How short aramid fiber improves wear resistance

By Y.T. Wu*

Super wear-resistant thermoplastic composites have been developed using short aramid fiber as reinforcement for nylon-66 and polyphenylene sulfide. The composites offer enhanced mechanical properties and higher use-temperatures, with significantly lower wear rate and essentially zero abrasive action

IMPROVED wear resistance in plastics components is an ongoing quest that cuts across market lines. The phenomenon of wear occurs when two solid surfaces in contact are sliding relative to each other. There is normal (pressure) force involved, which induces friction at the contact line. Friction leads to breakdown of the softer (or brittle) surface, which we call wear. Depending on our subjective view, we may elect to call erosion of the surface of interest “wear” and erosion of the counter surface “abrasion or “galling.” In addition to wear, friction generates heat because work is done at the contact surface. If the thermoplastic is sensitive to temperature change (typified by low heat-deflection temperature or low melting point), this frictional heating may cause the polymer to soften or even melt. This means the wear mode (thus the wear rate) and part shape are changed rapidly, and the wear part can no longer function adequately due to large dimensional deformation. High friction coefficient is usually indicative of such a softening of the thermoplastic part.

If the wear particles are hard and abrasive (e.g., glass fiber), they will roll between the surfaces and scratch the counter surface, causing severe abrasion. This roller-bearing type action also creates a cooling effect because there is now a small air gap between the surfaces. Whether cooling helps lower the wear rate depends largely on which factors will dominate in this complicated happening.

All the above mechanisms can occur at the same time. This makes interpretation of laboratory wear data and the prediction of actual wear difficult.

It has been established (1)’ that for thermoplastic materials, the wear rate is related to pressure and relative velocity as follows:

$$\frac{x}{t} = K*(PV) \qquad \text{Eq.1}$$

where x = thickness worn (in.), t = wear time (hr.), P = pressure (p.s.i.), V = velocity (ft./min.), and K = wear factor, (in.3-min./ft.-lb.f -hr.).

The wear factor K, although shown here as a proportional constant, in fact does vary with the PY multiplier. But at a given PV condition, a lower wear factor also indicates lower wear rate. The PV multiplier also represents the work done per unit area per unit time at the contact surface. A part of this work is then transformed into heat as follows:

$$\textit{Heat generation} = (PV)*f \qquad \text{Eq.2}$$

where f is the friction coefficient.

For a given wear system where heat-transfer rate is defined, heat generation can be measured through temperature rise as follows:

$$\Delta T \sim (PV)*f \qquad \text{Eq.3}$$

This equation indicates that in selecting a wear material, one should consider the temperature capability of the polymer.

A general rule is that a high heat-deflection temperature and high-melting-point polymer should be used at high PV. Measurement of the temperature rise in a friction test can reveal useful data about the polymer.

Friction coefficient varies with the polymer type, the mating surface material, and the PY multiplier. In addition, f is related to shear strength and apparent hardness of the thermoplastic:

$$f \approx \frac{Shear - strength}{Apparent - strength} \quad \text{Eq.4}$$

This equation shows that for a given thermoplastic, the friction coefficient may be lower as the molecular weight of the polymer increases. The addition of lubricants such as polytetrafluoroethylene (PTFE) to the thermoplastic lowers the friction coefficient, generally to the range of 0.1 to 0.2. This effectively reduces heat generation, and in most cases has positive effects on wear resistance of the plastic by allowing the part to be used at higher PV. As a result, PTFE is used widely in nylons, acetals, and other plastics to reduce the K factor and friction.

Molybdenum disulfide is another commonly used lubricant in nylons. The exact role of this compound is sometimes controversial, but its use is still generally regarded as an effective way to reduce wear at a lower cost than PTFE.

Among laboratory wear tests of plastics, the most common is the thrust washer test described in ASTM D3702. It generates wear information for a material based on area contact, not line or point contact as needed in some bearing applications. The thrust washer test

Fig. 1: Pellets, 1/2-in, long, are made from continuous aramid yarn meltcoated with nylon-66.

