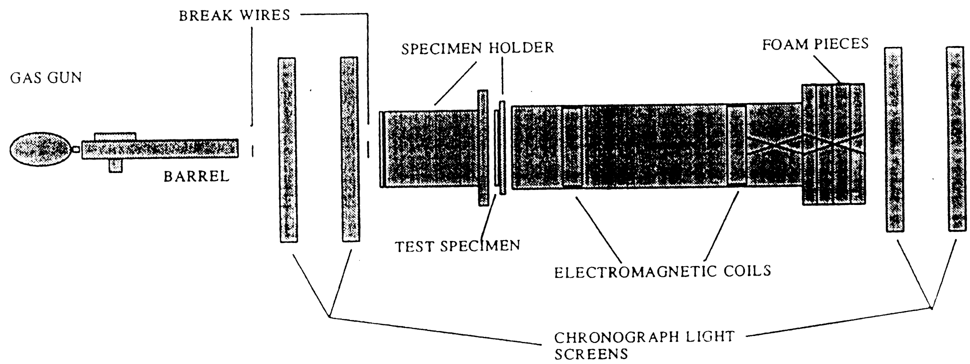


Fig. 4. Schematic of the test set up at the WPAFB.

fracture morphology involved at microstructure level and the effect of low temperatures on the fracture morphology. A comparison was made on energy absorption parameters of 1.27 mm. (0.05 in.) thick 6061-T6 aluminum and graphite/epoxy composite panels of same areal density. Figures 5(a) and (b) show that unidirectional graphite/epoxy panels show high-energy absorption at low velocity ranges when compared to the 6061-T6 aluminum panels of same areal density. But as the impact velocity increases, aluminum panels show higher energy absorption than unidirectional graphite/epoxy panels. As the unidirectional graphite/epoxy panels used are very thin, consisting of only 16 plies, they should be considered as flexible targets in which the damage incurred from impact depends on many factors like bending of the plate, membrane stretching, etc. High energy absorption in unidirectional panels is credited to the high flexural strength of the carbon fibers.

Figures 6(a) and (b) show that cross-ply graphite/epoxy panels absorb more energy over the 2.54 mm. (0.1 in.) thick 6061-T6 aluminum panels when impacted at the same velocity at room temperature. But when the same cross-ply panels are impacted at low temperatures, they did not absorb any higher energy than the aluminum panels.

Aluminum is proved to be very insensitive to the low temperatures, whereas composites exhibit strength degradation as the temperatures are lowered. The strength degradation of the composites at low temperatures is caused by the microcracks formed within the composite due to the mismatch of thermal properties of the polymer matrix and graphite fibers. Increase in the brittleness of the composite at low temperatures is also a factor for strength degradation of the composite. It is also possible that low temperature induced microcracks were already present in these laminates, and they reduced the energy transferred from the moving projectile.

Figures 7(a) and (b) show that energy absorption due to impact of the quasi-isotropic $(0°/22.5°/45°/67.5°/90°/-67.5°/-45°/-22.5°)_{2s}$ graphite/epoxy panels

