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Comparison of the Low and High Velocity Impact Response of Kevlar Fiber-Reinforced Epoxy Composites

REFERENCES: Shaker, M., Ko, F., and Song, J., "**Comparison of the Low and High Velocity Impact Response of Kevlar-Fiber Reinforced Epoxy Composites,**" *Journal of Composites Technology and Research,* JCTRER, Vol. 21, No. 4, October 1999, pp. 224–229.

ABSTRACT: Failure mechanisms of basket weave and 3-D braided Kevlar-fabric reinforced epoxy composites under low and high velocity impacts have been studied. The purpose of this study is to examine the initiation and development of damage under these two widely differing loading conditions on 2-D and 3-D structure fabric composites. The critical evaluation of post-damage composite panels was conducted using a combination of high magnification photography, optical microscopy, and scanning electron microscopy (SEM). The first objective, quantification, has been realized in principle with regards to laminated composites, and it has been demonstrated that dispersive failure occurs in these composites. The second objective in this work established the relationship between kinetic energy absorbed and the damage tolerance of interleaved composites as assessed by the impact tests. High velocity impact loading by a small projectile is generally more detrimental to the integrity of a composite structure than low velocity dropweight impact loading.

KEYWORDS: Kevlar-fabric reinforced epoxy, impact test, low velocity, high velocity, 3-D braid, basket weave

Many researchers have studied impact failure mechanisms, and much effort has been concentrated on studying low velocity impact failure mechanisms. The failure mechanisms of composites have become of great academic and practical interest [*1–5*]. However, the failure mechanisms of composites are still poorly understood, possibly because of the complex structures of these materials. With the increasing use of advanced composite material in both civil and military structural applications, attention is currently being centered on assessing their response to localized impact loading. The impact threat may take many forms, ranging from a dropped tool traveling at perhaps three or four meters per second to small arms fire traveling at many hundreds of meters per second. In these two extremes the response of the structural component is likely to be completely different. Under conditions of low velocity impact loading, where the time of contact between the projectile and target are relatively long, the whole structure responds, enabling kinetic energy to be accommodated at points well away from the point of impact [*6*]. Here, the geometrical configuration of the target is likely to be important since it will determine its energy-absorbing capability. Indeed, Broutman and Rotem [*7*] have shown that increasing the length of a glass-fiber reinforced composite beam increases its low velocity impact response. Conversely, high velocity impact loading by a light projectile tends to induce a more localized form of target response, resulting in the dissipation of energy over a comparatively small region [*8*]. Clearly, these two distinct forms of impact loading will create differing levels of damage with differing consequences on the subsequent load-carrying capability of the structure.

The work presented here examines the low and high velocity impact response of basket weave and 3-D braided structures of Kevlar fabric reinforced epoxy composite and assessed the relative severity of these two loading conditions. Information obtained from optical micrographs and a scanning electron microscope (SEM) was used to examine the initiation and development of impact damage in these composites and was then used to investigate the influence of target geometry on impact response.

Experimental and Sample Preparation

Ballistics Impact Testing

Ballistic impact testing was performed using the high-speed impact apparatus located at the Army Research Laboratory, Aberdeen Proving Grounds, MD. The tests were conducted in accordance with Military Standard MIL-STD-662E, V50 Ballistic Test for Armor [*9*]. The fragment-simulating projectile was the .22 caliber type 2 conforming to MIL-P-46593, weighing 17 grains. The impact points were a minimum distance of 3.81 cm (1.5 in.) from each other. The samples were rigidly mounted with the area of impact normal to the lines of fire.

Testing Conditions:

- Type of projectile: Fragment simulating projectile
- Weight of FSP: 17 grains (1.1 g)
- Shape of FSP: Cylinder with chiseled head
- Diameter of FSP: 5.59 mm
- L/D of FSP: 1.0
- FSP Material: Steel
- Modulus of FSP: 200 GPa
- V50 of Actual Helmet: 2150 ft/sec (656 m/sec)
- Density of Steel: 7.8 g/cm^3

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Assuming that the projectile mass is constant during the penetration of the target, the kinetic energy (KE) absorbed by the target is:

$$KE = 1/2\ \mathrm{m}\ (V_s^2 - V_r^2) \qquad (1)$$

where m is the projectile mass (kg), and V_s and V_r are striking and residual velocities (m/s), respectively.

