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The Application of High-Modulus Fibers to Ballistic Protection

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EDITOR'S NOTE: All three types of X-500 high-modulus organic fiber studied by Laible, Figucia, and Ferguson were made from the same polymeric composition by use of different spinning techniques. The particular polymer was the same PABH-T polyamide-hydrazide based on p-aminobenzhydrazide and terephthaloyl chloride reported on in detail by Black, Preston, Morgan, Raumann, and Lilyquist, J. Macromol. Sci.—Chem., A7(1), 137 (1973). Accordingly, the "X-500" studied by Laible et al. was just one member of the X-500 class of high-modulus organic fibers investigated by the Monsanto Company. The nature of the fibers investigated by Laible et al. was not identified to them other than that the fibers were high-modulus organic fibers of the aromatic amide type.

ABSTRACT

A new family of experimental organic fibers (X-500) produced by the Monsanto Research Corporation has been evaluated ballistically. The development of this family of fibers made available for the first time a series of organic fibers with moduli and heat resistance more nearly comparable to inorganic fibers such as glass. Tensile analysis of three material types tested in yarn form at conventional loading rates showed physical properties ranging from typically brittle (10.1 g/den tenacity, 2.4% extension, and 550 g/den modulus) to moderately ductile (5.4 g/den tenacity, 15.4% extension, and 135 g/den modulus).

The three samples were evaluated ballistically in fabric, felt, and laminate form. The most ductile sample (Type III) showed considerable promise with a ballistic resistance significantly greater than normal for a material of such modest tensile strength. Tensile recovery tests on this Type-III material showed a large amount of permanent set compared to most commercially available yarns. It appears that this capacity for plastic flow, combined with the inherent high modulus, act in combination to provide good energy absorption.

Scanning electron micrographs of ballistic missile impact areas showed for the more brittle yarns, longitudinal splitting with little evidence of plastic deformation, or fusion of fibers around the hole produced by the missile. The more ductile yarns exhibited a combination of some longitudinal splitting with plastic deformation and fusion around the hole. This latter combination of energy absorbing mechanisms proved to more effective.

INTRODUCTION

The performance of aerial delivery systems, ballistic protective systems, climbing ropes, and seat belts could be improved not only by the use of more specifically engineered fibrous structures but also by the use of tailor-made fibers possessing the proper combination of properties. Fiber technology in industry is advancing to the point where, to a large extent, properties can be controlled.

The major difficulty in utilizing this advanced technology lies in defining this optimum combination of properties.

In textile materials the property of ultimate strength and its importance in preventing failure is immediately apparent. This is especially true in the area of ballistic resistance, where fabrics prepared from high-strength yarns such as nylon, Fortisan R, and polyester have proven to be much more effective than those prepared from lower strength yarns. However, there are exceptions such as fabrics prepared from various high-strength glass yarns which are not effective for providing ballistic protection in simple unlaminated form. On the other hand, a moderate strength material such as silk may possess ballistic protective qualities equivalent to nylon although its ultimate strength or tenacity (strength per unit of linear density) is significantly less.

The fact that strength, elongation, and work-to-break properties change with rate of testing has been well documented [1-3] and has been related to areas, such as ballistic protection and air delivery, where it applies [4, 5]. The form and complexity associated with the fibrous material during test or actual use also may influence the strength, elongation-to-break, and work-to-rupture exhibited. The present authors have discussed aspects of this interaction between structural complexity and speed of testing in a recent article [6]. However, the strong emphasis on strength and work to rupture as the important factors in impact resistance may have resulted in insufficient attention being devoted to other properties such as modulus and heat resistance.

The former property, modulus, influences the speed with which a material can respond to impact. The simplified formula for the speed of the longitudinal sonic wave:

$$C = \left(\frac{d\sigma/d\epsilon}{\rho}\right)^{1/2} = (E/\rho)^{1/2} \tag{1}$$

where C = sonic velocity, E = modulus, ρ = density, ϵ = strain, and σ = stress, illustrates this point, showing the direct dependence of the longitudinal wave velocity C upon the stiffness or modulus of the material E. Additionally, the strain energy imparted during impact may be partially converted to heat, and the second factor of heat stability may play a role in determining the response of a textile material to impact. Specifically, Susich [7] noted that the fibers in the area of impact where a metal fragment hit or penetrated a nylon vest were melted, and Wells [8] has pointed out that the relatively high ballistic performance of an aromatic nonmelting polyamide fabric, such as that from m-phenylene diamine and isophthaloyl chloride, suggests possible benefits resulting from the use of more highly heat resistant materials.

These observations, plus the fact that glass, a high-modulus material, is very effective in laminate form, have helped formulate a mental image of the "better" fiber for applications involving impact. The static properties of the fiber should be such that it has high strength, 10-20 g/den (grams per denier) in textile terms or 200,000-400,000 psi in engineering terms. The modulus should be high, greater than the 40-120 g/den characteristic of commercial polyamide and polyester fibers. It is not known how high the modulus should be; perhaps in the range of glass fiber (300 g/den).

The deficiency of glass fibers in unlaminated fabric form, despite their efficiency in laminated form, suggests that some degree of ductility is required for use in textile structures. This degree of ductility may be measured by knot or loop strength which should be a major percentage of the simple tensile strength. Work-to-date has indicated that about 4-8% elongation is required to furnish this ductility [6].

The fourth requirement is that the textile material have a high degree of heat resistance; for example, a polyamide material with a melting point of 255°C appears to possess better impact properties ballistically than does a polyolefin fiber with equivalent tensile properties but a melting point half as high.