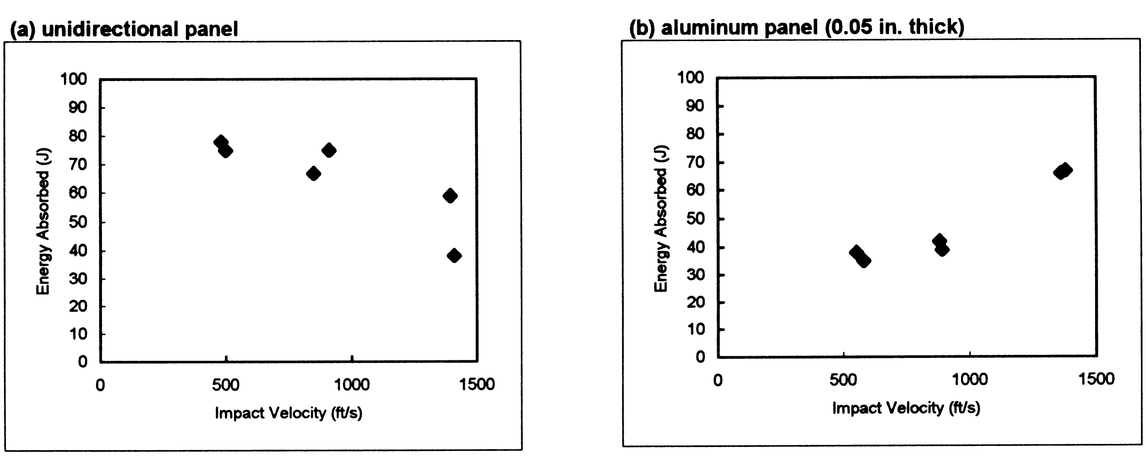


Fig. 5. (a) Energy absorbed by unidirectional Gr/Ep composite panels, (b) Energy absorbed by 1.27 mm (0.05 in.) thick 6061-T6 aluminum panels.

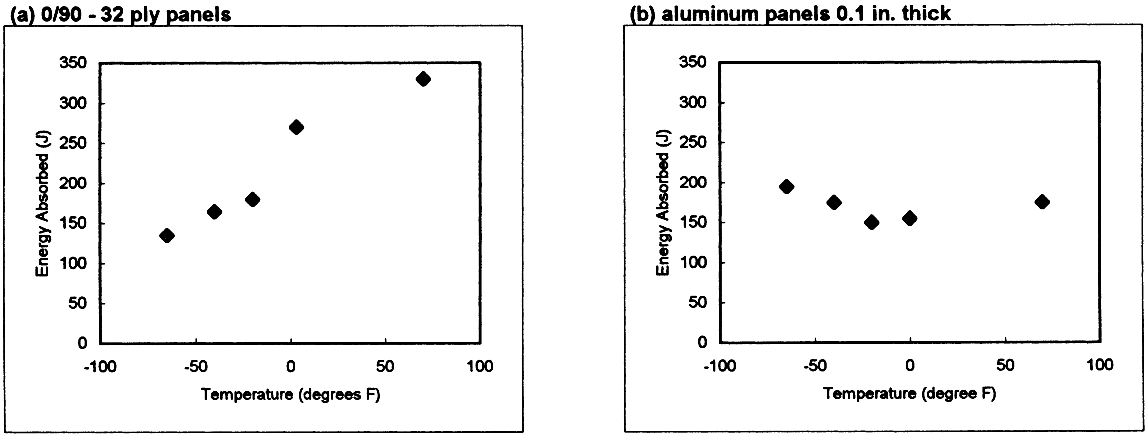


Fig. 6. (a) Energy absorbed by cross-ply Gr/Ep composite panels, (b) Energy absorbed by 2.54 mm (0.1 in.) thick 6061-T6 aluminum panels.

is high when compared to unidirectional graphite/epoxy panels, which implies that the toughness increases with multiple orientations of the lay up angles. From Fig. 7(b) note that the V_{50} is approximately 107 m/s (350 ft/s).

4. Microstructural observations

Investigation of shear plugs revealed that a minimum level of impact energy is required to shear out a plug from the plate material. In the quasi-isotropic laminate test, Fig. 8 shows that the shear plug size is maximum at approximately 230 m/s (750 ft/s) velocity and decreases thereafter. Reduction in the size and shape of the shear plugs (or core plug fragment) at higher impact velocities imply that the plug might be disintegrating or breaking up into several small pieces due to high forces and pressure generated at that particular velocities. Kinetic energy of the shear plugs is very negligible when compared to that of rest of the spall fragments. Energy expended by the projectile in generating the spall fragments increased with increase in impact energy.

