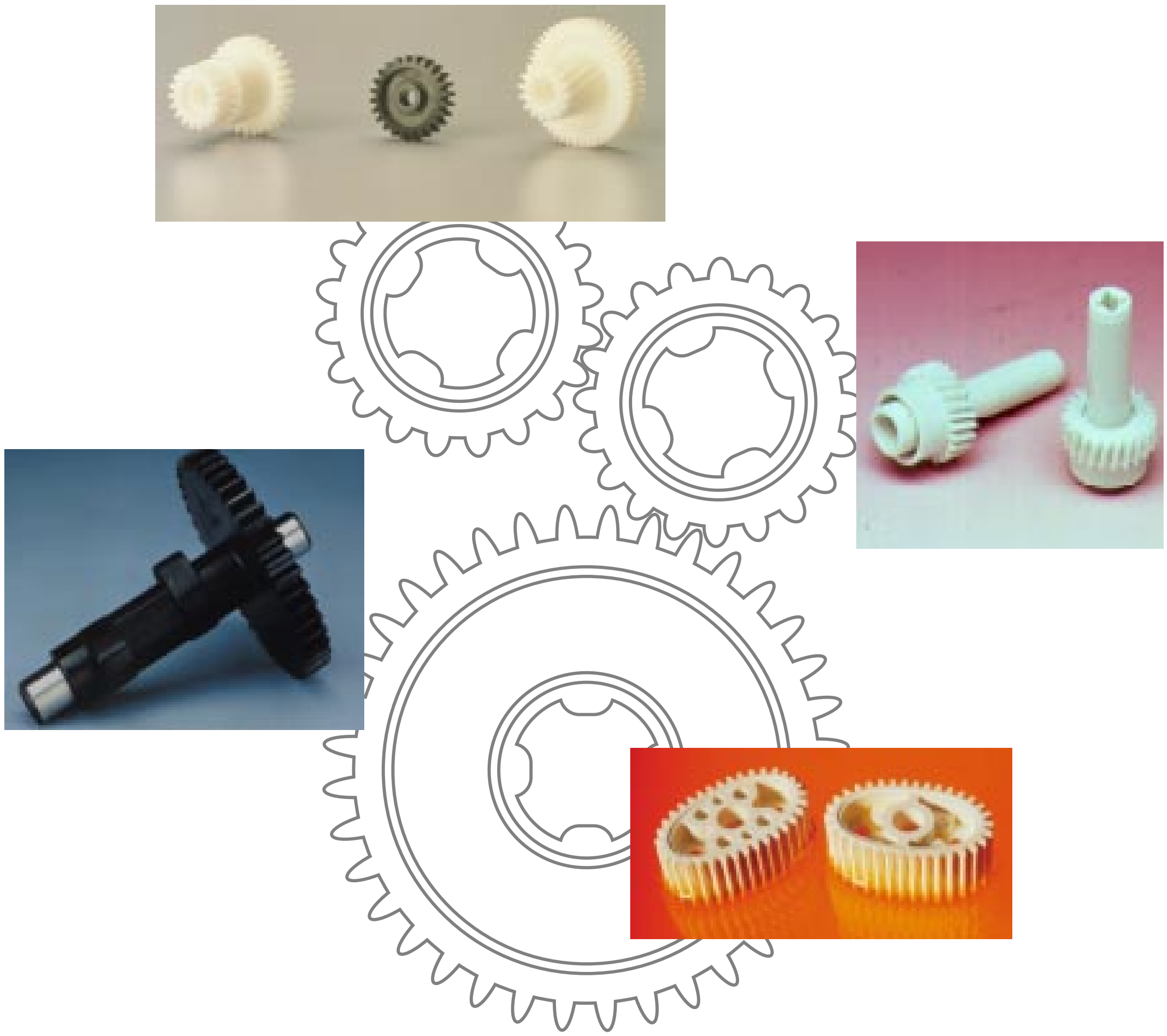
DuPont Engineering Polymers



Engineering polymers for gears from DuPont.

More high-performance materials.

More skillful solutions.

Pinpoint the performance you need with DuPont polymers.