Man-made and natural organic fibers have moduli which are generally in the region of 20-120 g/den. To obtain available fibers and yarns with higher moduli, one must shift to metallic fibers such as steel, or boron, to ceramic fibers, such as glass, or to carbon fibers. All of these materials have deficiencies, such as low elongation-to-break and poor translation of mechanical properties when involved in complex structures and subjected to high-speed impact. To raise the moduli of organic fiber types, it is generally conceded that it is necessary to cross-link the polymer, raise the crystallinity, or introduce chemical entities such as the phenyl group in the backbone in order to stiffen the chain. All of these procedures also confer some degree of intractability to the polymer and make the preparation and optimization of fibers from such polymers very difficult. In recent years, industry has developed an increased ability to deal with such "intractable" polymers [9, 10].

This paper describes an investigation of a family of experimental fibers exhibiting a combination of high modulus and heat resistances not found in commercial organic fibers.

MATERIALS INVESTIGATED

The X-500 fibers were identified only as high-modulus fully aromatic polyamide fibers available in three types or variations. (See footnote on p. 295. Editor.) Neither the method used to prepare these fibers nor the exact chemical structure was disclosed by Monsanto. It was known only that these fibers were organic, possessed high but variable modulus, and that the degree and perfection of crystallinity was high. This was especially true for the higher modulus, higher strength members of this family.

The three types are as follows:

Type I—The most highly oriented member of the X-500 family was Type I with reputed tenacities of 12-14 g/den, moduli of 500 g/den and elongations-to-break of 2-4%. The density of this material is approximately 1.47 g/cm³.

Type II—The Type II fiber appeared to be an attempt to attain a better balanced fiber by orienting (stretching) the material less. The tenacities and moduli were in a lower range (7-9 g/den and 300-400 g/den, respectively) with a higher elongation-to-break of 5-7%. The density of the Type II fibers is approximately 1.46 g/cm³.

Type III—The Type III fiber represents the highest ductility with elongations-to-break in the range of 18%. The tenacity and modulus are consequently lower, 5-6 and 130-160 g/den, respectively. The density of these fibers is approximately 1.44 g/cm³.

EXPERIMENTAL TECHNIQUES

Tensile Properties

Static tests were conducted on an Instron Tensile Tester at a strain rate of 100%/min. High-speed tests were conducted on a Frits Pneumatic Piston Tester at extension rates of 288,000%/min. Loop and knot tests were conducted as a measure of the effect of complexity upon strength properties, especially at high rates of testing. This type of test and its significance have been described previously [6].

Thermal Properties

The thermal stability of the fibers was measured by Thermal Gravimetric Analysis using the Perkin-Elmer TGS-1 Thermobalance.

Ballistic Properties

The relative protection afforded by each of the fibrous materials in woven fabric, felt, and laminate form was measured by the "ballistic limit test." This test involves impact with a 0.22 caliber, 17-grain missile, which is somewhat representative of a fragment from a mortar shell. The velocity of the test missile can be varied by changing the quantity of the powder used. A series of firings at different velocities are made and a statistical result is obtained which represents the velocity whereby 50% of the missiles are defeated by the target. Other probabilities of penetration could be obtained such as 0%, the velocity at which all missiles would be defeated, but in general the statistical accuracy would be less and more firings would be required. Also, it should be noted that the shape and size of the missile could be varied and, in fact, do vary when emanating from a munition such as a mortar shell, and the 17-grain fragment is only selected for convenience. Specific procedural details are set forth in Military Standard MIL-Std-662, Ballistic Acceptance Test Method for Personal Armor Material.

Scanning Electron Micrographs (SEM)

The technique used to investigate the impacted fabrics involved a 50-Å carbon precoat followed by a gold-palladium overcoat of 400 Å. The micrographs were obtained using secondary electrons and a relatively low accelerating voltage of 3-5 kV. Both the Cambridge and the AMR instruments were used.

Sonic Velocity and Sonic Modulus

The sonic velocity was measured using the KLH Pulse Propagation Meter, Model Number PPM-5R. Piezo-electric ceramic elements are used as the transducers and operate at a resonant frequency of 5 kHz. The longitudinal wave velocity was measured and converted into sonic modulus using a conversion factor involving the linear density of the fiber:

$$E = C^2 \times 11.3 \tag{2}$$

where E = modulus (g/den) and C = sonic velocity (km/sec). Values were recorded over a range of strain levels approaching the breaking point for each material.

TEST RESULTS

Tensile Measurements

The tensile properties of the experimental yarns were measured by removing them from the fabrics, untwisting them, and testing them with essentially zero twist. In addition, for the static tests, yarns as received on spools were tested so that a comparison would be available between the properties of the yarns as produced and the properties of the yarns after weaving and scouring. This was necessary because high-modulus yarns may be damaged by processing.

The results of these tests are given in Table 1 with the first row of values for each yarn type representing the spool yarn and the second row the fabric yarn untwisted.

Considering the brittle nature of these experimental yarns, the losses observed due to processing are minimal.

Typical static stress-strain curves for the three yarns are shown in Fig. 1. The compromise between modulus and strength on the one hand and ductility on the other is readily apparent.

Qualitatively, it can be seen from Fig. 2 that nylon tire cord has a greater area under the stress-strain curve than is characteristic of any of the experimental yarns. The actual work-to-rupture values obtained by planimeter readings given in Table 1 confirm this quantitatively.

Because impact applications involve subjecting materials to high strain rates, the three yarns were also tested at 20 ft/sec (288,000%/min) or approximately 3000 times the static rate. These results are listed in Table 2.

The results follow the same general pattern as the static test results. When compared to the data in Table 1, it can be seen that the tenacities and moduli have increased and the elongations have been reduced. The effect of strain rate upon the stress-strain properties of these yarns is also shown in Figs. 3 and 4 where Type II and Type III yarn stress-strain curves are given at the two strain rates. Several features are interesting.