Three different types of surface textures were found on the impact-generated fragments: (1) gravel, (2) hackles and (3) matrix-rich area. Among the three types of surface textures, "gravel" is the dominating surface morphology on the whole, the next one is hackle-like texture, and the last and least is matrix-rich area. Figure 9 gives the texture of the micrograph focused on different areas of a fragment (center) from 21°C (70°F) impact. The fragment belongs to the shear plug of the test panel. Various areas along the thickness of the plug are exposed and SEM was focused on

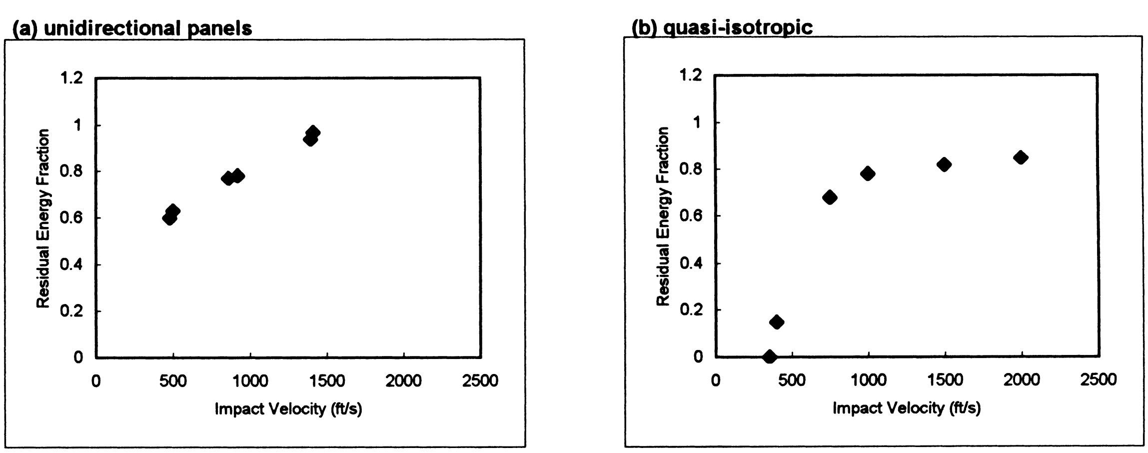


Fig. 7. Comparison of residual energy for the three targets. (a) Unidirectional Gr/Ep composite panels. (b) quasi-isotropic ($0°/22.5°/45°/67.5°/90°/-67.5°/-45°/-22.5°)_{2s}$ graphite/epoxy panels.

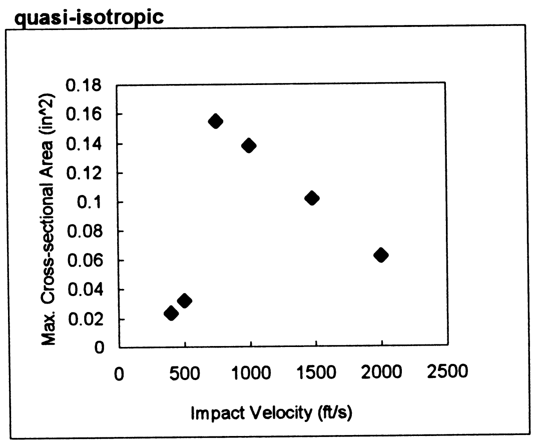


Fig. 8. Influence of impact velocity on shear plug size.

these areas to take the image. Images A and B were taken from the front side (impact side) of the fragment, and the most dominating surface texture here is gravel. At intermediate depths (B,C and E) the amount of gravel tends to decrease. The rearmost shows an abundance of hacklemarks. Thus, it is clear that the front side of the shear plug (i.e., facing the projectile) is dominated by gravel type surface texture, and the rear side is covered with lot of hackle-like texture. The matrix-rich area is seldom seen on the plug's surface.

At low temperatures, for example at −53°C (−64°F) (see Fig. 10), the most dominating surface texture found on the impact face of the fragments is also gravel. The smooth matrix-rich area is the second dominating surface texture (C,D,E and F). This type of surface texture is very smooth and looks like neatly arranged resin (even if it was having some striations) and it is found only at low temperatures. The matrix rich area found at room temperature is rough in nature.