**The Du Pont Co., Textile Fibers Dept., Wilmington, DE*

1. *Numbers in parentheses designate references at end of article.*
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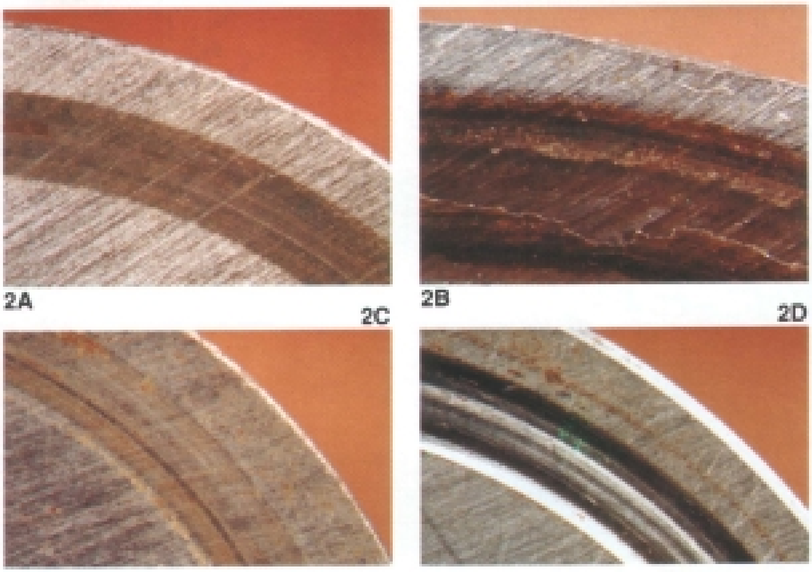

Fig. 2: Steel washer surfaces worn by composites (lOx magnification). 2A: Nylon-66/aramid fiber, 190 hr.; 2B: Nylon-66/glass fiber, 201 hr.; 2C: PPS/aramid fiber, 202 hr.; 2D: PPS/glass fiber, 42 hr.

is regarded as one of the most effective ways to define the true material characteristics in wear.

Thermoplastic wear parts are fabricated by injection molding or machining from rod or sheet stock. Shaped stocks are made by extrusion, followed by annealing to give low residual stresses; as a result, these stocks are typically used for high-performance, dimensionally critical, low-volume wear parts, and for prototype work.

In addition to the wear factor K, a second key parameter that is often ud to select a material for parts requiring excellent resistance to the effects of wear is the PV-limit (2). By definition, the PV-limit is simply a PV multiplier above which the material can no longer function as a wear part due to softening, melting, and deformation. But in reality, the PV-limit remains more a concept than a clear-cut number that one can determine experimentally.

A common technique used to determine the PV-limit is observation of critical changes of friction coefficient and temperature. In this paper, we shall present PV-limit data on nylon-66 using a wear index that is the ratio of wear factor based on volume loss to wear factor measured by weight loss. Kevlar®2 aramid fiber has been found to enhance the useful applications range of nylon by lowering its wear rate and increasing its PV-limit.

Du Pont introduced Kevlar® commercially in 1972 as a tough, high-strength, lightweight fiber for industrial use. In addition to its high strength, the aramid fiber also has excellent damage tolerance, high-temperature durability, impact resistance, tension-tension fatigue, dimensional stability, and vibration-damping characteristics. These properties make aramid fiber an important reinforcing material in advanced composites for aerospace applications. In the last few years, short forms of aramid fiber have found important applications in wear parts such as clutches, brakes, and thermosetting bulk molding compounds. Effective high-temperature reinforcement, superior wear resistance, and nonabrasiveness to mating surfaces are key contributions. Properties of aramid and E-glass fibers are shown in Table I.

One very important fiber characteristic that distinguishes aramid from glass and carbon fibers is its lack of notch sensitivity. Aramid fiber is inherently very tough and bends without breaking. This toughness is the source of wear resistance. In contrast, glass fiber is brittle and breaks easily into short, abrasive particles that are detrimental to mating surfaces and to the matrix itself. This causes severe galling of the metal counter surface and high wear rates for brittle polymers such as polyphenylene sulfide.