TABLE 1. Static Stress-Strain Properties of Experimental Yarns (100%/min extension rate)

Type	Twist (tpi)	Tenacity (g/den)	Elongation (%)	Modulus (g/den)	Work-to-rupture (g cm/den cm)
I	1	10.1	2.4	550	
	0	9.7	2.5	550	0.13
II	2	7.0	5.2	280	
	0	7.1	5.0	250	0.24
III	4	4.9	17.8	160	
	0	4.6	15.4	135	0.56
Nylon 66 tire cord	0	9.5	19.0	36	0.86

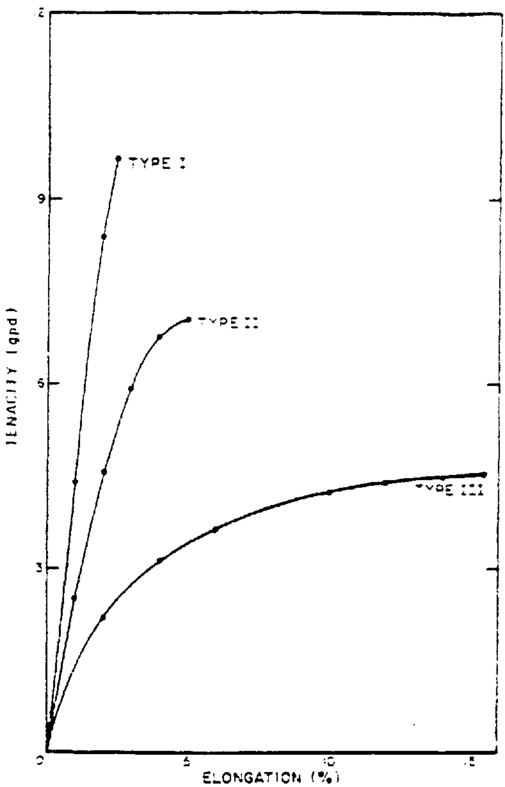

FIG. 1. Comparison of three X-500 yarns at low strain rate.

TABLE 2. Stress-Strain Properties of X-500 Yarns at an Extension Rate of 288,000%/min

Type	Tenacity (g/den)	Elongation (%)	Modulus (g/den)	Work-to-rupture (g cm/den cm)
Type I	13.4	2.2	615	0.15
Type II	10.3	3.8	300	0.22
Type III	5.7	6.9	179	0.30
Nylon 66 tire cord	10.8	16.6	60	0.80

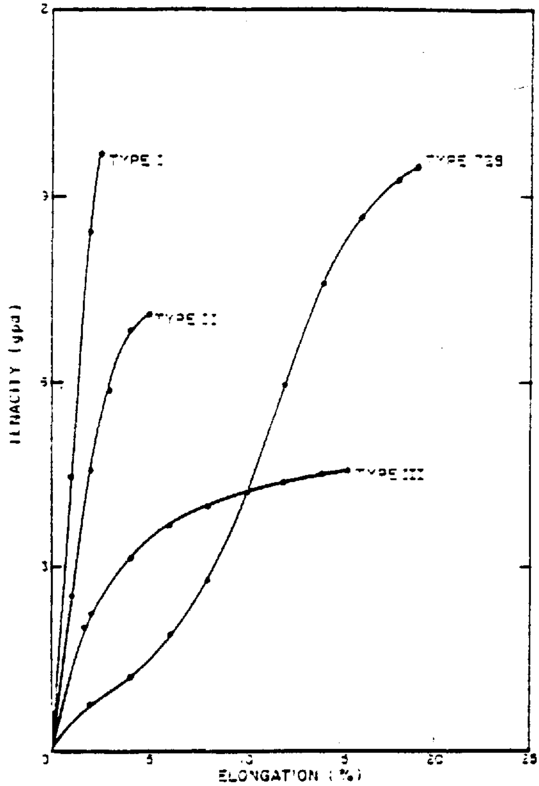

FIG. 2. Comparison of X-500 and nylon yarns at low strain rate.

The first is that their moduli do not appear to be very strain-rate dependent although the ultimate properties follow the usual trend of higher strength and lower elongation as the strain rate is increased. A second feature is that the stress-strain curve of the Type II yarn at high speed appears to be almost completely linear. This may indicate a tendency for nearly 100% elastic behavior at this speed. Other factors of interest are the sharp drop in elongation-to-break for the Type III yarn at high strain rate and the interesting shape of this stress-strain curve at high speed. This shape is reminiscent of a theoretical elastic-plastic stress-strain curve with perfect linearity to 3% elongation followed by a nearly horizontal post yield section from 3% elongation

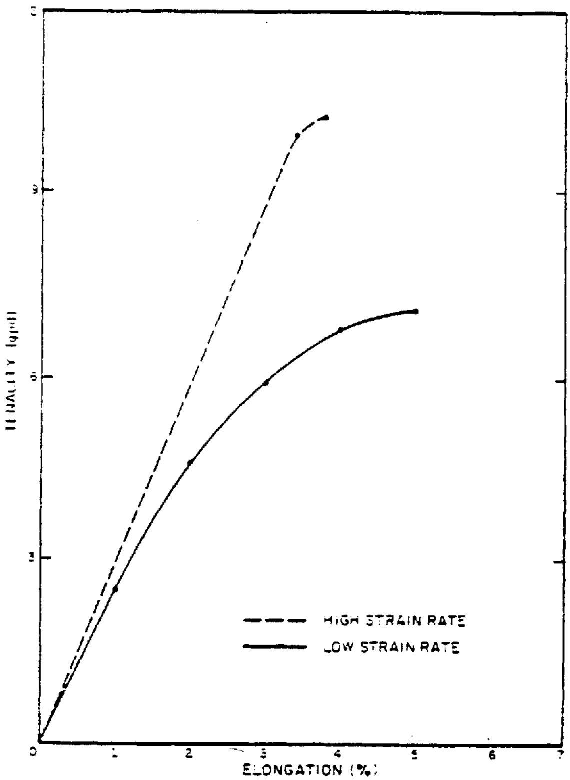

FIG. 3. Stress-strain curves for X-500 Type II yarns at high and low strain rates.

to the rupture point. This elastic-plastic curve may be a very important consideration in ballistic performance where the application is a one time affair or essentially a "throw-away" item after use.