Gravel is observed mainly on short length fibers generated at high impact velocities and on the face of the shear plug, where the compressive forces are high in both the cases. Hence we conclude that the gravel texture is a result of excessive compression developed due to higher impact energies. Hackles are observed mainly on the long fragments, fragments from the last ply and on the rear side of the shear plug, where tensile stresses

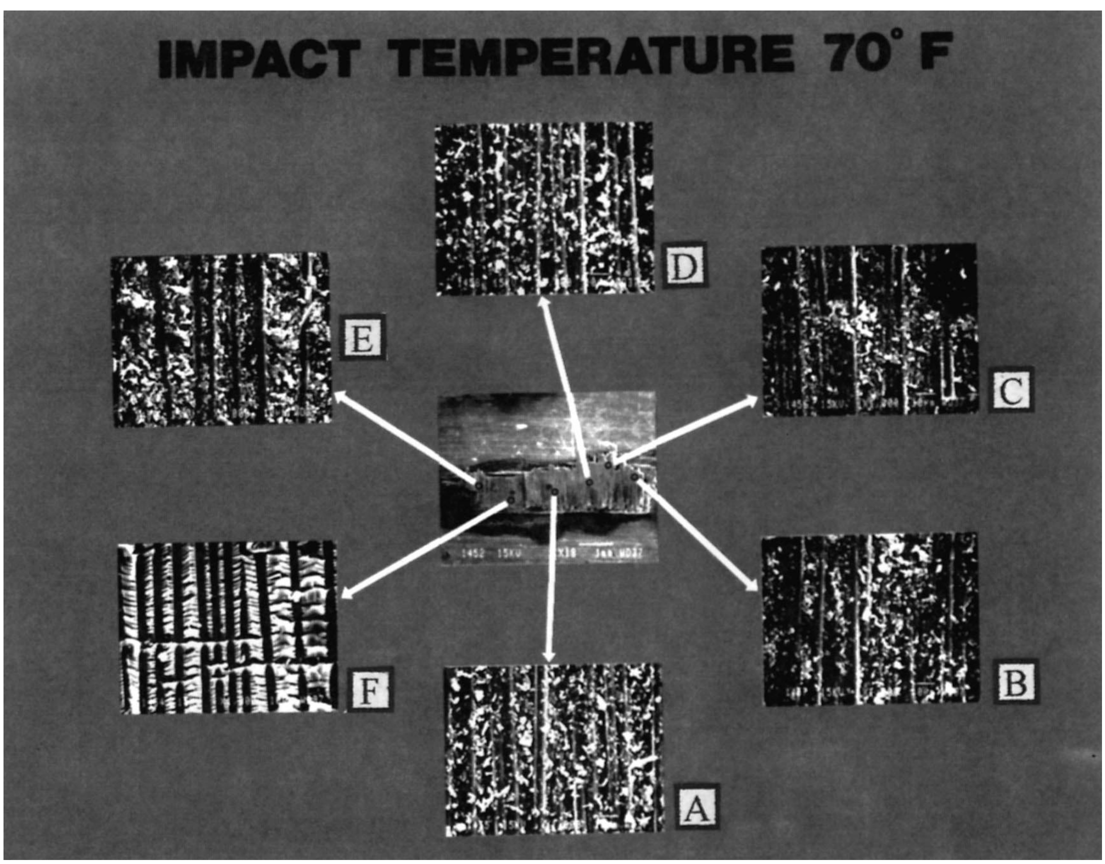


Fig. 9. Texture changes of micrographs with depth in shear plug at 21°C (70°F).