Drop Weight Impact Testing

Low velocity impact tests were performed on a Dynatup model 8140 instrument impact tester in conjunction with a Dynatup model 730-1 data acquisition system [*10*]. Under normal testing conditions, the striking energy should be greater than needed in order to penetrate the tough samples, while not exceeding the load cell capabilities. Through testing, it was found that the following is a suitable combination for the samples in this study:

- Drop Weight: 295 kg (606 lb)
- Tup Diameter: 1.27 mm (0.5 in.)
- Velocity: 3.1 *m*/s (10.18 ft/s)
- Impact Energy: 1332 J (982.36 ft-lb)

Microscopy

An optical microscope was employed to evaluate the internal features of composites. In addition, optical microscopy was used to observe morphological changes to the fibers. The surface features of these composites were viewed using scanning electron microscopy (SEM JOEL model JSM-35CF), which provided a three-dimensional perspective of both fibers and yarns.

Results and Discussion

The kinetic energy absorbed by four different types of fabric structure reinforced composites during drop-weight impact and ballistic impact is shown in Fig. 2.

As it can be seen, in all cases, kinetic energies absorbed under ballistic impact (high velocity impact) were considerably lower than those under drop-weight impact (low velocity impact). Furthermore, it is clear that the most dramatic differences were observed in 3-D structure composites (3-D braided and multi-axial warp knit (MWK). In fact, kinetic energy absorbed by these composites under low-velocity impact were more than twice of the kinetic energy absorbed under high-velocity impact.

In the case of 2-D structure composites (basket and triaxial), the basket weave composite shows higher energy absorption over the triaxial weave composite under both low and high-velocity impact loading.

For detailed failure behavior of the different structures, the basket weave composite and the 3-D braided composite were chosen as representations of 2-D and 3-D structure, respectively.

1. Comparison of the Low and High Velocity Impact Response of Basket Weave Kevlar Fiber-Reinforced Epoxy

For conditions of low velocity impact loading, the size and shape of the target determines its energy-absorbing capability and, therefore, its impact response. High velocity impact loading by a fast moving projectile induces a localized form of target response, and the level of damage incurred does not, therefore, appear to be governed by the areal size of the component.