To satisfy the demand for lighter, faster, quieter, more durable, cost-effective products, innovative designs increasingly include the use of high-performance plastics. In applications ranging from automotive components to office automation equipment, engineering polymers successfully replace metals—even in fine critical gears—and contribute superior performance. As design engineers worldwide discover the remarkable benefits of polymers for gears, they also discover that identifying the right product for the job can sometimes be a difficult proposition.

DuPont can help you hit the mark.

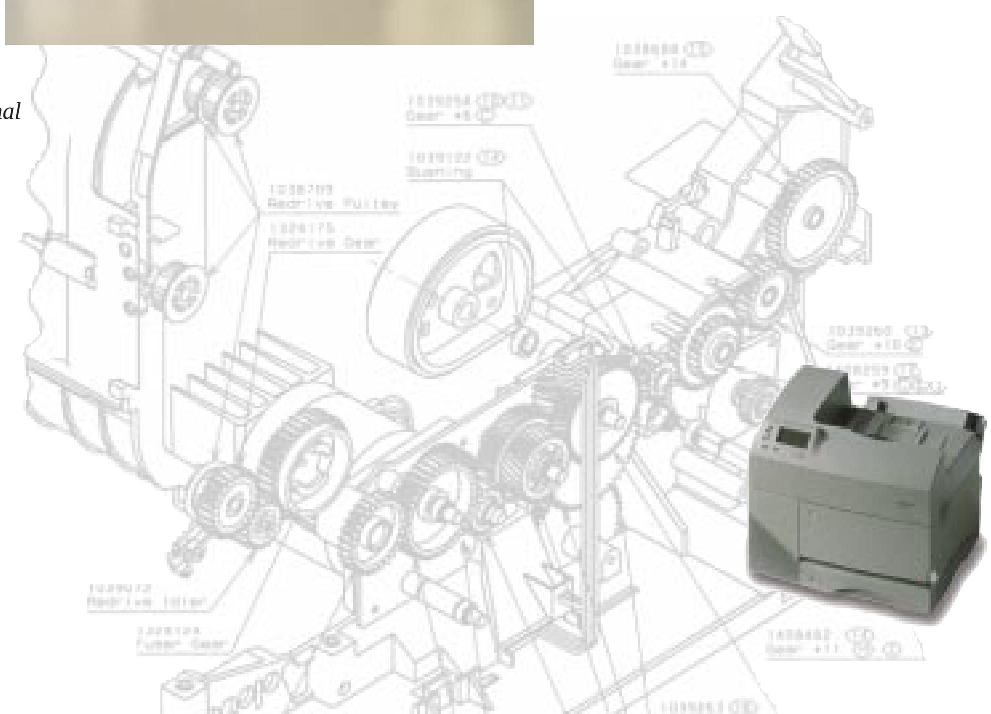
DuPont has been helping to solve tough gear design problems almost as long as we've been making polymers. In fact, the earliest plastic gears were made with the industry's first engineering polymer, DuPont Zytel® nylon resin.

DuPont Delrin® acetal resins and Zytel® nylon resins have been used in gears for more than 35 years in hundreds of diverse products, including windshield wipers, windowlifts, speedometers, rotary pumps, appliances, power tools, clocks, and copy machines.

No other supplier today offers more high-performance polymers for gears and more expertise—from design consultation to molding assistance—to streamline material selection. With the recent introduction of additional grades to many product families, DuPont offers a wider range of solutions than ever before.

Delrin® acetal resin

Gear trains used in Lexmark's Optra laser printers have 11 gears molded from Delrin®. The gears drive the printer's toner drum, fuser rollers, and other media transport rollers or in ink transfer and fusion operations to an output tray. In the spur gears, Delrin® 500P offers dimensional stability, high strength, low friction and wear, and high molding productivity. In the helical gears, Delrin® 500CL satisfies additional requirements for low wear and friction at high PV conditions.



DuPont polymers: The right choice, right from the start.