The stress-strain curves for all three types of experimental yarn at the high strain rate are given in Fig. 5. Again, the typical high performance tire yarn is used for comparison. The contrast in the area under the curve (work-to-rupture) for the tire yarn with that for any of the experimental yarns is even more pronounced than at low strain rates. This low energy to rupture is not encouraging when considering these new materials for energy absorption applications at high rates of straining.

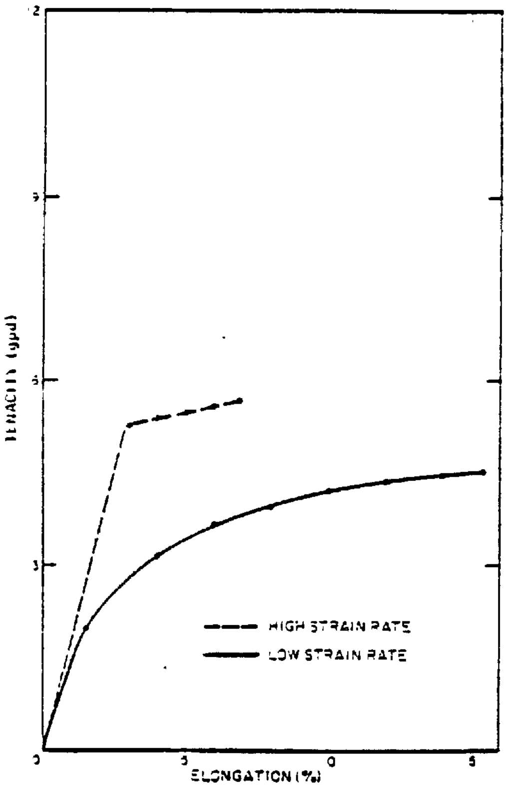

FIG. 4. Stress-strain curves for X-500 Type III yarns at high and low strain rates.

Thermal Test Results

The Type I and Type III yarns were subjected to a Thermal Gravimetric Analysis [11] to a temperature of 760°C. The results showed maximum weight losses of 65% for Type I and 79% for Type III. Two decomposition points were evident for both materials at 392 and 528°C for Type I and at 408 and 508°C for Type III. Actually, 400°C was reached before any significant weight loss could be established and about 20% weight loss was experienced at 500°C.

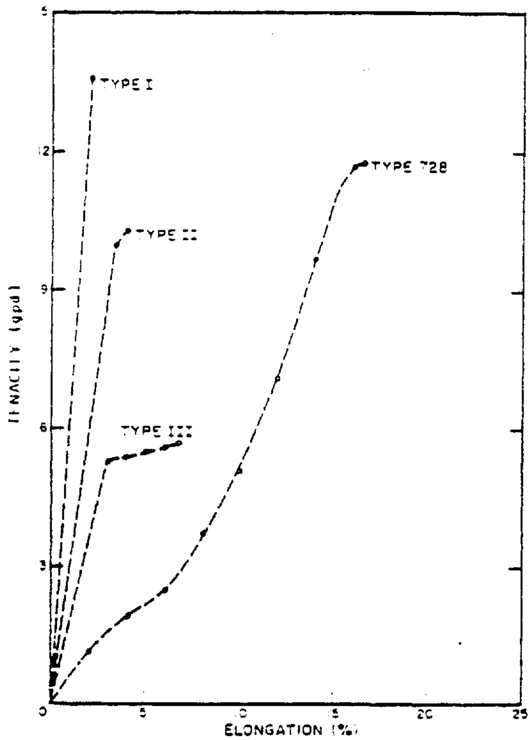

FIG. 5. Comparison of X-500 and nylon yarns at high strain rate.

Sonic Test Results

The sonic test results obtained on the Pulse Propagation Meter with materials under a tension of 2 g/den are given in Table 3.

Ballistic Test Results

Woven Fabric Results

Woven fabrics were prepared for ballistic testing by the "ballistic limit test" (V-50) described in the Experimental Techniques section. Results of these tests are shown in Table 4.

TABLE 3. Longitudinal Wave Velocity and Sonic Modulus

Material	Wave velocity (cm/sec)	E (g/den)
Type I	8.2×10^5	760
Type II	5.5×10^5	342
Type III	4.7×10^5	250
Nylon 66	3.1×10^5	109

TABLE 4. Woven Fabric Ballistic Limit Values

Material	Areal density (oz/ft^2)	Plies	Finish[a]	V-50 (ft/sec)
Type I	18.4	15	S	1070
	18.6	15	G	938
	11.1	9	S	862
Type II	18.6	14	S	1074
	18.6	14	G	854
	10.7	8	S	840
Type III	19.2	13	S	1244
	18.4	13	G	1132

[a]S and G are scoured and greige, respectively.

The results given here have significance only when compared to values obtained on more familiar materials. The minimum V-50 value used for acceptance testing of fabric prepared from nylon tire yarn plied to an areal density of 18.6 oz/ft^2 is 1225 ft/sec.

It can be readily seen from Table 4 that Type I and Type II materials at equivalent areal densities fall far short of this minimum value.