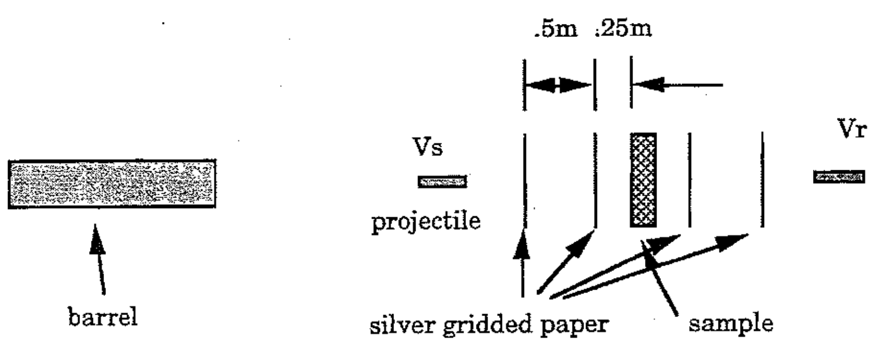

FIG. 1—*Schematic of ballistic test setup.*

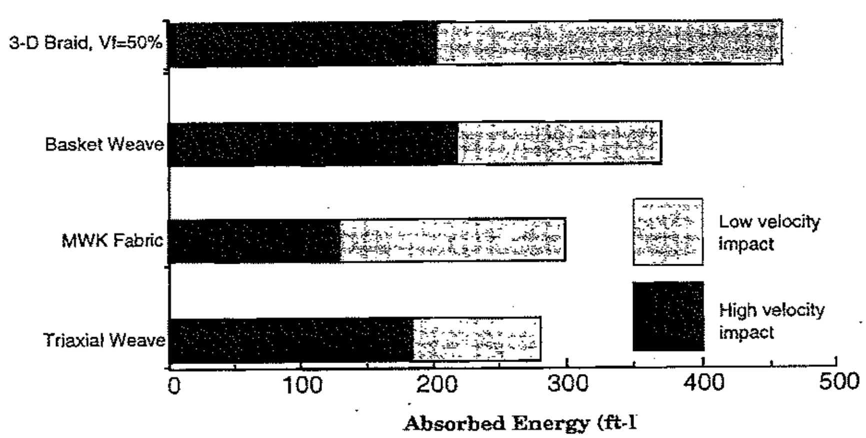

FIG. 2—*Kinetic energy under drop-weight and ballistic impact testing.*

Fracture Surface Observation

A side view of the basket weave ($Vf = 50\%$) composite in low velocity impact is shown in Fig. 3. When sufficient energy to crack the matrix was applied (Fig. 3), delamination and fiber fracture was extensive throughout the thickness of the laminate, spreading to points well away from the point of impact. Here, the penetrating action of the impact tended to shear the fibers to the direction of impact, resulting in formation of a frustrum-shaped fracture zone. Initiation and development damage in this laminate is detailed in optical micrographs (Figs. 4 and 5).

Damage development in the laminate plies after high velocity impact loading is shown in Fig. 6. When sufficient energy to crack the matrix was applied, delamination extended well away from the point of impact, and damage on both the upper and lower surfaces of the target was clearly visible. Complete target perforation occurred at high velocity (this being somewhat higher than that measured for drop-weight loading) and again resulted in the formation of the characteristic conically shaped shear zone around the point of impact (Figs. 7, 8, and 9).

High-velocity impact loading induces a localized form of target response (Fig. 6) where most of the energy is dissipated over a small zone immediate to the point of impact. Conversely, low velocity impact loading generates an overall mode of target response whereby energy can be dissipated at points well away from the point of contact (Fig. 3). These phenomena are clear in SEM photos of the impact area for high and low velocity impact (Figs. 10 and 11).

