An Experimental Investigation of High Velocity Impact and Penetration Failure Modes in Textile Composites

M. P. FLANAGAN* AND M. A. ZIKRY**
Department of Mechanical and Aerospace Engineering
MS 7910
North Carolina State University
Raleigh, NC 27695-7968

J. W. WALL AND A. EL-SHIEKH
College of Textiles
MS 8301
North Carolina State University
Raleigh, NC 27695-7968

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ABSTRACT: The dynamic failure evolution of textile composites, which were subjected to impact velocities up to 1100 m/s, was investigated. Specialized machines were used to fabricate composites from combinations of Spectra®, Kevlar®, and Twaron® fibers and two- and three-dimensionally woven, braided, and needle-punched nonwoven fabrics. This control of fabrication and processing enabled us to characterize response as a function of areal density, fabric finish, and consolidation techniques. Failure was categorized in terms of material layers, debris mass, matrix cracking, fiber failure, and shear-plugging. Results indicate that shear-plugging occurs at velocities corresponding to decreases in debris mass.

KEY WORDS: textile laminate composite, high velocity impact, shear plugging, tensile and shear fiber failure, matrix cracking.

INTRODUCTION

LOW DENSITY, HIGH strength polymeric fibers, such as aramid and ultra high molecular weight polyethylene (UHMWPE) fibers, have been extensively

*Major, U.S. Army, currently assigned to the PEO, Armored Systems, Warren, MI.
**Author to whom correspondence should be addressed.

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used in composites used for high velocity impact resistance in applications such as vehicles, armor penetration, body armor, and structural and mechanical elements. Angle-plied unidirectional fibers and woven fabrics are the most commonly used textile reinforcements for these composite materials. Due to material flexibility, textile composites can be shaped and manufactured for optimal and desired response. However, textile composites generally do not have high strength characteristics in the transverse direction (see, for example, Cantwell [1]).

Cunniff [2,3] has conducted detailed investigations of the ballistic response of fabric armor using Fragmentation Simulating Projectiles (FSPs) for fabric systems such as Spectra®, Kevlar®, and nylon subjected to impact velocities that ranged from 400 m/s to 1600 m/s. His results indicate that Spectra® has the highest energy absorption of these three materials, and that transverse deflection association with the wave propagation that occurs due to impact, is the dominant mechanism that results in projectile arrest. He also noted that additional material layers actually decrease the efficiency of energy absorption of the materials, since the layers have discontinuous interfaces that restrict transverse deflection. Jenq [4,5] conducted dynamic tests of woven and braided three-dimensionally braided E-glass. They identified failure modes such as indentation, matrix failure, and fiber pullout for impact velocities that ranged from 70 m/s to 170 m/s. These woven laminates also suffered from delamination, while the three-dimensionally braided composites did not delaminate for the velocity ranges used in Jenq's experiments. Le, Song, and Ward [6] investigated damage progression in fabric reinforced and angle-plied reinforced Spectra® fiber composites subjected to multiple impact ballistic conditions. They found that the stiffer vinylester resin composites outperformed the flexible polyurethane composites for impact velocities that ranged from 150 m/s to 300 m/s. This material resistance was mainly due to the flexible resin preventing delamination growth along the principal directions of fiber alignment. They also determined that low areal density, unidirectional angle-plied Spectra® laminates and woven Spectra® laminates did not delaminate for the range of velocities used in their study. At higher areal densities, the angle-plied Spectra® was the material that most resisted delamination. Kang and Lee [7] investigated the effect of stitching woven laminate composites with S-2 glass/polyester, Kevlar®/PVB-phenol, and Spectra®/vinylester. Their results indicate that stitching improved both mechanical properties in the transverse direction and energy absorption for impact velocities of up to 40 m/s. They concluded this is due to the presence of the transverse fibers, which resulted in a spatial distribution of stresses that minimizes the delamination.

The dynamic mechanical response and structure of textile composites is inherently complex. There are a multitude of factors such as fabrication, processing defects, impact velocity, areal density, layer thickness, interfacial properties, fiber type, orientation and distribution, matrix strength, and interlaminar adhesion, that can affect and control the high velocity mechanical response and failure of these materials. Hence, the potential use of these composites in structural and mechanical elements for tailored damage tolerant applications requires a detailed understanding of the dominant interrelated material mechanisms that can result in failure. The major objective of this work is to investigate damage progression and failure evolution in textile composites subjected to ballistic impact velocities. A 19-mm powder gun was built to generate impact velocities that ranged from 200 m/s to 1100 m/s. Specialized braiding and weaving machines were used to fabricate textile composites at the College of Textiles at North Carolina State University. Ten textile composites were specifically fabricated and designed to obtain a comprehensive understanding of the effects of material preform type, epoxy resin type, fiber type, processing conditions, and consolidation techniques on dynamic damage progression and failure. These ten composites were chosen as a representative class of materials that spans two- and three-dimensionally braided, woven, and needle-punched fabrics, all with different fiber combinations. The textile composites were fabricated, as fiber assemblages that included combinations of woven Spectra® 1000, woven Kevlar® 129, woven Twaron® 2000, and four-step, 3-D braided Spectra® 1000. Additionally, 6-mm Twaron® staple fiber was used in to introduce transverse reinforcement in the needle-punched fabrics. This control of the fabrication process enabled us to systematically characterize the effects of areal density, fabric finish, and consolidation techniques on dynamic failure initiation and evolution, penetration resistance, and energy absorption of textile composites. Failure modes that included indentation, matrix cracking, tensile and shear fiber failure, and shear-plugging were also categorized in terms of velocity regime, the number and combination of material layers and type, and debris mass. This categorization resulted in an improved understanding of the effects of fiber orientation and distribution on interlaminar adhesion, matrix cracking, and fiber pullout and breakage and overall tolerance of the textile composites to damage initiation and progression.