Glass fabric at 8-9 oz/ft^2 areal density has a V-50 of 650-700 ft/sec and at 18 oz/ft^2 a V-50 of 900-950 ft/sec. This is quite comparable to the results shown in Table 4 for the Type I and Type II fabrics. The yarn physical properties of these two types are also comparable to those of glass which has a modulus of 350 g/den, a strength of 7-10 g/den, and an elongation to break of about 4%.

The Type III yarn is quite different from glass, however, with the modulus a factor of two lower, and the elongation to break more than a factor of three greater. This yarn, when prepared into fabric form, scoured and tested ballistically, resulted in a more respectable ballistic limit value of 1244 ft/sec. This is much higher than would be obtained from any glass-like material and, in fact, exceeds the minimum specification value of 1225 ft/sec used for acceptance of nylon fabric prepared from tire yarn.

Felt Ballistic Results

Because of the brittle nature of the Type I fibers, they could not be manufactured into a satisfactory needle-punched felt. Consequently, felts were prepared only from the Type II and Type III experimental fibers. Ballistic results obtained are shown in Table 5.

TABLE 5. Felt Ballistic Limit Values

Fabric material	Areal density (oz/sq ft)	Plies	V-50 (ft/sec)
Type II	7.1	6	671
Type III	7.9	6	788

The Type III material is better than the Type II, but both results are considered poor. The obtained values are far below those characteristic of polyamide felts for which the specification requires a minimum of 1125 ft/sec at this areal density for acceptance in body armor.

Laminate Ballistic Results

Because of the glass-like nature of the experimental fibers (especially Type I and Type II), it was of special interest to prepare laminates for ballistic evaluation. Laminates were first prepared using a 60% fabric loading in P-43 styrene polyester resin (supplied by Rohm & Haas Co.). This loading was less than that for glass-reinforced plastics (80%) because of the lower density (1.47 g/cm^3 of the experimental fiber as compared to 2.50 g/cm^3 for glass fiber.

Ballistic measurements were made on the prepared laminates as well as on separate panels made from the same number of unlaminated fabric plies. These results are shown in Table 6.

TABLE 6. Ballistic Limit Values for Laminates of Experimental Fabric in P-43 Resin (60% loading)

Type	Condition		V-50 (ft/sec)
I	9 ply, 11.1 oz/ft^2 fabric only		888
	9 ply with resin P-43 to 1.14 oz/ft^2		639
		Loss	249
II	8 ply, 10.7 oz/ft^2 fabric only		830
	8 ply with resin 1.2 lb/ft^2		623
		Loss	207
III	8 ply, 11.6 oz/ft^2 fabric only		998
	8 ply, with resin P-43 to 1.2 lb/ft^2		727
		Loss	271

The ballistic values for all three fiber types are low when compared to glass laminated structures (18.6 oz/ft^2 areal density) which offer values in excess of 1200 ft/sec. In the case of the experimental fibers, losses of 200 ft/sec or more accompanied lamination for all three fiber types.

The ballistic losses resulting from laminating the fabrics with P-43 resin suggested additional experiments to determine if fabric loading or type of laminating resin was responsible for the poor results. Some of the more obvious parameters were varied and these results are given in Table 7.

The amount of styrene in the P-43 polyester resin was varied from 5 to 15 pph with no effect as shown by entries 1, 2, 3, 4, 5,

TABLE 7. Ballistic Limit Values for Laminates of X-500

Item	No. plies	Type fabric	Fabric (wt %) Loading (%)	Areal density (oz/ft)	Styrene resin content	V-50 (ft/sec)
1	12	III	60	19.2	P-43 5 pph	679
2	12	III	60	19.1	P-43 10 pph	673
3	12	III	60	18.3	P-43 15 pph	659
4	12	III	40	34.0	P-43 5 pph	1043
5	15	III	60	39.3	P-43 5 pph	1185
6	14	III	60	33.8	P-43 10 pph	1152
7	15	III	60	35.9	P-43 15 pph	1112
8	15	III	60	35.0	P-43 10 pph	1118
9	22	III	80	40.1	P-43 10 pph	1373
10	12	II	60	19.7	Epoxy-828	649
11	12	II	60	19.7	Phenolic XC-1008	511
12	12	II	60	19.7	Polycarbonate	491

6, and 7 in Table 7. Fabric loading was varied from 40 to 60% (Items 4 and 5) and from 60 to 80% (Items 8 and 9) with little effect other than that which can be ascribed to the greater number of fabric plies. Experiments with different resin systems such as phenolic, polycarbonate and epoxy resin (Items 10, 11, and 12) gave little encouragement but showed that the epoxy resin had the greatest promise.

DISCUSSION

The availability of these new types of high modulus-heat resistant organic fibers have provided some new dimensions for consideration in tailor-making a fiber for impact and ballistic applications. Previously, parameters such as strength, elongation-to-break, and work-to-rupture were emphasized in attempting to correlate yarn properties and impact performance. Modulus and heat resistance were not studied in sufficient detail to establish their influence in achieving fibrous structures with high impact resistance. In fact, little leeway was possible because the moduli were all centered around 20-100 g/den for the organic fibers and only an inorganic, glass, was available with a higher modulus (320 g/den). Likewise, with heat resistance, the only comparisons possible were between polypropylene with a melting point of 123°C and nylon with a melting point of 255°C. The results favored nylon but were inconclusive as to cause and effect. The behavior of the Type III X-500 experimental fiber now has shown that a material with a much lower static or dynamic work-to-rupture than nylon can be nearly competitive in ballistic resistance.