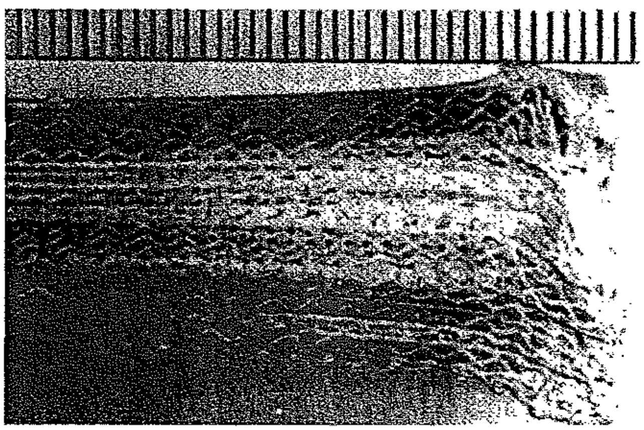

FIG. 3—*Side view of fracture surface of low velocity impact.*

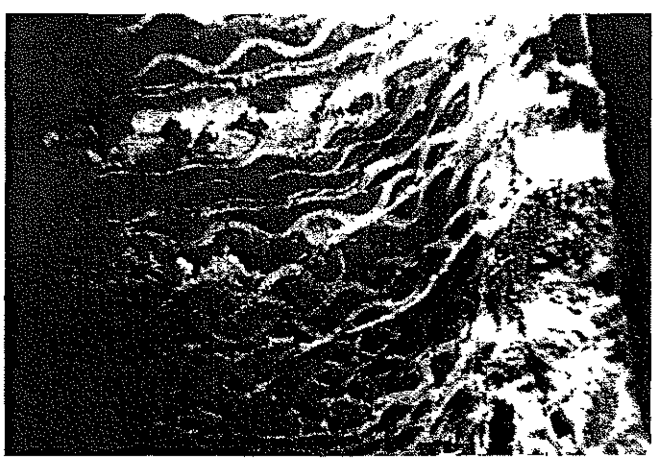

FIG. 4—*Optical microscope photo side of low velocity impact.*

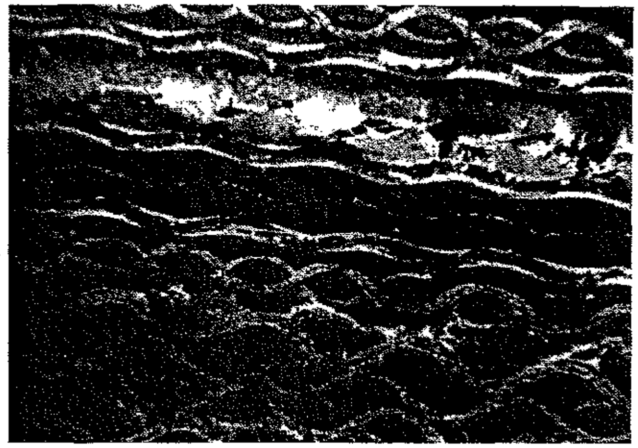

FIG. 5—*Optical microscope photo side of low velocity impact.*

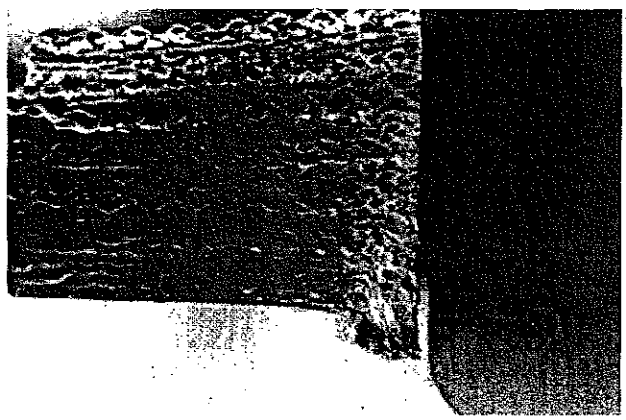

FIG. 6—*Side view of fracture surface of high velocity impact.*

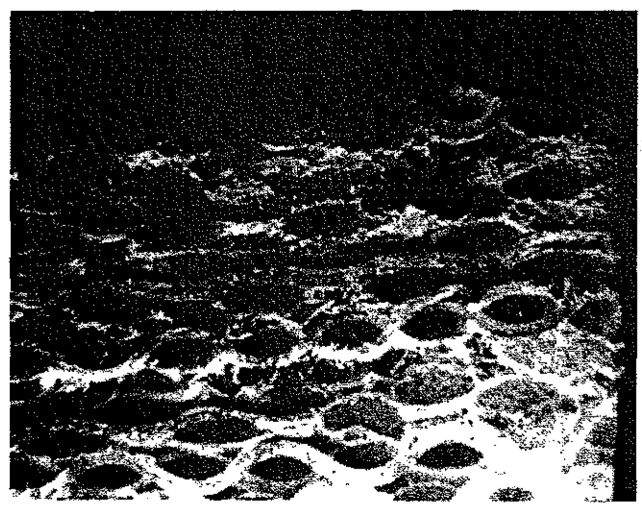

FIG. 7—*Optical microscope photo side of high velocity impact.*

In the case of high velocity impact loading, the level of delamination was significantly greater. Clearly, under these conditions of