The method used to embed short aramid fibers in thermoplastics is different from that used for glass fibers. Conventional extruder compounding does not produce high-quality pellet products. In addition, feeding of short aramid fiber is difficult and prohibitive for large-scale commercial operations. In the last few years, a unique, long-fiber pellet (¼ to 1 in.) has been developed for extrusion and injection molding. This pellet is made by first melt-coating continuous aramid yarn into strands, followed by chopping so that specific pellet length is obtained. In this process, the fiber is wet out by the polymer melt in the coating die without damaging the fiber, and fiber length is the same as pellet length (Fig. 1). These fiber-containing pellets can be fed reliably either by themselves or by letdown through proprietary formulation. Injection molding and extrusion conditions are similar to those used for glass-fiber-reinforced polymers. One advantage of aramid fiber is that it is gentle on screws and barrels, whereas glass fiber is abrasive and damaging to the equipment.

All nylon-66 work presented in this paper is based on the use of these melt-coated fiber pellets. Pellets containing Kevlar® 49 in nylon-66, polycarbonate, Delrin2 acetal, polyphenylene sulfide, Hytrel2 polyester elastomer, and thermoplastic polyurethane are now available for development work.

Table II lists mechanical properties of nylon-66 and nylon-6 reinforced with ¼-in. Kevlar® 49 fiber. The neat resin properties are shown as controls because they are the base wear materials commonly used. As expected, nylon's strength and stiffness are increased by fiber reinforcement. Although tensile strength is lower than that of material reinforced with glass fiber, it is much more isotropic than the glass-fiber-reinforced specimen. This is due to the fact that aramid fibers do not break down during molding, and they tend to entangle as a network that experiences less fiber orientation during polymer melt flow. On the other hand, glass fibers break down easily into needle-like fibers that are aligned effectively by the melt flow, thus making molded-part properties more directionally dependent.

Also significant in Table II is the increase of heat-deflection temperature (HDT) in the presence of aramid fiber. HDT at 264 psi. is elevated from 190° to 490°F. for nylon-66, and from 135° to 424°F. for nylon-6. This means a higher service temperature capability in general. Fiber reinforcement also increases hardness, which leads to lower friction. We now have a nylon-66 composite with a significantly higher PVlimit. This is supported by wear and friction data.

Super wear-resistant nylon-66

The test equipment used to study wear and friction characteristics (ASTM D3702) measures the wear of a thermoplastic disc (with wear ridge) against a steel washer. The applied pressure (P)

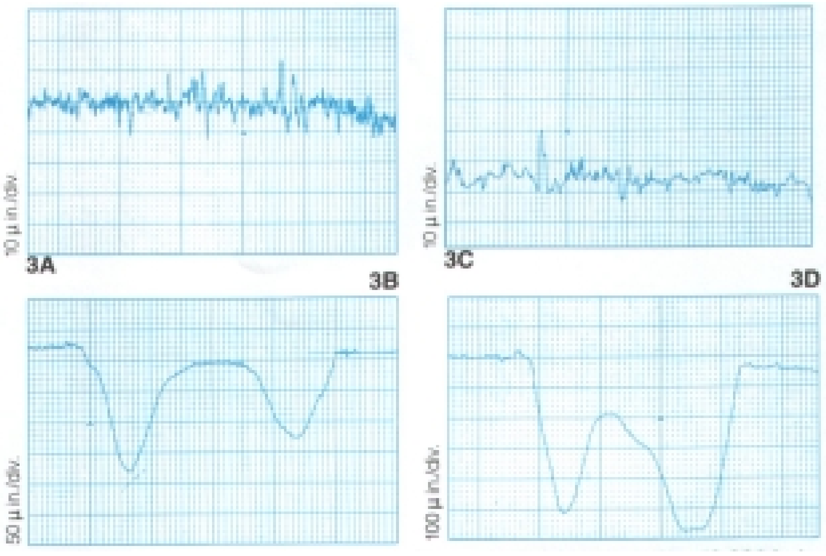

Fig. 3: Surface profiles of steel washers after wear against composites (0.002 in./ div. on horizontal scale). 3A: 190 hr. against nylon-66/aramid fiber: 3B: 201 hr. against nylon-66/glass fiber: 3C:

and the rotating speed (V) are controlled to give the desired PV condition.