In addition to evaluating the mechanical properties of the materials in various forms and at different rates of straining, it is also instructive to view panels which have actually been subjected to ballistic impact. This was done using the scanning electron microscope in the conventional manner. The brittle nature of the failure of the Type I material is very apparent in Figs. 6 and 7. The splitting of the fiber, apparent in Fig. 7, is actually a possible toughening mechanism characteristic of fibrous materials where a lateral crack is converted to a longitudinal one retarding failure. However, this amount of deformation and work absorption is insufficient to achieve ballistic performance comparable to that characteristic of nylon materials. Figure 8 illustrates the magnitude of the deformation which occurs

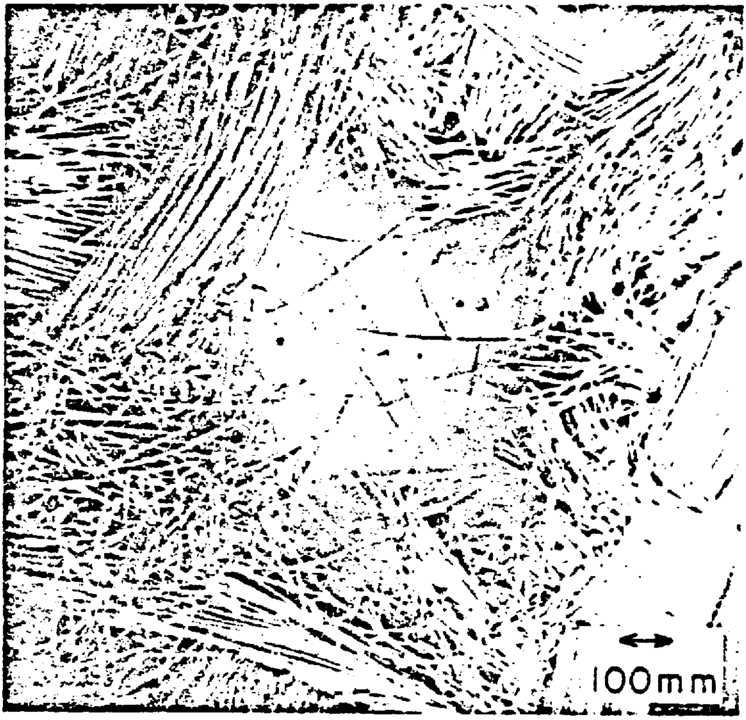

FIG. 6. SEM micrograph of Type I X-500 fabric impacted with 17-grain fragment simulator (16×).

in a nylon fabric impacted with a fragment simulator. The extent of the damage created is even more evident in Fig. 9 where the broken fiber ends are fused. This fusion appeared to be essentially absent in the Type I fibers similarly impacted. Figure 10 shows the type of damage which occurred when the Type III fabric was impacted with the simulator. In this case extensive deformation and fusion were evident reminiscent of that seen in the case of nylon. Figure 11 shows not only these characteristics but also some of the splitting characteristic of the more brittle Type I material. This indicates the possibility of multiple deformation responses in the case of the more ductile Type III material.

Despite the initial emphasis in this work on the importance of modulus and heat resistance, it appears from the results that a third factor, the ability to plastically deform, may prove to be

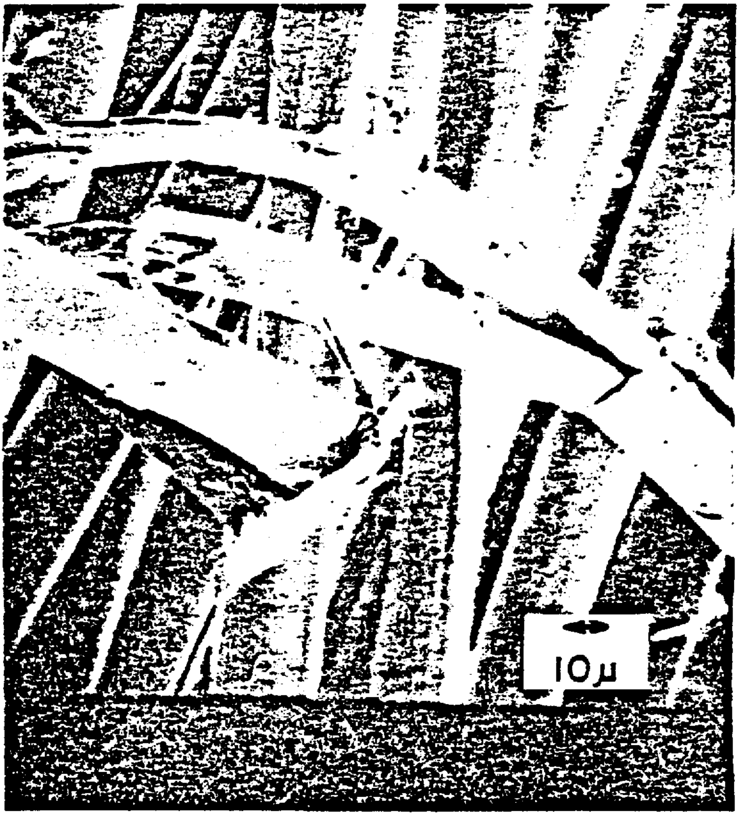

FIG. 7. Type I X-500 fibers damaged by impact with 17-grain fragment simulator (510×).

the major reason for the good ballistic behavior of the Type III yarn. This must be true when comparing Type III to Types I and II or glass. Strength, modulus, and heat resistance are all present to an equal or greater degree in the case of these latter materials. The big difference is in the ability of Type III to plastically deform. This characteristic was inferrable from the shape of the high-speed stress-strain curve (Fig. 5) with the sharp break in the curve at 3% elongation followed by an almost horizontal portion. Preliminary tensile recovery experiments in which all three yarn types were stretched to 50% of their ultimate extension tended to confirm this important difference between the yarn types. The Type III