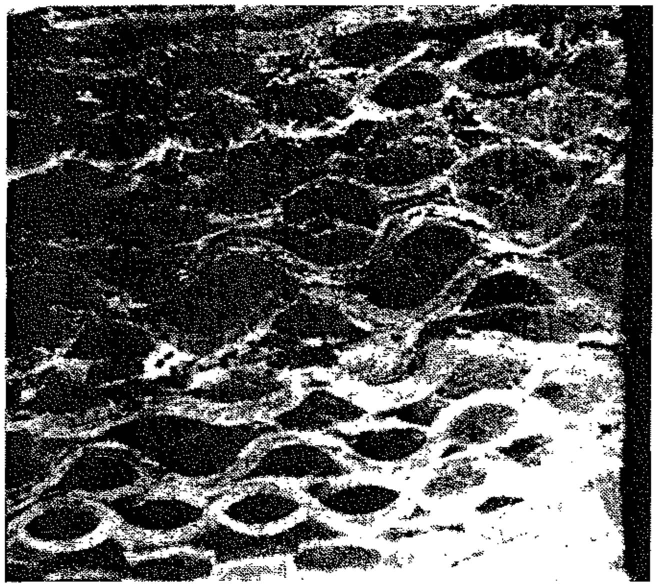

FIG. 8—*Optical microscope photo side of high velocity impact.*

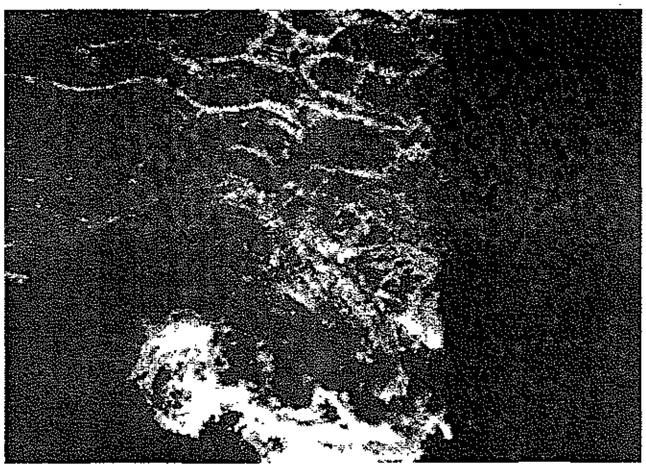

FIG. 9—*Optical microscope photo side of high velocity impact.*

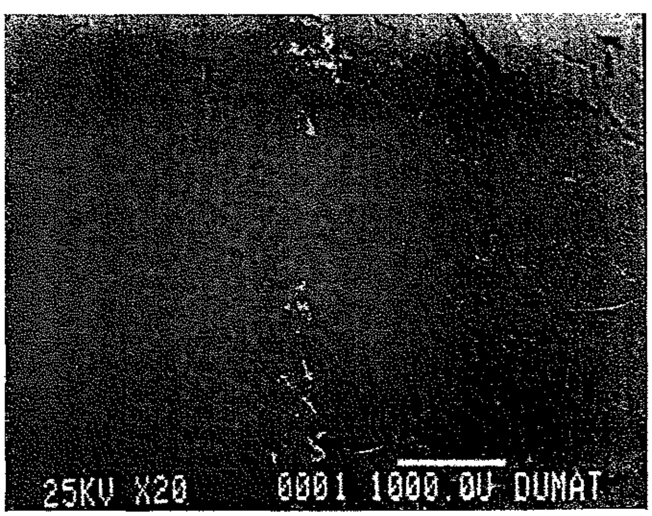

FIG. 10—*SEM photo for impact area at high velocity impact.*

high velocity impact loading more energy was dissipated in creating these zones of interlaminar fracture. Previous photos clearly show that high velocity impact represents a more severe form of loading condition.

2. Comparison of the Low and High Velocity Impact Response of 3-D Braided Kevlar Fiber Reinforced Epoxy

Fracture surface observation: The side view of the 3-D braided composite in low and high velocity impact are shown in Figs. 12 and 13, respectively.

At low velocity, the penetrating action of the impactor tended to shear the fiber to direction of impact, resulting in the formation of a frustrum-shaped fracture zone (Fig. 12). However, at high velocity impact, complete target perforation occurred, this being somewhat higher than that measured for drop weight loading, and again resulted in formation of the characteristic conically shaped shear zone around the point of impact cup—cone fractures can be seen at both sides of the sample (Fig. 13).

The matrix is shown in Figs. 14 and 15 cracking along the braiding yarn path near the penetration entrance. This clearly shows that high velocity represents a more severe form of loading condition. The same phenomena can be seen in Figs. 16 and 17, showing the bottom of the sample at low and high velocity impact. An examination of the bottom of the high velocity impact sample (Fig. 17)