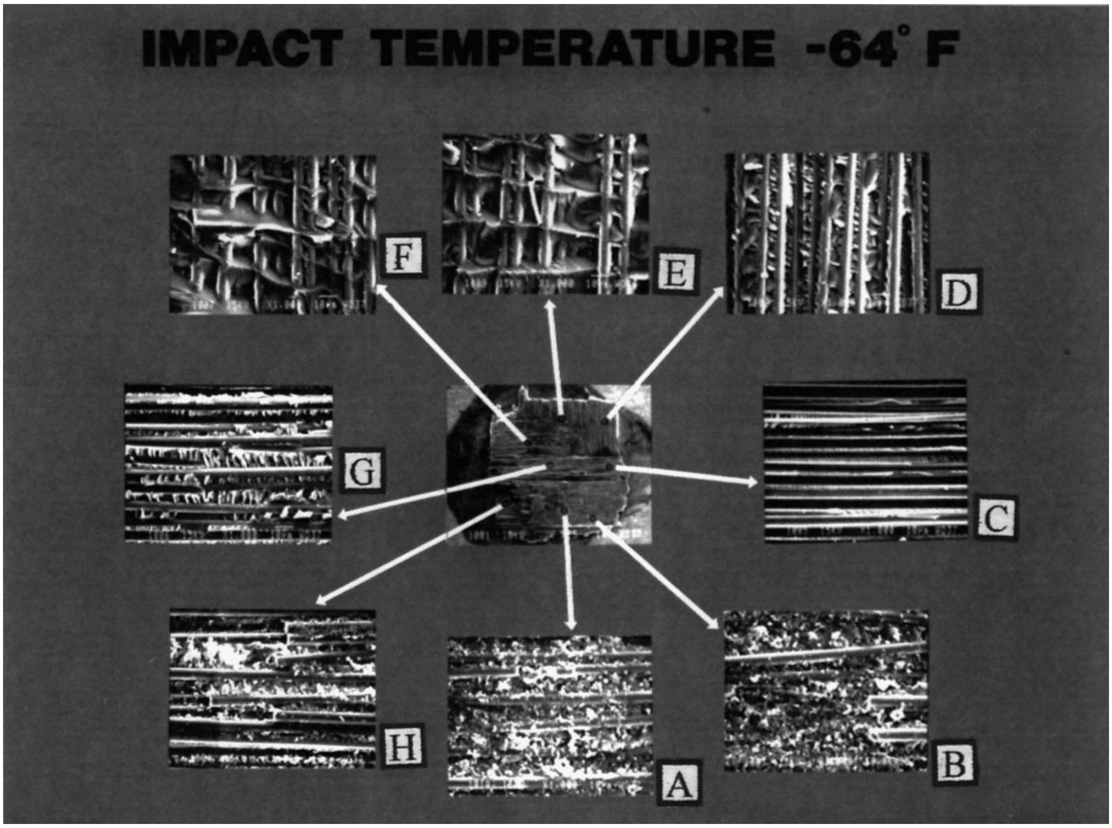


Fig. 10. Texture changes of micrographs with depth in shear plug at −53°C (−64°F).

as a result of flexure or bending is the source of failure in all three cases. Hence it is concluded that hackles are formed due to tensile failure as a result of flexure or bending. As observed by Dutta and Taylor [19], the smooth matrix at low temperatures is as a result of the preexisting microcracks within the composite.

5. Conclusions

In summary, the conclusions from the tests were following. (1) Unidirectional graphite/epoxy panels absorb more energy at low velocity range. (2) Cross-ply graphite/epoxy absorbs more energy than 6061-T6 aluminum at room temperature, but not at low temperature. (3) At low temperature, composites require much less energy to delaminate per unit delaminated area. (4) Energy absorbed in quasi-isotropic panels was higher than cross-ply panels indicating that toughness increases with multiple orientations of the fibers. (5) Of the three different types of surface textures, i.e., gravel, hackles and matrix rich areas, gravel is the most dominating morphology. (6) At low temperature, because of clean debonding, the smooth matrix area is more common; at room temperature the matrix-rich area is relatively rough.

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