The nylon-66 test disc is dried at 79°C. and 28-in, of Hg vacuum for 24 hr. before and after the test for accurate weighing. The test starts with a wear interval of about 20 to 24 hr.; this serves as a first break-in period that is intended to even out any surface geometric imperfection. The second break-in interval is again a period of 20 to 24 hr., designed to ensure good contact. It should be noted that wear data taken in these two intervals are used only for the purpose of reference.

The third wear interval, lasting from 160 to 180 hr., is the main period used to record wear and friction data. Wear rate is determined by weighing the disc specimen for weight loss and by measuring the thickness change for volume loss. We designate the K factor calculated from the weight loss as K~ and that calculated from the thickness loss as K0. The ratio of K0 over K~ is a useful indicator of material deformation that can be caused by softening, melting or chipping. We call this ratio Φ, the wear index:

$$\Phi = K\frac{K_X}{K_W} \qquad \text{Eq.5}$$

When no melting or softening occurs at the wear surface, 4 remains near unity. But when melting or softening occurs, 4 can increase rapidly to above 30. This means the wear part is losing its shape and is no longer useful at this specific PV. If 4 drops below *0.95,* it usually indicates loss of plastic in chunks due to fatigue or cracks. At this point, also, the wear part is no longer useful. We find that 4 (wear index) is the most powerful tool to clearly define the PV-limit.

At PV= 2500 psi.-ft./min. (P= 250 psi., V = 10 ft./min.), aramid fiber lowers the nylon-66 wear rate by a factor of 4 and also lowers the friction coefficient (Table III). These are very important changes because nylon-66 is generally considered to be self-lubricating. The very low weight loss of the steel washer indicates the nonabrasive nature of the aramid fiber (Fig. 2A). In contrast, glass fiber has adverse effects; it scratches the steel and causes severe abrasion (Fig. 2B). Surface profiles of these two washers, measured by a moving diamond stylus in order to show the surface valleys and hills, are shown in Fig. 3. Note that the vertical scale in Fig. 3B is five times that in Fig. 3A. The erosion of the steel washer surface by glass fiber (Fig. 3B) is clearly shown.

In addition to the property of nonabrasiveness, aramid fiber also brings a 70% lower wear rate than glass fiber. Nylon-6 has an unstable friction coefficient, indicating softening and possible melting at the surface. It is questionable whether nylon-6 can be used at this PV condition.

The K factor reported in Table III for dry nylon-66 is based on thickness loss and is higher than that commonly recognized for the material. This K factor of 917 is an average of seven test runs involving three nylon-66 samples. Coefficient of variation of these seven data points is only 6.8%, which is unusually low for a wear test. It indicates the care that has been put into the test work and the reliability of the results.

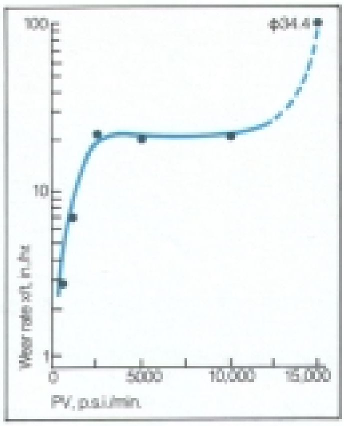

Fig. 4: Effect of pressure on nylon-66 wear rate (V = 10 *ft.Imin.).*

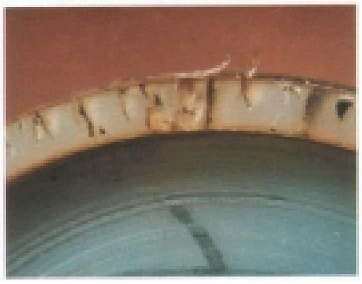

Fig. 5: Nylon-66 disc tested at PV = 5000 and V = 100 *ft.Imin.,* showing cracks (16x magnification).

But we still must address why there is a difference. To answer the question, we conducted the wear test again at PV = 2000 psi.-ft./min. (P = 40 p.s.1., V = 50 ft./min.). The neat nylon-66 K factor is now 727, or 21% lower, whereas the fiber containing nylon-66 is lowered by more than 65% (Table III). This means at PV = 2000, aramid fiber reduces the wear rate of nylon-66 by a factor of eight. The wear factor for glass fiber containing nylon-66 is now 137, and is consistent with the number reported in the literature. This confirms the validity of our test, but also reveals the dependence of K on PV. What K value should one use in designing a wear part?