EXPERIMENTAL METHODS

A 19-mm powder gun was designed and built to specifically investigate the failure modes and damage progression of the textile composites subjected to high impact velocities [Figures 1a and 1b]. This powder gun is capable of generating impact velocities of up to 2000 m/s with a 12-gram Lexan® right cylinder projectile and with a length to diameter ratio of 3. The target chamber was designed for planar impact as shown in Figure 1a. Also, a catcher assembly equipped with a residual velocity measurement device and a projectile soft recovery box were utilized. The entire powder gun system was evacuated with a vacuum pump, prior to impact to prevent velocity measurement errors due to air shocks. Muzzle and residual velocities were recorded using three Hewlett-Packard oscilloscopes. The oscilloscopes had sampling rates ranging from 20 M sample/s to 1 G samples/s, which resulted in velocity measurements that were accurate to within ±1 m/s. Velocities were recorded at the barrel and at the muzzle. The muzzle velocity was used as the

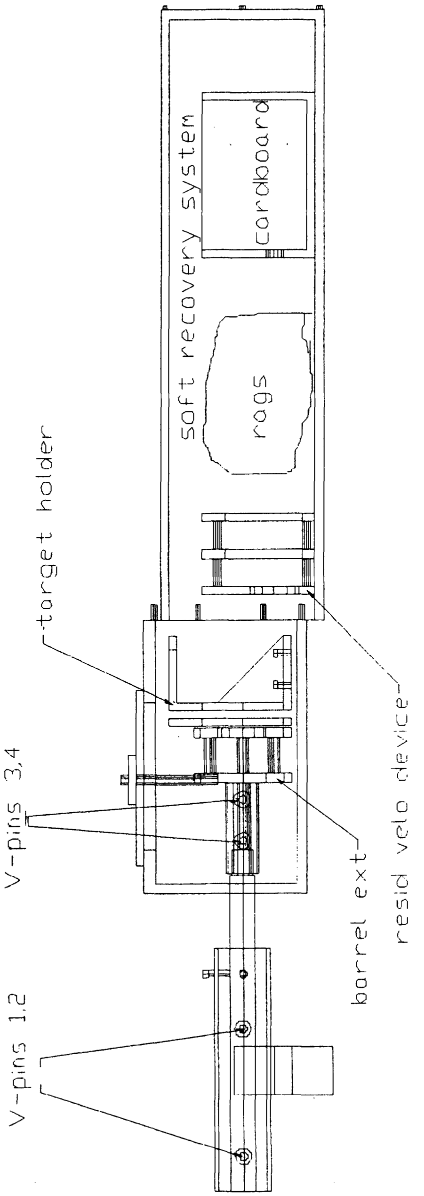


Figure 1a. *Target area of the 19-mm powder gun system.*

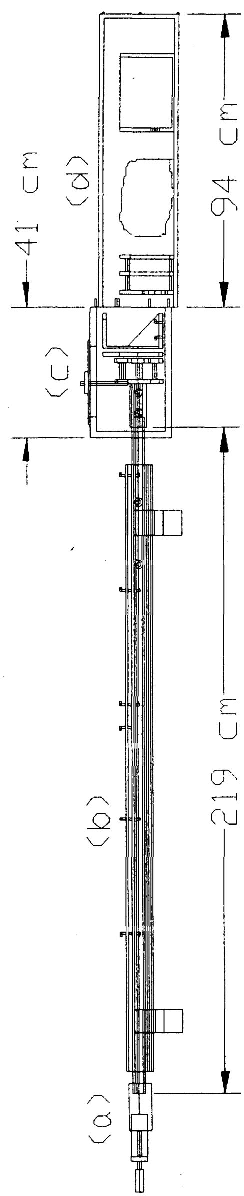


Figure 1b. *19 mm power gun with trigger assembly (a), barrel with sleeve (b), target assembly (c), and catcher assembly (d).*

impact velocity. A custom velocity measurement device that included a trip wire circuit was placed behind the specimen to record residual velocities [Figure 1a]. A detailed description of the apparatus and the velocity measurement system are given by Flanagan [8].

Targets were cut to 12.7 cm × 12.7 cm, and were rigidly attached to the target holder with an aperture diameter of 7.62 cm. Each target was weighed before and after impact to determine the debris mass. After target impact, debris mass and the projectile were collected for inspection. The projectile's radial deformation was recorded to characterize the effect of the projectile on energy absorption and the penetration region.

MATERIAL SYNTHESIS

Ten textile composites were fabricated and designed to obtain a detailed understanding of the effects of material preform type, epoxy resin type, fiber type, processing conditions, and consolidation techniques on dynamic damage progression and failure. The preform types used were combinations of aramid and polyethylene; the material processing methods used were weaving, braiding, and needlepunching; the manual compression molding consolidation techniques used were hand-layering and straight resin application—both manual methods. The preform materials chosen for the textile composites included woven aramids such as Kevlar® 129 and Twaron® 2000, and UHMWPE fabrics such as woven Spectra® 1000, and three-dimensionally braided Spectra® 1000. The woven Kevlar® 129 and woven Spectra® 1000 both had a wetting agent finish applied, while the woven Twaron® 2000 and the braided Spectra® 1000 did not have a finish. The mechanical properties of the materials used are given in Table 1.

Table 1. Mechanical properties of preform materials.

Fabric Type	Fabric Mass in Denier (g/9000 m)	Fabric Density (ends/cm)	Areal Density (g/cm^2)	Tensile Strength Warp/Fill (MPa)	# Layers
Twaron 2000 2D plain, style 704	840	11 × 10	1.89E-2	Note 1	6, 12, 18
Kevlar 129 2D plain, style 704	840	12 × 12	220E-2	6.21/6.55	6
Spectra 1000, style 960	350	12 × 12	1.08E-2	4.00/3.86	12
Spectra 1000	1300	45° Incident angle	4.41E-2	Not tested, note 2	2

Note 1: Tested differently with a breaking strength of 6300/6300 N/5 cm.
Note 2: Textile Lab has not conducted static testing on this braided textile.

The three-dimensionally braided preforms were fabricated on the fully automated 4-step, 3-D braiding machine (Figure 2), which was developed at the College of Textiles at North Carolina State University. Spectra® 1000 (1300 denier) was braided about a 3″ OD tubular mandrel. A constant 45°-braid inclination angle was maintained by integrated mandrel drive mechanism.

Some of the woven Twaron® 2000 fabric was needle-punched prior to consolidation to investigate the effects of this process on failure modes and penetration resistance. A Dilo Needle Loom with 40-Gauge Groz Beckert needles was used to punch through four layers of Twaron® 2000. One sample was needle-punched, while two other samples were needle-punched with a fiber web placed on top of each of the four layers.