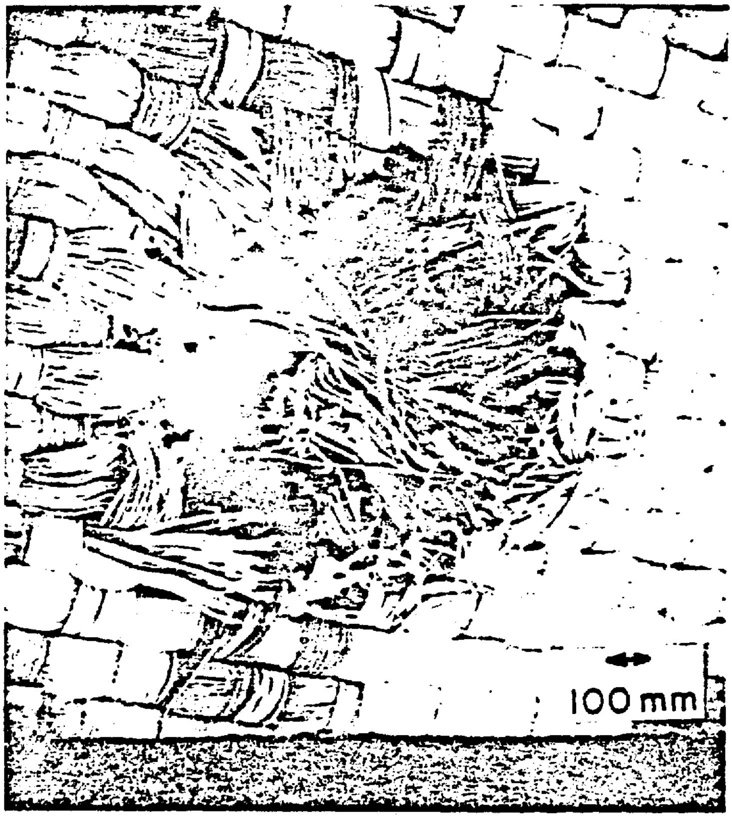

FIG. 8. SEM micrograph of hole created by 17-grain fragment simulator I impacting nylon fabric (24×).

yarn exhibited 50% permanent set as contrasted with 12% for Type II and 5% for Type I [12]. Even yarns such as nylon 66, which are usually considered ductile under these same conditions, exhibit values of permanent set of the order of 5% or less. The continuing study of elastic recovery, delayed recovery, and permanent set for a large number of fibers currently active may result in some minor modification of the conclusions reached. However, even these initial results show that the new high-modulus

FIG. 9. Nylon fibers broken and fused from missile impact (450×).

organic fibers have a much greater ability to yield plastically than has been found in similar investigations of other high-modulus fibers such as glass. Where a one-time use of these materials is contemplated such as in a ballistic vest or certain air delivery applications, it is advantageous to have the fibers deform plastically rather than break and transfer large amounts of elastic energy to the surviving fibers.

The laminate work shows the difficulty in preparing laminates

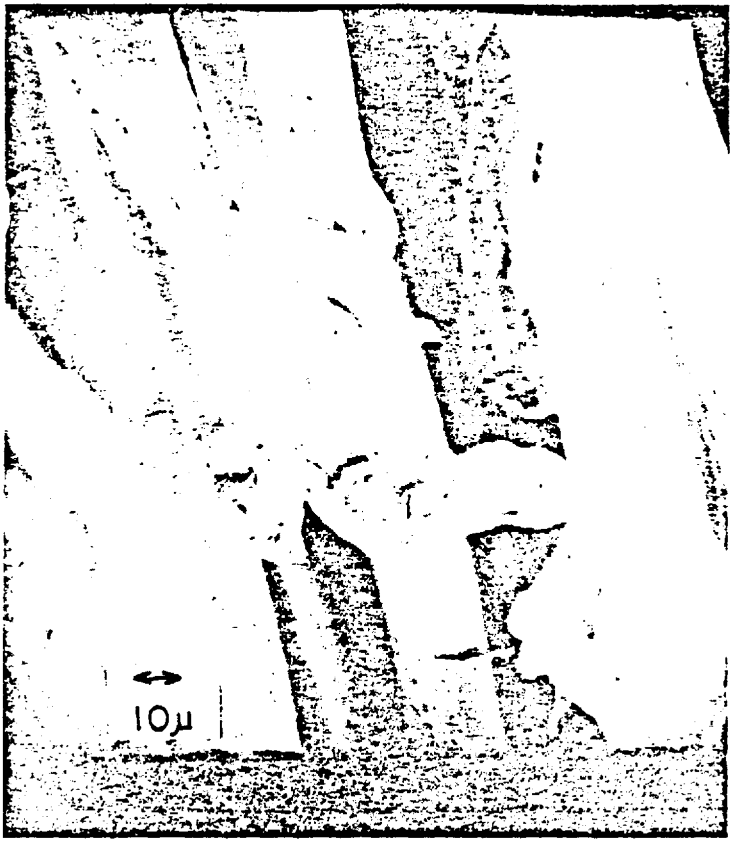

FIG. 10. X-500 Type III fibers after impact with 17-grain fragment simulator (493×).

competitive with glass. Previously, organic fibers were not considered suitable for laminates because their moduli were so low compared to glass. However, the poor results obtained on this experimental family of fibers with moduli below, equivalent to, and higher than that for glass indicated that high modulus alone does not guarantee good laminate performance. Other factors such as surface characteristics are apparently equally important and must be investigated further. Figure 12 shows a single delaminated layer of Type II material after failure in tension. The material had been bonded with phenolic XC-1008

FIG. 11. X-500 Type III fiber ends after impact with 17-grain fragment simulator (450×).

resin. Note the strong bonding that still exists between adjacent yarns. Delamination in this plane is thought to be one of the keys to improved laminate performance. To date, various auxiliary surface treatments and other methods of achieving this have proved unsuccessful.