To understand the effect of pressure (P) and velocity (V) on wear rate, we conducted tests on neat nylon-66 at two velocities (10 ft./min. and 100 ft.! mm.) and P ranges from 50 psi. to 1500 psi. This gives PV values of 500 to 15,000 (Table IV and Fig. 4). At V

Table I: Properties of aramid and glass fibers

Property[a]	Kevlar® 29	Kevlar® 49	Kevlar® 149	E-Glass
Tensile strength, 10~ psi.	525	525	500	350
Tensile modulus, 106 psi.	12	18	26	10
Elongation to break, %	4.4	2.9	1.9	3.5
Density, *g.lcm.3*	1.44	1.44	1.47	2.54
Notch sensitivity	Tough	Tough	Tough	Brittle
Abrasive	No	No	No	Yes

a: Resin-impregnated strand tor composite properties.

Table II: Mechanical properties of nylon-66 and –6 reinforced with short aramid fiber

Property	Nylon-66[a] Unreinf.	20. wt.-% Kevlar® 49 ¼-in, pellet	Nylon-68 Unreinf.	20 wt.-% Kevlar® 49 ¼-in, pellet
Fibervolume,%	0	16.2	0	16.2
Tensile strength, 10~ psi.	11.9	18.2	11.2	19.1
Tensilemodulus,103p.s.i.	610	1630	450	1070
Elongation, %	4.0	2.3	—	2.3
Flexural strength, 10~ psi.	18.0	27.3	14.3	23.5
Flexural modulus, 10~ psi.	480	880	360	800
Izod,notched,ft.-Ib./in.	1.15	3.13	0.8	3.8
Izod unnotched, ft-Ib/in.	No break	9.0	6.2	11.5
Heat-deflection temp.°F.				
66p.s.i. load	428	505	352	433
264p.s.i. load	190	490	135	424

a: Dry as-molded.

Table III: Wear dataa on nylon-66 (dry) and PPS compositesb

Material	Wear factor K, coefficient	Friction wt. loss, mg.	Steel washer 10-5 in./hr.	Wear rate K*PV,
Nylon at PV = **2500 (P = 250 p.s.i., V =10 *ft.Imin.)***				
Nylon-66	917	0.435	0.2	22.93
Nylon-66 containing 33 wt.-% of glass fiber	424	0.420	0.4	10.60
Nylon-66 containing 20 wt.-% of ¼-in. Kevlar® 49	239	0.390	<0.01	5.98
Nylon-6		0.744/1.13c	—	
Nylon at PV = 2000 (P = 40 p.s.i., V = 50 *ft.Imin.)*				
Nylon-66	727	0.574	—	14.54
Nylon-66 containing 33% glass fiber	137	0.476	—	2.74
Nylon-66 containing 2Owt.-%¼-in. Kevlar® 49	88	—	—	1.76
Polyphenylene sulfide at PV = 2500 (P = 250 p.s.i., V =10 *ft.Imin.)*				
PPS containing 40 wt.-% glass fiber	4867	0.425	500.8	121.68
PPS containing 20 wt.-% ¼-in. Kevlar® 49	270	0.349	1.8	6.75

a: Thrust washer test (ASTM 03702).
b: All test disks were machined from injection-molded plaques.
c: Surface melting occurs.

Wear factor K = $10^{-10} \frac{in^3 \min}{ft.-lb.hr.}$

= 10 ft./min. and PV is less than 2500, the wear rate is linearly dependent on PV. When PV is greater than 2500, the wear rate plateaus until it suddenly jumps up at high PV (15,000). This sudden increase in wear factor (K0) indicates that there has been a change in wear mode caused by surface softening or melting. For nylon-66 at V = 10 ft./min., this surface softening occurs somewhere near PV = 10,000. Examination of the nylon-66 discs tested at PV = 10,000 using a microscope shows strings of material hanging from the outer edges and some scattered radial cracking near the edges. This indicates moderate softening of the material and possibly a mild thermal fatigue. Material loss due to cracking leads to a higher K~ (weight loss) and relatively low K0 (thickness loss). This is reflected in the lower than 0.95 value of the wear index (Table IV). We have exceeded the PV-limit of nylon-66 at 10,000.