By involving DuPont early in the development process, along with an experienced team of gear molders and designers, DuPont can help you select the ideal product to meet your exact needs and help you enjoy the following benefits of plastics:

Lubricity. A low coefficient of friction provides gears of Delrin®, Zytel®, and other DuPont engineering polymers with a distinct performance advantage over metals in applications that do not permit external lubrication or where lubrication is limited to initial installation. DuPont offers a variety of internally lubricated polymer compositions to further improve wear resistance and reduce friction without the expense or assembly complication and inconvenience of external lubricants.

Shock Resistance. The intrinsic resilience of plastic gears provides superior damping of moderate shock or impact loads. Toughened grades of Delrin® and Zytel® are available for high-shock applications.

Noise Reduction. Pliable plastic gears offer smoother, quieter operation than metal gears. When designed with adequate clearance, plastic gear teeth will deflect slightly under loading. This deflection makes small differences in pitch and profile less critical, thus helping to reduce noise from meshing teeth. DuPont's toughened resins are more flexible and help to enhance this effect. For highly sliding meshes, like those found in worm or helical gear arrangements, potential plastic squeak can be prevented by selecting one of DuPont's many internally lubricated polymers.

DuPont polymers at a glance.

Delrin® acetal resin. The most widely used DuPont resin for gears, Delrin® is a homopolymer that provides a superior combination of performance benefits: excellent mechanical properties—strength, toughness, fatigue endurance, and surface hardness—good lubricity, and resistance to wear, moisture, and chemicals. Many grades of Delrin® are designed specifically for demanding applications.

Zytel® nylon resin. The first engineering polymer for gears, Zytel® offers exceptional strength, toughness, temperature resistance, and excellent moldability. It can be modified in a number of ways to optimize performance, and is frequently used in conjunction with Delrin® to reduce gear noise and wear.

Zytel® HTN high-temperature nylon resin. Compared with other Zytel® nylons, Zytel® HTN exhibits enhanced moisture stability, increased chemical resistance, and better mechanical properties at elevated temperatures.

Zytel® DMX nylon resin. Zytel® DMX provides significantly improved dimensional stability and more consistent mechanical properties across varying humidity levels, as compared with traditional Zytel® nylons.

Minlon® mineral-reinforced nylon resin. Minlon® offers better strength and stiffness than unreinforced nylon. Compared with glass reinforced nylon, Minlon exhibits less potential for part warpage and is less costly.

Hytrel® thermoplastic polyester elastomer. Hytrel® provides extra tough teeth for gears subject to extreme shock or when mesh noise reduction is required. Often, just one gear made of Hytrel is enough to reduce noise in an entire gear train.

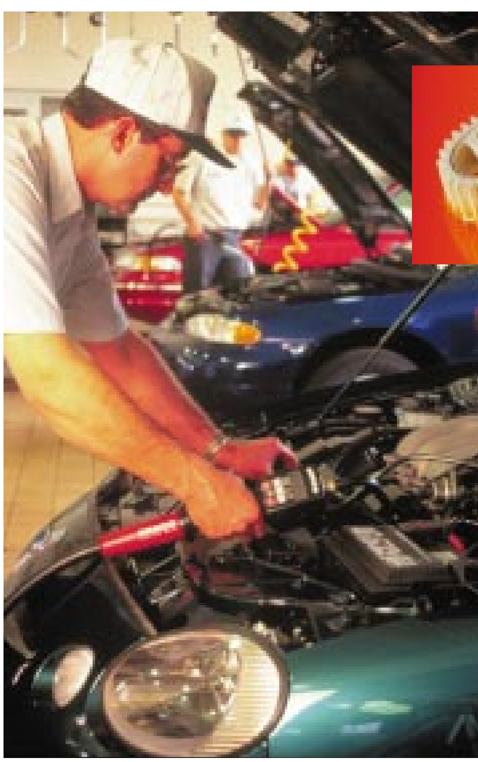
Crastin® PBT thermoplastic polyester resin and Rynite® PET thermoplastic polyester resin. Crastin® PBT and Rynite® PET are selected for strong, stiff gears in environments where a high degree of dimensional stability is required at high service temperatures.