FIG. 11—*SEM photo for impact area at low velocity impact.*

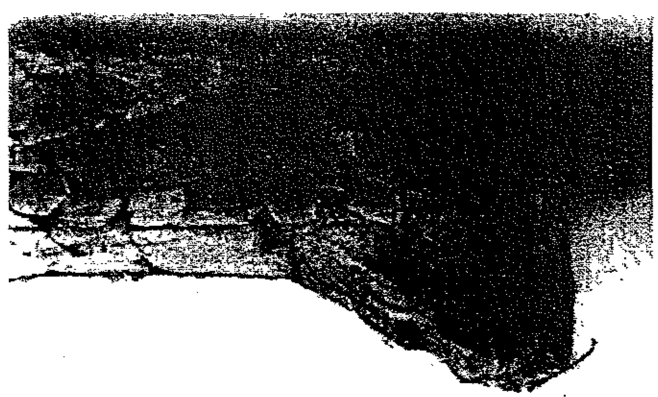

FIG. 12—*Side view of fracture surface of low velocity impact.*

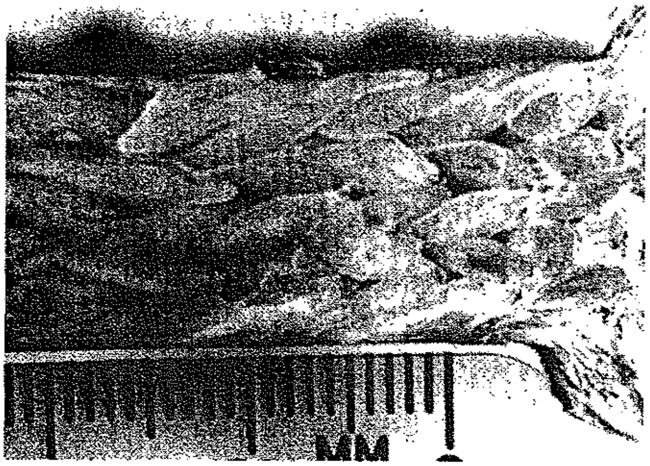

FIG. 13—*Side view of fracture surface of high velocity impact.*

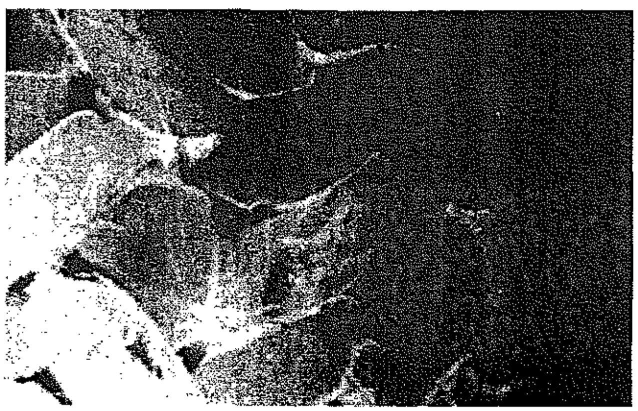

FIG. 14—*Optical microscope photos of the center of high velocity impact.*

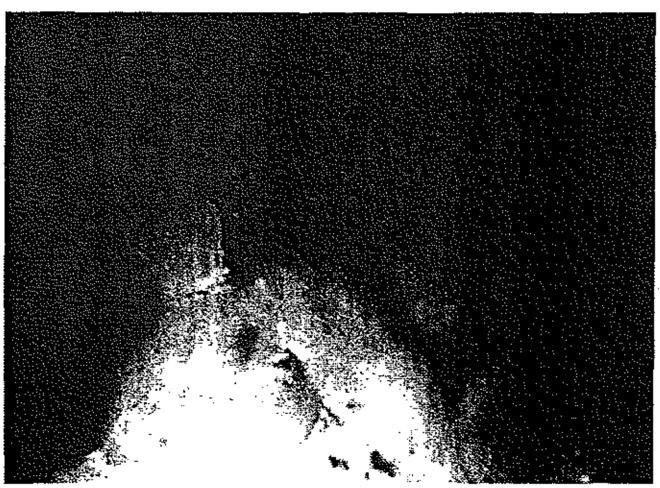

FIG. 15—*Optical microscope photos of the center of low velocity impact.*

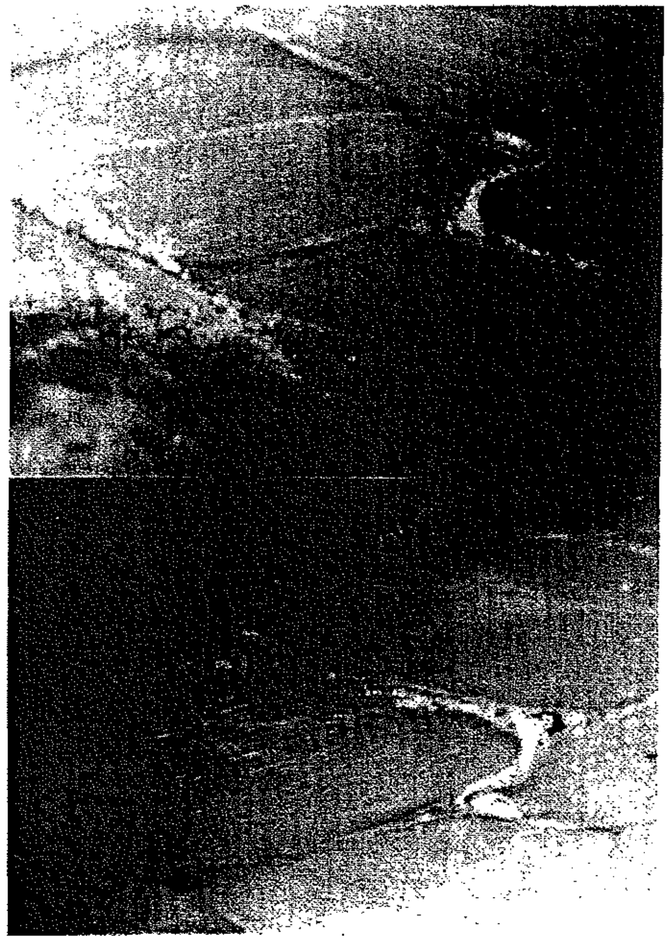

FIG. 16—*Bottom of the sample at low velocity impact.*

shows that the cracks grew along the matrix fiber and are more severe than those produced under low impact.