The fiber webs were made using a Brudderhaus wet lay former machine with 6-mm Twaron® staple fibers. Two formation speeds were used to form a light

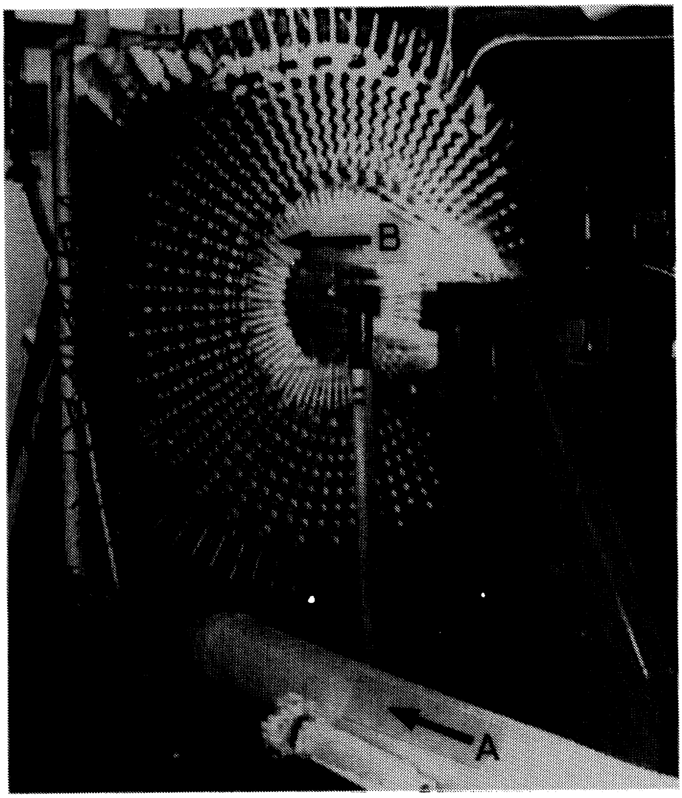


Figure 2. *Fully automatic, 3-D braiding machine, NC State University, College of Textiles. Tubular mandrel (A), machine bed (B).*

fiber web with an areal density of 3.4E-3 g/cm^2, and a heavier web with an areal density of 9.3E-3 g/cm^2. Prior to consolidation, each of the needle-punched samples was sandwiched between a single, non-punched layer. This was done to ensure that the fabric areal density was approximately the same as the other composites.

The composites were consolidated by hand-laying each layer of the preform material into an aluminum mold with epoxy resin, followed by compression molding. The material processing, areal density, and fiber volume fraction for the ten materials are given in Table 2. Composites one through four were consolidated with a room temperature curing resin (Epon 862 with 44 pph Epicure), while the remaining composites were consolidated with a different resin (Tactix 1-2-3 with 17 pph Ancamine), which required a 80°C cure temperature. The composites were cured at 1000 psi for one hour. The Epon 862 cured composites were post-cured for three days, while the Tactix 1-2-3 cured composites were post-cured at 240°C for two hours. Further details pertaining to processing and fabrication are given in Wall [9].

Table 2. Textile composites.

Preform Material	Material Process	Areal Density (g/cm^2)	% Fiber Volume Fraction
Spectra (d350)	12 Layers, plain weave, 32 × 32 ends/inch, finish	0.400	35
Spectra (d1300)	2 Layers, 3D braided, no finish	0.445	26
Aramid (d840)	6 Layers, plain weave, 31 × 31 ends/inch, finish	0.402	37
Aramid (d840) and Spectra (d350)	Both plain weave, alternate 1 layer Aramid, 3 layers Spectra for a total of 3 layers Aramid, 6 layers Spectra	0.364	35
Aramid (d840)	6 Layers, plain weave, 28 × 28 ends/inch, no finish	0.225	44
Aramid (d840)	12 Layers, plain weave, 28 × 28 ends/inch, no finish	0.472	46
Aramid (d840)	18 Layers, plain weave, 28 × 28 ends/inch, no finish	0.585	54
Aramid (d840)	6 Layers total, plain weave, 28 × 28 ends/inch, no finish, 4 layers punched w/out a fiber web	0.393	25
Aramid (d840)	6 Layers total, plain weave, 28 × 28 ends/inch, no finish, 4 layers punched w/thin fiber web (AD = 1.008 oz/yd^2)	0.432	23
Aramid (d840)	6 Layers total, plain weave, 28 × 28 ends/inch, no finish, 4 layers punched w/thick fiber web (AD = 2.739 oz/yd^2)	0.508	26

RESULTS

The major objective of this study was to investigate the high velocity impact failure modes and the penetration resistance of the ten fabricated textile composites. A 12-gram lexan projectile was used with a 19-mm powder gun to generate velocities that ranged from 200 m/s to 1100 m/s. This velocity range was broad enough to obtain a detailed understanding of damage progression and material failure. The effects of preform fiber type (aramid, UHMWPE), composite consolidation process (resin adhesion during compression and hand-layering), and material processing (woven, braided, and needle-punched) on the initiation and evolution of damage progression were characterized as a function of impact and residual velocities, delamination, matrix cracking, fiber breakage, and plug size. Penetration resistance was also characterized as a function of projectile arrest, energy absorption, and material damage. The number of shots at each velocity was determined by the reproducibility of the results.

The results pertaining to the deformation and failure modes of the ten textile composites were categorized in terms of penetration as follows: penetration resistance, penetration at low and intermediate velocities, and penetration at high velocities. In this study, penetration at low and intermediate velocities is defined as penetration that is initiated with fiber breakage along principal fiber alignment directions. At these velocities, this generally resulted in square penetration areas in plain woven preforms and elliptical penetration areas in braided preforms. At higher velocities, penetration areas were circular. These circular penetration holes are usually associated with a transition from tensile to shear failure, and this is generally a harbinger of shear plugging (see, for example, Cantwell [1]).

Penetration Resistance

For velocities that ranged from 200 m/s to 360 m/s, transverse deflection, matrix cracking, edge collapse, and delamination characterized material deformation. In this velocity range, there was transverse deflection and conical deformation for all materials that resisted penetration. A representative deformation of this type is shown in Figure 3 for the 6-layer aramid at 280 m/s. The composites with preform materials treated with a surface finish had complete matrix failure on the impact and rear sides and through the thickness of the composite. These materials also had edges that collapsed towards the impact point due to matrix failure, as shown in Figure 4 for the Spectra®/aramid combination at a velocity of 290 m/s.

The three-dimensionally braided Spectra® was the only non-finished preform, with an areal density less than 0.450 g/cm^2, that resisted penetration for velocities up to 360 m/s. As shown in Figure 5, at a velocity of 220 m/s, there was conical deformation with no penetration. However, there were axial cracks and extensive matrix deformation beyond the 7.62-cm aperture (Point B, Figure 6).