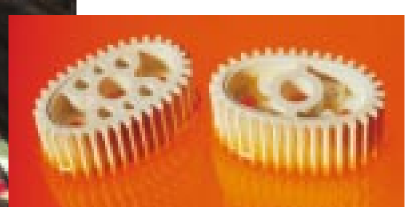
Zenite™ LCP liquid crystal polymer resin. Zenite™ LCP may be the best solution in applications requiring any or all of the following: extremely thin or small gears, exact tool replications, ultra-high temperature resistance, superior chemical resistance, exceptional dimensional stability.

Vespel® polyimide parts and shapes. Vespel® tackles high-performance gear applications. DuPont offers finished gears of Vespel® manufactured to your specific requirements.

Zenite™ LCP liquid crystal polymer resin

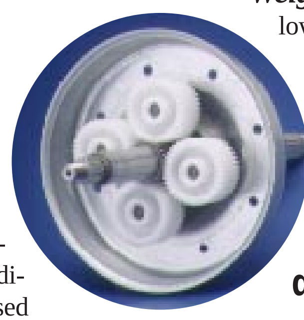
Two mating oval gears molded from Zenite™ LCP precisely meter motor oil or other automotive fluids flowing through the hand-held EM5™ electronic meter made by Graco, Inc. Zenite™ 6330, a 30% mineral reinforced formulation, fulfills Graco's demanding requirements for molding accuracy, exceptional dimensional stability, and resistance to attack by automotive lubricants, brake fluid, and antifreeze. The gears are installed with minimal clearance in the meter body. They are molded to high precision with zero draft.





Cost Efficiency. Gears made with DuPont polymers can be a cost-effective alternative to metal. The nature of molded plastic permits parts consolidation and therefore reduces costly manufacturing and assembly operations. Cams, bearings, ratchets, and gear shafts can be designed as an integral part of an injection molded plastic gear. Multiple gear clusters also may be molded as a unit, decreasing part count and significantly increasing costs savings.

Durability. In low-stress environments, plastic gears typically offer longer lasting performance than their metal counterparts. Unmodified Delrin® and Zytel® both exhibit excellent friction, wear, and mechanical properties which can be enhanced by modifications. Selection of modifications should be based on the expected failure mode, such as wear, fatigue, tooth shear, or bending. Unlike metal gears, plastic gears should be designed to allow for tooth deflection, which is a result of the flexural modulus of the polymer. Gear life can be maximized by selecting a polymer, family and modification that balances friction and wear properties, strength, and fatigue resistance all at operating temperature.



Chemical Resistance. Compared with most metals, plastics offer superior resistance to the corrosive effects of a wide range of chemicals. Gears made of Delrin®, Zytel®, and other semi-crystalline DuPont polymers resist most oils and lubricants, solvents, and more.

Weight Reduction. Plastics have lower density than metals even when reinforced with glass and other materials. Gears made with DuPont polymers can significantly reduce inertia and total assembly weight.

What a few pages can do for you.

This brochure is designed to introduce you to DuPont's wide selection of polymers for gears and to offer some general material selection guidelines. We hope you'll use this information as just one part of a material selection process that includes technical support from DuPont.

More products, more solutions.

In addition to our widely specified resins for gears—Delrin® and Zytel®—DuPont offers the broadest assortment of engineering polymers in the business. With so many high-performance products to choose from, it would be difficult to list every available resin grade. Table I presents the DuPont polymer families for gears along with applicable modifications, reinforcements, and lubricants. Recently introduced compositions are highlighted.

Table I
DuPont Engineering Polymers for Gears

Product Composition	Unmodified, General Purpose	Multiple Flow Grades	Enhanced Crystallinity/ Nucleated	Toughened	Reinforced/Modified			Lubricated			Finished Gears
					Glass	Mineral	Kevlar™ Aramid	Teflon® Fluoro-carbon Resin	Internal Chemical	Silicone	
Product Family											
Delrin® acetal resin	■	■	▲	▲	▲		▲	▲	▲	▲	
Zytel® nylon resin	■	■	■	■	■		▲				
Zytel® HTN high-temperature nylon resin				▲	▲	▲					
Zytel® DMX nylon resin				▲	▲						
Minlon® mineral reinforced nylon resin				■	■	■					
Hytrel® thermoplastic polyester elastomer	■	■									
Crastin® PBT thermoplastic polyester resin	■	■		■	■	▲					
Rynite® PET thermoplastic polyester resin				■	■	■					
Zenite™ LCP liquid crystal polymer resin					■	■					
Vespel® polyimide parts and shapes[1]											▲

Key: ■—available grades
▲—new compositions since 1995.