SEM photos for the impact area reveal that the impact area (Fig. 18) of a high velocity impact is very small when compared to a low velocity impact (Fig. 19). Some similarities apparently do exist between processes of damage development under low and high velocity impact conditions. In both cases initial failure occurred at the lower surface of target, probably as a result of a locally high flexural stress field. Furthermore, the shear zones observed at the perforation thresholds were remarkably similar considering the enormous difference in impact strain rates.

In Figs. 18 and 19, SEM photos illustrate how the cracks in the matrix grew along the fiber (near the circumference of each fiber bundle) and were retarded by the fiber under low and high velocity impact are same.

Conclusion

Impact tests on a number of Kevlar fiber-reinforced epoxy composites indicate that the low and high impact responses of a composite structure may very considerably. Under low-velocity impact loading (where the energy absorbing capability of the structure is important), structural geometry determines the target's impact response. Conversely, under conditions of high velocity impact loading (where the projectile generates a localized form of target re-

FIG. 17—*Bottom of the sample under high velocity impact.*

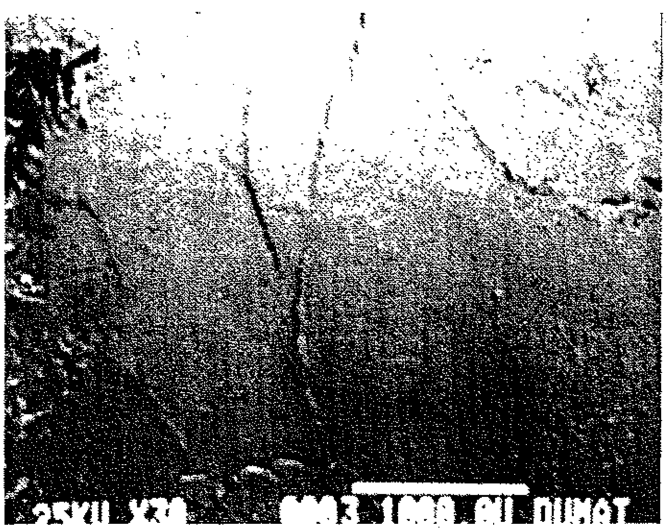

FIG. 18—*SEM photo for side view at high velocity impact.*

sponse), geometrical parameters such as the width and length of the target appear to have very little effect on impact response. Consequently, ballistic impact loading tends to produce greater levels of damage.

High velocity impact loading by a small projectile is generally more detrimental to the integrity of a composite structure than low velocity drop-weight impact loading at the impact point.

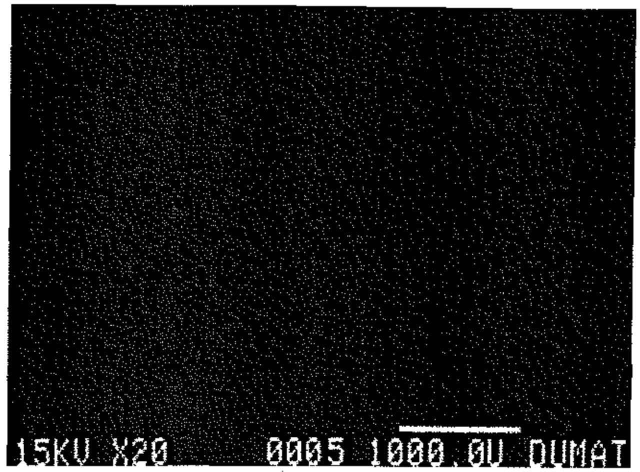

FIG. 19—*SEM photo for side view at low velocity impact.*

Acknowledgment

The authors gratefully acknowledge the financial support for the project from the U.S. Army Natick Research, Development and Engineering Center, Natick Massachusetts.

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