A similar examination was made on the disc tested at PV = 5000 and V = 10 ft./min. The surface was smooth and no cracking was observed. We conclude the PV-limit for nylon-66 at V = 10 ft./min. is slightly lower than 10,000. WhenPV= 15,00O andV= 10 ft./min., frictional heating was so excessive that the test disc was melted and squeezed back to a mushroom shape. Thickness change was high (K0), but the weight loss was small (low K~). This led to an unusually high 4 value of 34. Neat nylon-66 should not be used at this PV condition.

Also shown in Table IV are the wear test results for nylon-66 at V= 100 ft.! mm. The increase in velocity has dramatic effects on the PV-limit and washer surface temperature. At PV = 2500, the same mild stringing and edge-cracking phenomena were observed, indicating the PV-limit was reached. At PV = 5000, edge cracking due to thermal fatigue was very severe (Fig. 5). As a result, the wear data at PV >2500 can only be used as references, not in design. We conclude that the PV-limit for nylon-66 at V= 100 ft./min. is 2500 p.s.i.-ft./min. Preliminary study showed that aramid fiber increased the PV-limit of nylon-66 from 9000 to 15,000 at V= 10 ft./min., and from 2500 to about 10,000 at V= 100 ft.! mm. We are continuing research work in this area.

Super-wear-resistant PPS

Polyphenylene sulfide (PPs) has excellent temperature capability and chemical resistance. When properly formulated (e.g., with PTFE) it has the potential to be a high-performance wear material replacing bronze. PPS is also brittle. It is mostly used with glass fiber reinforcement, even in wear applications. Glass fiber has a detrimental abrasion effect on the counter surface and on the **PPS** matrix itself.

Wear data show that aramid fiber can upgrade **PPS** to a super-

Table IV: Effects of pressure and velocity on wear rate of nylon-66 (dry)

Velocity, *ft.Imin.*	Pressure, p.s.i.	PV, p.s.i. ft./min.	Washer temp., °F.	K_x factor, ft.-lb..hr.	Wear rate x/t, $1O^{-5}$ in./hr.	Wear index, Φ
10	50	500	90	566	2.83	0.96
	100	1,000	94	695	6.95	0.98
	250	2,500	104	911	22.78	0.99
	500	5,000	142	419	20.95	1.03
	1,000	10,000	210	211	21.10	0.928
	1,500	15,000	238	637	95.55	34.4
100	25	2,500	140	424	10.7	0.90
	50	5,000	244	574	28.7	0.968
	100	10,000	295	550	55.0	0.82a
	150	15,000	308	21	31.5	0.75k

Wear factor K = $10^{-10} \frac{in^3 \text{ min}}{ft. - lb.hr.}$

wear-resistant material (Table III). The wear rate (K factor) for PPs/aramid is in the same range as that of nylon-66/aramid and is only 1/18 of that for **PPS**/glass. The abrasion on steel washer for **PPS**/aramid is a more dramatic 1/278 of the PPS/glass material. The washer surface is only slightly marked by the PPs/aramid material after 202 hr. (Fig. 2C), whereas it is severely grooved by the PPS/glass into a 2800 micro-inch channel after only 42 hr. wear (Fig. 2D). This is supported by the 500-mg. weight loss of the steel washer reported in Table III and by the surface profiles shown in Figs. 3C and 3D.

The friction coefficient between **PPS**/aramid and the steel washer is 0.349, lower than that for PPS/glass. This implies some lubricity effect by the aramid fiber. With the addition of lubricating material such as **PTFE,** the **PPS**/ aramid/PTFE may be the material of choice for such high-temperature wear parts as bearings, piston rings, and compressor vanes.

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References

1. J.F. Archard and W. Hirst, *Proc. Royal Soc.* (London), Ser. A, 236 (Apr. 1956).
2. R.B. Lewis, “Rubbing-Contact Evaluation of Polymers,” p. 203 in *Testing of Polymers*, edited by J.V. Schmidt and WE. Brown, Vol. 3, John Wiley and Sons, 1967.

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DuPont Company
Advanced Fibers Systems
Market Development Group Kevlar®
Richmond, VA
USA