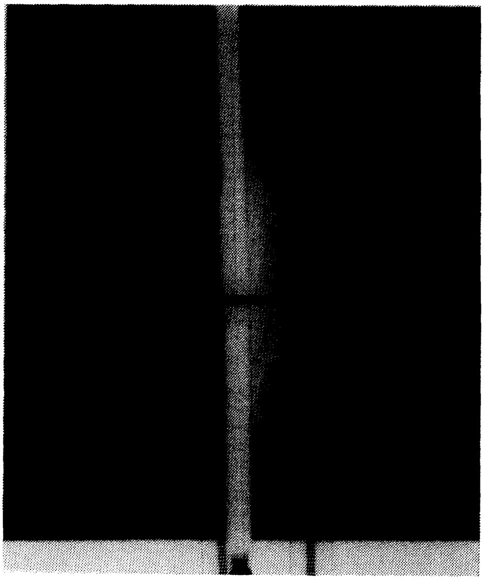


Figure 3. *Conical deformation of the 6-layer woven aramid with finish at an impact velocity of 276 m/s.*

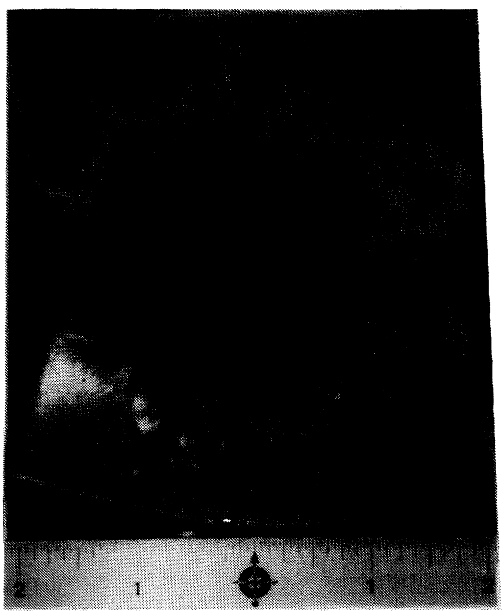


Figure 4. *Edge collapse and matrix failure of the woven Spectra®/aramid combination at an impact velocity of 290 m/s.*

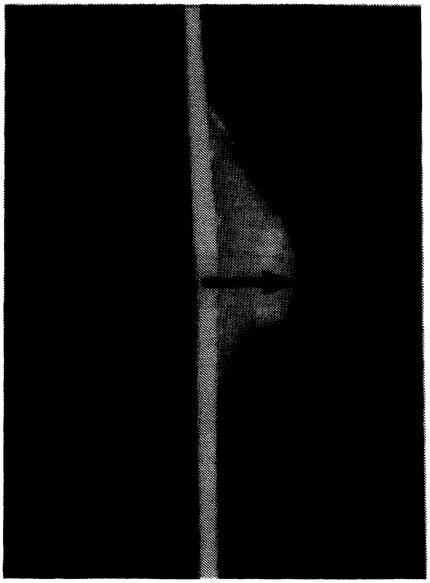


Figure 5. *Conical deformation of the 3-D braided Spectra® at an impact velocity of 220 m/s.*

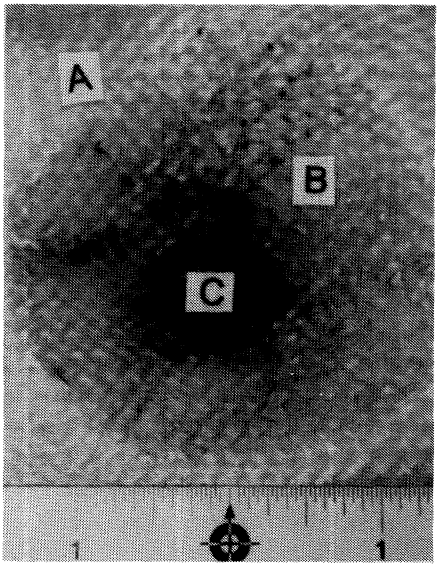


Figure 6. *Matrix cracking on the impact side of 3-D braided Spectra® at an impact velocity of 220 m/s.*

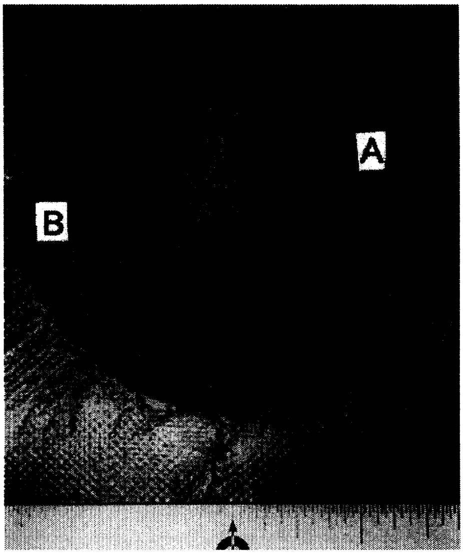


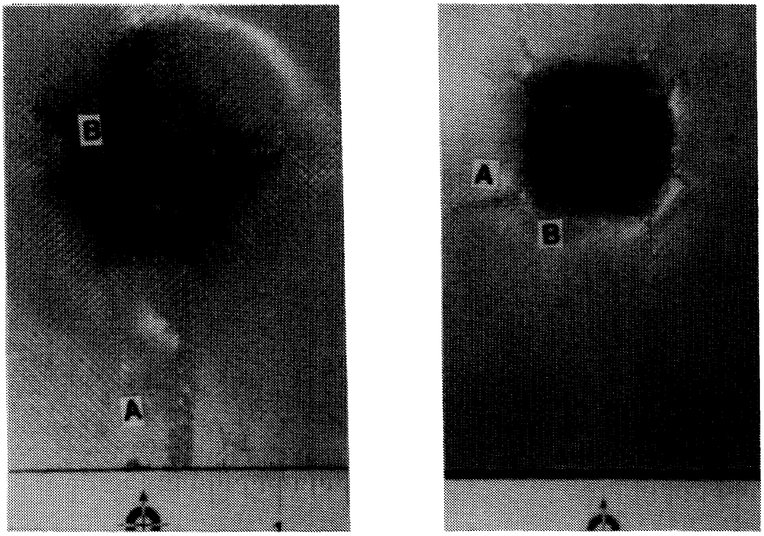
Figure 7. *Fiber breakage on the back side of 12-layer woven aramid at an impact velocity of 300 m/s.*

The 12-layer aramid resisted penetration for velocities up to 300 m/s, and the 18-layer aramid resisted penetration for velocities up to 360 m/s. Failure for these aramid composites were characterized by fiber breakage on the backside, as shown for the region between Points A and B in Figure 7 for the 12-layer aramid at a velocity of 300 m/s. As noted by Lee et al. [6], this damage is due to tensile failure along the primary weave [or braid] directions.

Penetration at Low and Intermediate Velocities

Penetration at velocities ranging from 250 m/s to 800 m/s was characterized by fiber breakage and fiber pullout on the impact face and rear surface. However, there was much less matrix cracking and delamination in comparison with the materials that resisted penetration at the lower velocities. The composites that were fabricated from preform materials with finish had matrix failure on the impact and rear sides at the lower velocities. As the velocity was increased, there was less matrix cracking and the penetration area was square-shaped for the composites with finished preforms. The composites with non-finished preforms also had square shaped penetration areas as the velocity was increased. However, in comparison with the finished composites, there was little matrix damage beyond the penetration region.