[1]Vespel® is the only polymer made into finished gears by DuPont. Vespel® is not available for purchase as molding resin.

Delrin® acetal resin

Cagiva of Italy uses Delrin® 500 for the gears in its motorcycle oil pumps. Delrin® was selected for its excellent fatigue endurance, chemical resistance, and dimensional stability. The gears made of Delrin® provide smooth operation, less noise, and reduced assembly costs.

Fine tuning the selection.

Once an appropriate resin family is selected for a particular application, resin properties can be enhanced through compositional modifications. Unmodified resin is the most economical, widely available choice. It is usually recommended for general gearing; press-fit applications; and lubricated self-mating gears under low load conditions. Modifications are suggested only when necessary, as they will almost always increase cost.

Table II provides some of the principal benefits and limitations of common modifications compared with the unmodified resin.

Table II
Principal Effects of Resin Modifications on Gear Properties

KEY: Performance of modified composition compared with unmodified general-purpose resin.
Limitation – Performance Declines: ■ ◩ □ … ○ ◐ ● – **Benefit** – Performance Improves

Product Grade		Strength and Modulus	Impact Strength	Friction against Steel	Wear against Steel	Friction against Itself	Wear against Itself	Abrasive Wear	Slow-Speed Squeak	Impact Noise	Resin Cost	Typical Applications
Multiple Flow Grades	High Viscosity		◐									High-shock gears; auto windowlift gears
	High Flow		□									Extremely fine gears; sprinkler gears
Enhanced Crystallinity/ Nucleated		○										High-volume production; printer gears
Toughened		◩	●							●	□	High-shock gears; washer spin gears; applications requiring noise reduction
Reinforced	Glass	●	◐					◩		□	□	Lubricated power gears; garage door opener gears; door lock actuator gears
	Mineral	◐	□					■		□	○	Low-cost, lubricated gears
	Kevlar™	○			◐			●			■	Gears requiring modest increase in tooth strength without the abrasiveness of glass reinforcement
Lubricated	Teflon®	□	◩	◐	●		●	○			■	Unlubricated, high-load, high-speed helical gears mated with steel worm; high-performance, multifunctional gears and cams, first stage motor reduction gears
	Internal Chemical	□	□	◐	◐	◐	◐		○		◩	Unlubricated gears requiring low wear; gears mated with soft metals (e.g., brass, aluminum)
	Silicone	□	□			◐	◐		○		□	Unlubricated plastic gear meshes requiring low wear and low friction, printer gears

Delrin® and Zytel®: Your first choice for gears.

Acetal and nylon resins account for the vast majority of plastic gears in use today. Most designers will want to begin materials evaluation by investigating DuPont Delrin® and Zytel® first.

Delrin® homopolymer acetal resins and the polyamide (PA) 66 grades of Zytel® nylon resins offer greater strength and modulus than competitive copolymer acetals and PA 6 nylons, respectively, especially at elevated temperatures. Compared with other polymers, both Delrin® and Zytel® offer multiple performance benefits that make them ideally suited to a wide range of gears. When comparing the two, you'll need to consider the following:

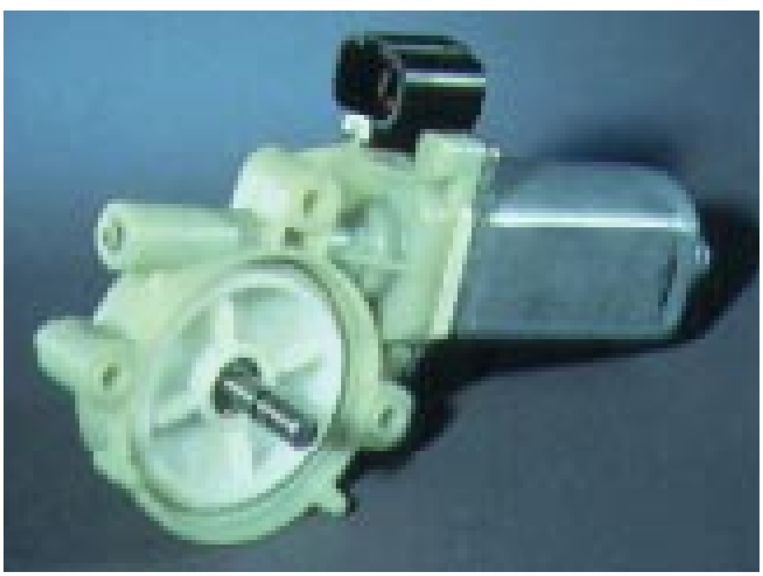
The advantages of Delrin®.