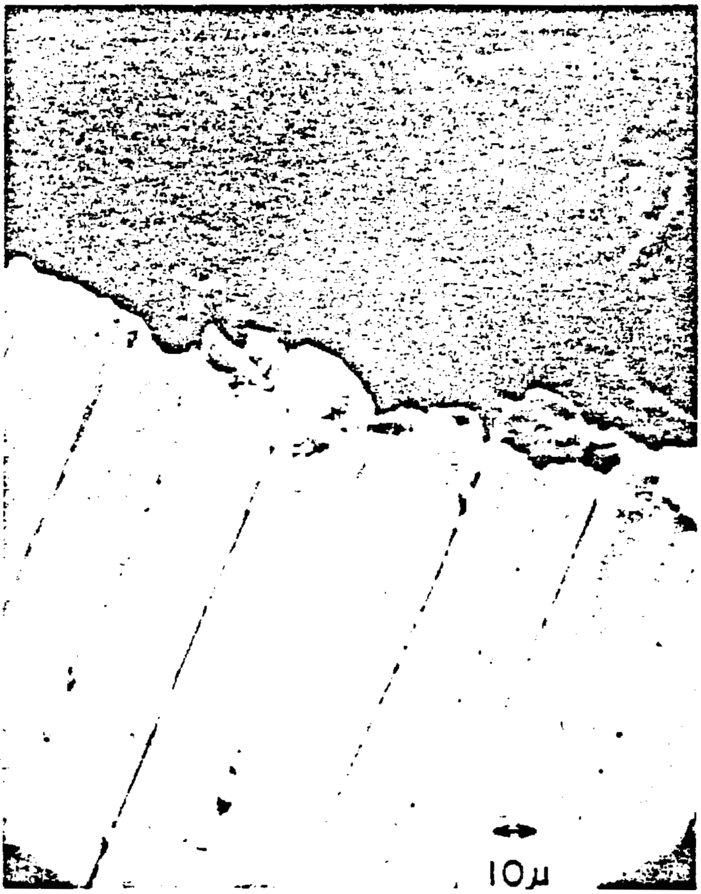

FIG. 12. X-500 Type II fabric laminated with phenolic resin (500×) and broken in tension.

CONCLUSIONS

The development of the X-500 family of fibers by Monsanto Research Corporation made available for the first time a series of organic fibers with moduli and heat resistance more nearly comparable to the inorganic fibers such as glass. This series of fibers possessed a wide range of properties with strengths from 4.9 to 10.1 g/den, elongations-to-break from 2.4 to 17.8%, and moduli from 160 to 550 g/den. The static and dynamic work-to-rupture values of these new materials were all markedly lower than those for nylon tire cord. However, fabric prepared from Type III yarn performed nearly as well ballistically as standard nylon fabric. This behavior was surprising in view of its modest stress-strain properties, and may be attributed to the following combination of properties:

High Modulus—The modulus of 135 g/den for the X-500 yields a higher longitudinal wave velocity than for nylon with a modulus of 40 g/den, according to the formula $C = (E/\rho)^{1/2}$ where E is the modulus, ρ is the density, and C the longitudinal wave velocity. In general the higher wave velocity should yield a faster response to impact and should involve more of the material per unit time. If this were the only property important in impact, the Type I with a sonic velocity of 8.2×10^5 cm/sec would be far superior to the Type III. However, results have shown that the opposite is true. Actually this sonic velocity is higher than that of any commercially available organic fiber and even approaches the theoretical value of 12×10^5 cm/sec obtained from force constants and discussed by Moseley [13].

Heat Resistance—The temperature of a fibrous material is raised considerably under high-speed impact. This is shown by the fused fibers characteristic of nylon fabric impacted by a high-speed missile (Fig. 9). The properties of such textile materials as nylon and polypropylene deteriorate fairly rapidly with increasing temperature while the X-500 series of fibers are much more heat resistant, preventing premature fusion.

Plastic Flow—All three types of X-500 possess the first two characteristics of high modulus and high heat resistance. However, the Types I and II exhibit no potential for resistance to high-speed impact (ballistic). Their deficiency can be attributed to their brittle nature or lack of ability to yield plastically. This in turn is demonstrated by the SEM photographs of ballistically impacted fabrics prepared from Type I fibers. The fibers split and break in a brittle manner without any evidence of plastic flow and consequently with little energy absorption. The Type III fabric, on the other hand, shows considerable evidence of plastic deformation in the micrographs. This tendency for plastic deformation is also confirmed by the shape of the stress-strain curve for Type III and by preliminary data on tensile recovery. The major overall conclusion is that the use of a wholly aromatic structure yields fibers with a potential for higher moduli due to the extended chain configuration which the stiffness and planarity of the structure should favor. In addition, heat resistance is imparted by the aromaticity of the backbone chain. However, these two properties alone do not confer impact resistance. In fact, the inflexibility of the structure and the absence of folded chains may actually ensure brittleness and minimize any tendency for plastic flow. Only the Type III yarn with its lower crystallinity (30% vs 90% for Type I) and lower orientation (birefringence 0.30 vs 0.57 for Type I) possesses enough lack of register to allow the polymer molecules to slip by each other at high stress levels as a form of plastic deformation and energy absorption. The high stress needed to cause plastic deformation and the apparent speed of plastic flow are both important features in the impact resistance of the Type III material. This latter property is shown by the fact that the plastic portion of the stress-strain curve is still present although reduced at a strain rate of 200,000%/min.

None of the fibers investigated produced laminates with good ballistic resistance as compared to glass laminates. The success of glass in laminate form had been attributed to its high modulus; however, the failure of X-500 laminates indicates that high modulus is not the sole requirement for success in laminate form. In general it appears that the surface characteristics of the organic fibers combined with their anisotropic character as compared to glass may be responsible for the poor laminate performance.

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