Representative failure modes for the non-finished aramids at low and intermediate penetration velocities are shown in Figures 8(a)–(b) for the 18-layer aramid at a velocity of 550 m/s. The 18-layer woven aramid had fiber breakage along the primary



(a) (b)

Figure 8. *Impact side of 18-layer woven aramid at (a) 550 m/s, and (b) 840 m/s.*

weave directions, and conical deformation on the impact face and rear surfaces [Figure 8(a)]. As the velocity was increased to 840 m/s, there was no deformation on the impact surface, some deformation on the back surface, and the penetration hole was square-shaped [Figure 8(b)]. The square penetration region is due to stress waves propagating radially from the projectile impact point. At low and intermediate velocities, stress concentrations occur at the fiber crossover points, as shown in Figure 9, and exceed the strength of the material. The penetration results from fiber breakage along the primary weave directions and square penetration holds. The 6- and 12-layer aramid composites had similar failure modes at lower velocities. An increase in the number of layers for the aramid composites delayed the transition from a conical impact point to a square penetration hole.

At a velocity of 460 m/s, the three dimensional braided Spectra® failed along the cross-over points, but due to the fiber geometry associated with braiding, the penetration region was elliptical, as shown in Figure 10. The braided Spectra® also had some matrix cracking along the braiding pattern as seen at point B (Figure 10).

The composites with preform materials with surface finish also had square penetration holes as velocity was increased. However, in comparison with non-finished preforms, there was extensive matrix cracking. A square penetration hole for the 6-layer aramid with finish is shown in Figure 11 at a velocity of 610 m/s. As also shown in Figure 11, there was matrix failure emanating radially from the impact point. All of the finished preform composites also had some deformation about the periphery of the hole, as shown in Figure 12 for the two dimensionally

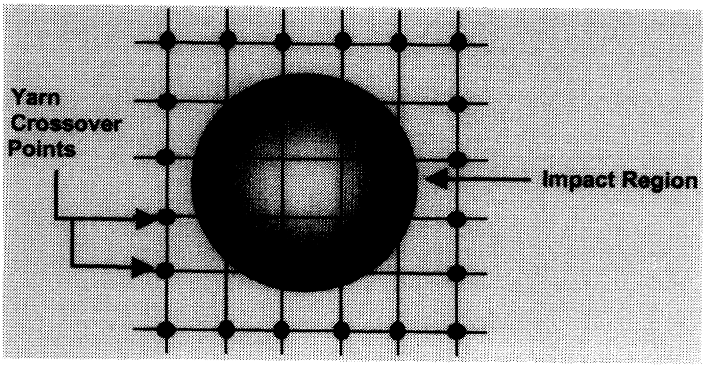


Figure 9. *Stress concentrations at fiber cross-over points with projectile at impact against a plain woven preform.*

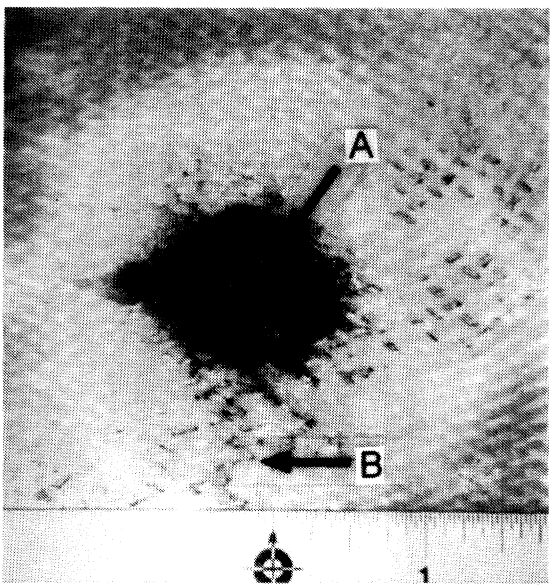


Figure 10. *Impact side of 3-D braided Spectra® at an impact velocity of 460 m/s.*

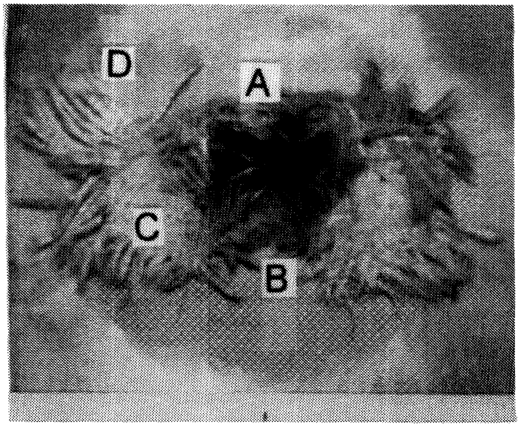


Figure 11. *Square penetration hole on back side of 6-layer aramid with finish at an impact velocity of 610 m/s.*

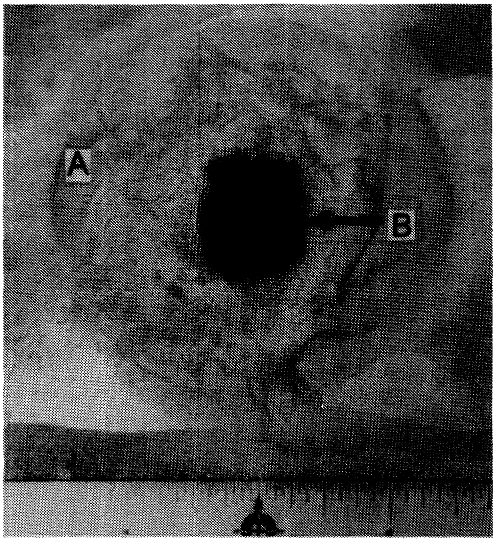


Figure 12. *Conical deformation and square hole on back side of woven Spectra® at an impact velocity of 550 m/s.*

woven Spectra® at a velocity of 550 m/s. However, the Spectra® composite had extensive conical deformation that extended past the periphery of the hole to the 7.62-cm aperture for all low and intermediate velocities.

The Spectra®/aramid hybrid material had similar failure modes as the other finished materials. However, due to the interlaminar material mismatches, the penetration areas were considerably different than those observed for composites with one material type. The penetration hole at intermediate velocities was square with portions of the front layer of the material pushing completely through the thickness of the material, as shown in Figure 13 for the Spectra®/aramid hybrid at a velocity of 480 m/s. As noted by Lee et al. [6], this type of failure is also characteristic of unidirectional, angle-plied composites subjected to ballistic impact.

The needle-punched composites were the only materials that had shear failure through-the-thickness at all low and intermediate velocities. The non-punched front and back layers had fiber breakage and pullout similar to the other materials. All four of the punched layers failed at the fiber cross-over points, as shown in Figure 14 of the back side of the needle punched aramid with light web at a velocity of 280 m/s. As Figure 14 also shows, the resulting debris for the punched-only samples were four equal squares, while the punched composites with fiber web samples had four squares of different sizes. The difference in debris sizes between the punched-only and the punched with fiber web indicates that needle punching with fiber webs resulted in interlaminar interaction and progressive delamination. The

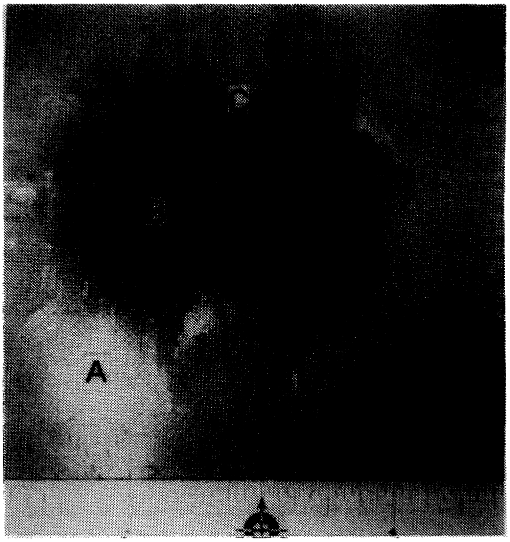


Figure 13. *Woven Spectra®/aramid combination at an impact velocity of 480 m/s with material pushed through from impact side (B).*

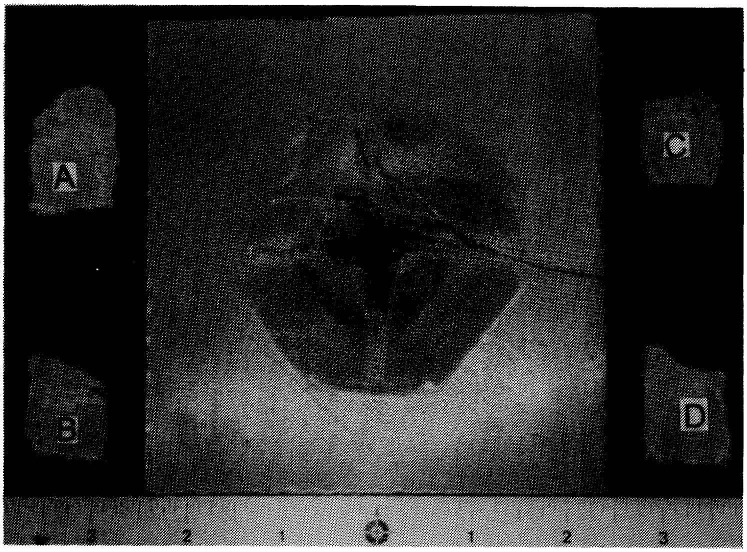


Figure 14. *Square debris of punched layers from the needle-punched/woven aramid with light fiber web at an impact velocity of 280 m/s.*

shear failure of all three types of needle punched samples indicates that needle punching can degrade overall composite strength. Some of this degradation is probably a product of the fiber breakage that is inevitable during the needle-punching process.

Penetration at High Velocities

Failure at velocities ranging from 800 m/s to 1100 m/s was characterized by shear-plug formation on the impact surface. Penetration holes for materials at this stage of failure were circular for all fiber arrangements. This occurred at this velocity range because the resulting strains exceeded the failure strain of the material. Failure at the impact surface was due to shear failure along the cross sectional area of the projectile. However, the back of the composites had tensile failure in the form of fiber breakage and pullout. The finished preform materials still had some matrix failure. The non-finished materials had very little matrix cracking, and material damage was limited to the periphery of the penetration hole.

There was shear plugging and limited damage past the periphery of the hole for the 18-layer aramid, as shown in Figure 15. The rear of the sample had extensive fiber breakage and pullout along the primary weave directions (Figure 16).

There was also shear plugging for the materials with surface finish, as shown in Figure 17(a) for the Spectra®/aramid hybrid at a velocity of 940 m/s. The rear of the Spectra®/aramid combination had fiber breakage and pullout, along with some

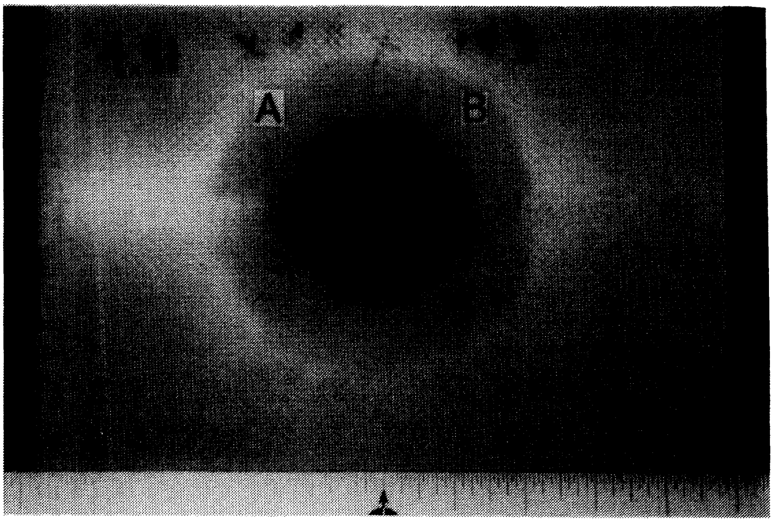


Figure 15. *Shear-plugging on the impact side of 18-layer woven aramid at an impact velocity of 920 m/s.*

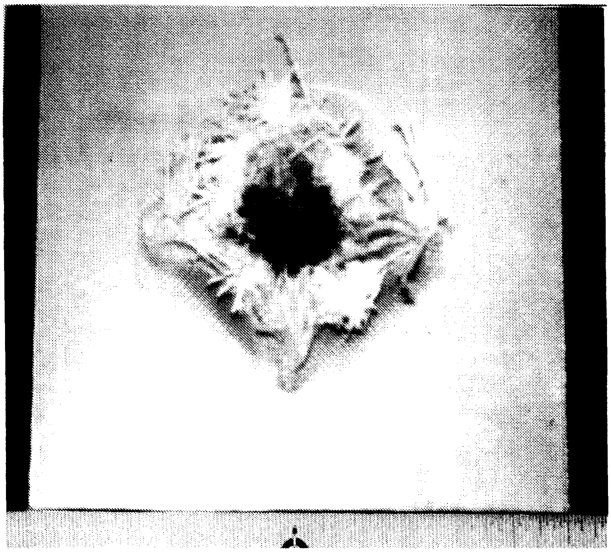
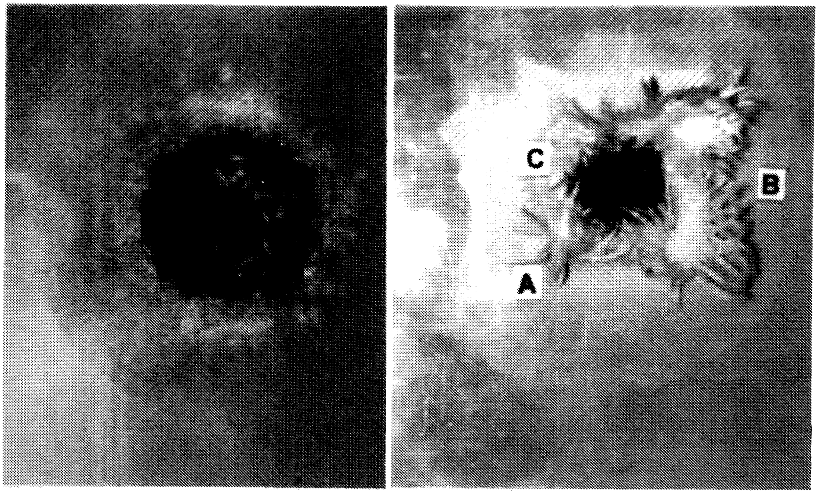


Figure 16. *Fiber breakage and pullout on back side of 18-layer woven aramid at an impact velocity of 920 m/s.*



(a) (b)

Figure 17. *(a) Front side of woven aramid/Spectra® combination, and (b) back side at an impact velocity of 940 m/s.*

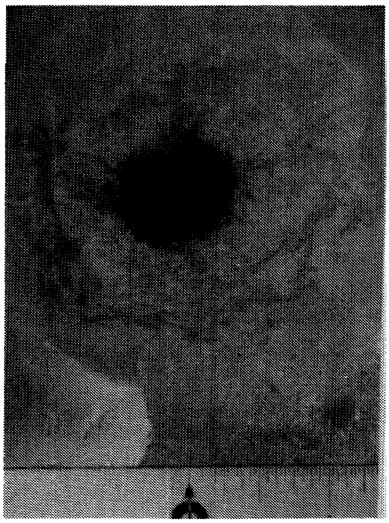
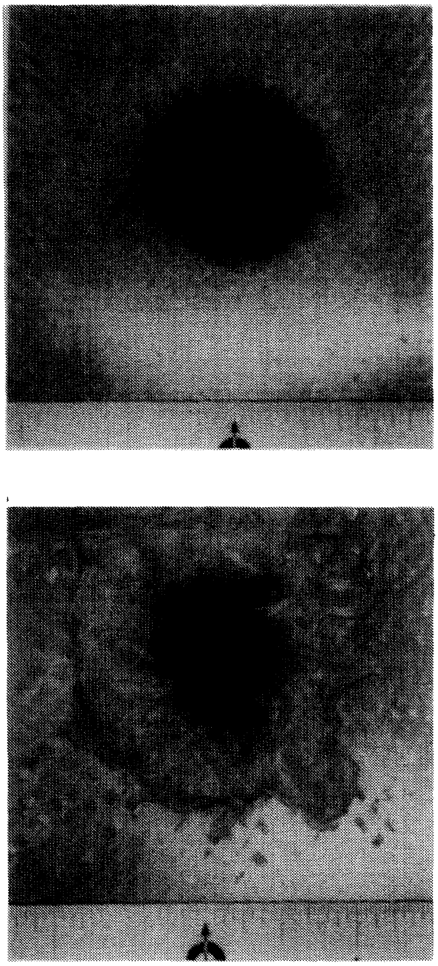


Figure 18. *Back side of woven Spectra® after shear-plugging with conical deformation at an impact velocity of 980 m/s.*



(a)

(b)

Figure 19. *(a) Front side of 3-D braided Spectra®, and (b) back side at an impact velocity of 970 m/s.*

matrix failure [Figure 17(b)]. The woven Spectra® had extensive deformation on the rear that extended to the edges of the 7.62-cm aperture (Figure 18).

There was shear-plugging for the three-dimensionally braided Spectra® on the impact surface at a velocity of 970 m/s [Figures 19(a)–(b)]. There was also fiber breakage and pullout along the periphery on the back side, as shown in Figures 19(a)–(b). The translucent quality of the braided Spectra® indicates that delamination emanates radially from the impact.

DISCUSSION

Plug Area and Failure Modes

The failure modes observed in this study are plotted in Figure 20 in terms of debris mass and impact velocity. The failure modes include: matrix cracking, fiber breakage, and shear-plugging on the impact face and progressive delamination and tensile fiber failure on the rear. Also, as shown in Figure 20, it is assumed that the strain energy is at a maximum at the lowest velocity, and that kinetic energy is the primary energy mechanism at the highest impact velocity. Hence, Figure 20 gives a correlation between the different failure modes, energy, and the penetration area. Therefore, at low velocities, there is penetration resistance due to high strain energy. As the results also indicate, conical deformation, matrix cracking, and delamination was associated with penetration resistance for all ten composites. Increasing impact velocities resulted in increased debris mass, square-shaped penetration holes, fiber pullout and breakage, and matrix cracking and delamination. As the velocity increased, the debris mass attained a maximum, which corresponded to shear-plug formation and circular shaped holes. The decrease in debris mass and shear-plugging marked the onset of kinetic energy domination.

To obtain a more detailed understanding of the effects of plug area on damage progression and failure for the ten composites, the penetration areas are plotted as a function of impact velocity (Figure 21). The penetration area was obtained by

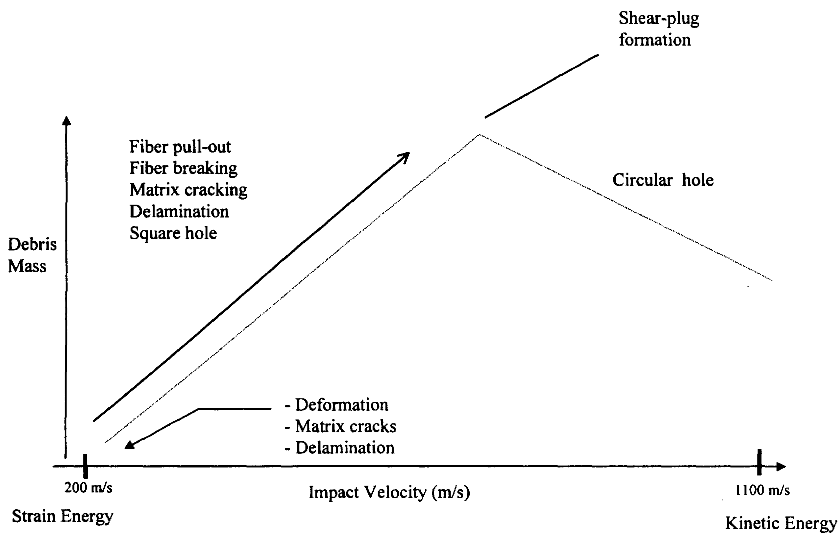


Figure 20. *Progression of penetration area and failure modes.*

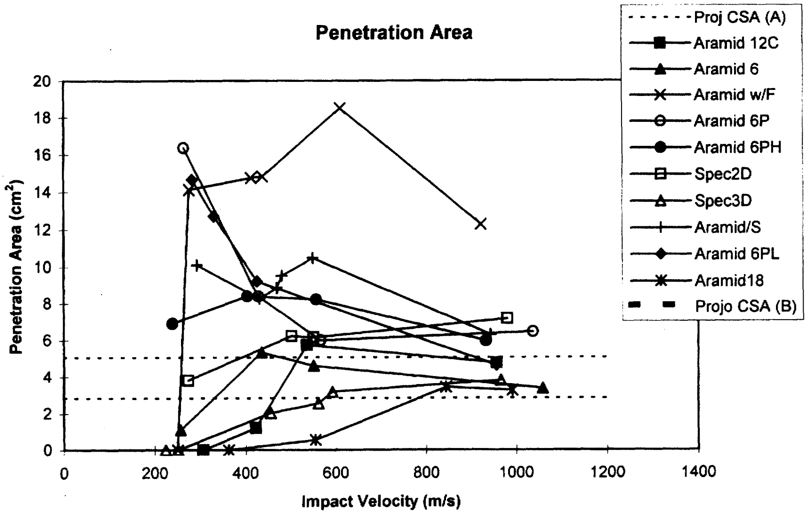


Figure 21. *Material penetration areas with increasing impact velocity.*

normalizing the debris mass by the areal density. This penetration area is the average cross-sectional area of the penetration hole. The projectile cross-sectional areas (CSA) before and after impact, at the highest velocity of 1100 m/s, are also plotted in this figure. All the plug areas, except those corresponding to the Spetra® and the Spectra®/aramid composites, asymptotically approach the projectile plug areas, as the velocities approach 1100 m/s. This indicates that for these materials, shear-plugging is the dominant failure mode in the high velocity regime. The penetration areas for the woven Spectra® and the 3-D braided Spectra® composites, continued to increase with increasing impact velocity. This indicates that tensile failure mechanisms such as matrix cracking and fiber pullout still had an effect on the plug area formation within the high velocity range.

As also seen from Figure 21, the aramid composites with finish had the largest plug area for all velocities in comparison with all the other materials. For the punched aramid and punched aramid with light fiberweb, the penetration areas decreased throughout the high velocity range. This is another indication that tensile failure mechanisms were not dominant factors for these materials in the intermediate to high velocity range.

Penetration Resistance and Energy Absorption

Energy loss during penetration can be attributed to energy absorption by the material, projectile deformation, and heat generation due to friction. Projectile defor-

Table 3. Composite penetration resistance.

Material	Areal Density (g/cm^2)	Threshold Velocity (m/s)	Specific Energy (J/g/cm^2)
Aramid/Spectra	.3641	290	1488
Aramid, 18 layers	.5712	360	1414
Aramid, 12 layers	.4719	300	1253
Aramid w/Finish (6)	.4023	290	1197
2 D woven Spectra	.4000	270	1180
3 D braided Spectra	.4454	250	886
Aramid, 6 layers	.2250	250*	1012
Aramid Punched-Heavy**	.5080	240*	706
Aramid Punched-Light	.4597	280*	1172
Aramid Punched	.3935	260*	1120

*Lowest velocity tested, but did not resist penetration.
**Rank ordered above the other punched materials due to higher energy absorption up to 1100 m/s [9].

mation was calculated as a function of impact velocity. Results given in Reference [9] indicate that the energy loss due to projectile deformation was similar for all ten materials. Furthermore, heat generation due to friction is generally negligible for the velocities in this study [2]; hence the dominant energy mechanism during penetration is due to material energy absorption.

The material's absorbed energy was determined using the impact and residual velocities and the conservation of energy,

$$E_{absorbed} = 1/2\,\mathrm{Mass}_{projectile}(V_{impact}^2 - V_{Residual}^2) \tag{1}$$

The ten textile composites were rank ordered by the threshold velocity in Table 3. The threshold velocity is the lowest measured velocity at which penetration was observed. In this table, specific energy is the materials' energy absorption normalized by areal density. These result show that the composite with the Spectra®/aramid combination had the highest specific energy absorption, and that the three-dimensionally braided Spectra® had the specific highest energy absorption of the non-finished preform composites.

CONCLUSIONS

Penetration resistance and structural integrity as a function of the consolidation process (fabric finish, resin adhesion, layering), fiber type of the preform material (aramid, UHMWPE, hybrid), and material process (woven, 3-D braided, needle punched) were investigated for ten tailor-made textile composites. These composites were subjected to velocities that ranged from 200 m/s to 1100 m/s. The woven aramids had increased penetration resistance as the number of material layers was increased. Furthermore, increasing the number of layers for the woven aramids delayed the onset of shear-plugging as the velocity increased. The aramid with finish had improved penetration resistance, however, due to poor interlaminar adhesion, it had extensive matrix and fiber damage in regions that extended beyond the impact region.

The introduction of fibers in the transverse direction, by needle-punching, significantly limited the growth of delamination, but resulted in shear-plug formation in the intermediate velocity range. Needle punching with the heavier fiber web did improve energy absorption in comparison with the light web and punched-only samples. However, the damage of the axial fibers associated with the introduction of transverse fibers by needle punching may outweigh any benefits gained by strengthening the transverse direction of the textile composites.

Due to the desirable weight and strength characteristics of Spectra® twice as many layers of this material as aramid layers could be used for penetration resistance for the same areal density. Composites with combinations of aramid and Spectra® fabrics had substantially higher energy absorption and lower damage in comparison with single material systems. The mismatch of material characteristics at the Spectra®/aramid boundary phases can improve energy absorption as well as material structural integrity.

The three-dimensionally braided Spectra® had the highest penetration resistance and structural integrity after impact for a specified areal density in comparison with all the other tested materials. The 3-D braided Spectra® had high penetration resistance with limited damage, even though it was consolidated with a low fiber volume fraction. These materials had extensive deformation at the impact point with very little matrix cracking and without the material edges collapsing toward the impact region. Delamination was also much less extensive than the woven Spectra® and the aramids. The improved material response is due to the presence of transverse fibers and the ability of braided fabric to conform to different shapes. The absence of fiber crimping also results in better energy absorption.

Results from this study indicate that there is a transition from tensile to shear failure modes in the intermediate and high impact velocity regime. Shear-plugging occurs when the projectile's kinetic energy surmounts the material's inherent strain energy at threshold velocities that correspond to decreases in debris mass. In future studies, the characterization and understanding of failure modes obtained in this study will be used to develop new physically based, predictive, computational tools for the high strain-rate deformation and failure of heterogeneous materials.

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