- Most frequently used polymer for gears
- Superior dimensional stability and low water absorption
- Superior strength, modulus, flexural fatigue endurance, and high surface hardness
- Lower coefficient of friction against steel
- Available in a variety of lubricated compositions for improved friction and wear performance

The advantages of Zytel®.

- Performs at higher service temperatures
- Resin of choice for worm gears
- Used as a dissimilar material against Delrin® to reduce gear wear and noise
- Lower surface hardness and modulus which reduces mesh noise against steel
- Better resistance to mild acids and bases
- Provides more forgiving, tougher gear teeth

The most commonly used compositions of Delrin® and Zytel® for gears are provided in Tables III and IV.



Delrin® acetal resin and Zytel® HTN high-temperature nylon resin

UTA Motor Systems' windowlift motors, installed in Ford Taurus and Mercury Sable automobiles, use gears made of Delrin® 100. Delrin® provides a combination of impact and moisture resistance, stiffness, and low coefficient of friction. The motor gear housing, injection molded from Zytel® HTN, marks a major shift away from traditional die-cast aluminum.

Table III
Delrin® Acetal Resins—Common Compositions for Gears

Product Composition		Product Grade	Description
Unmodified, General Purpose		Delrin® 100	High viscosity, maximum toughness
		Delrin® 100P	High viscosity, tough, improved mold release and thermal stabilizing system
		Delrin® 500	Medium viscosity
		Delrin® 500P	Medium viscosity, improved mold release and thermal stabilizing system
		Delrin® 900	Low viscosity, high flow
		Delrin® 900P	Low viscosity, high flow, improved mold release and thermal stabilizing system
		Delrin® 1700P	Ultra-low viscosity, maximum flow, improved mold release and thermal stabilizing system
Enhanced Crystallinity		Delrin® 111P	High viscosity, enhanced crystallinity, improved thermal stabilizing system
		Delrin® 511P	Medium viscosity, enhanced crystallinity, improved thermal stabilizing system
		Delrin® 911P	Low viscosity, enhanced crystallinity, improved thermal stabilizing system
Toughened		Delrin® 100ST	High viscosity, super tough
		Delrin® 500MT	Medium viscosity, medium toughened, improved thermal stabilizing system
		Delrin® 500T	Medium viscosity, toughened
Reinforced/ Modified	**Glass**	Delrin® 525GR	Medium viscosity, 25% glass reinforced, improved thermal stabilizing system
		Delrin® 510GR	Medium viscosity, 10% glass reinforced, improved thermal stabilizing system
	Kevlar™	Delrin® 100KM	High viscosity, modified with Kevlar™ aramid resin, improved thermal stabilizing system
Lubricated	**Teflon®**	Delrin® 100AF	High viscosity, tough, 20% Teflon® PTFE fibers, improved thermal stabilizing system
		Delrin® 500AF	Medium viscosity, 20% Teflon® PTFE fibers, improved thermal stabilizing system
		Delrin® 520MP	Medium viscosity, 20% Teflon® PTFE micropowder, improved thermal stabilizing system
		Delrin® 510MP	Medium viscosity, 10% Teflon® PTFE micropowder, improved thermal stabilizing system
		Delrin® 500TL	Medium viscosity, 1.5% Teflon® PTFE micropowder
	Internal Chemical	Delrin® 500AL	Medium viscosity, advanced lubricant system, improved thermal stabilizing system
		Delrin® 500CL	Medium viscosity, chemical lubricant
		Delrin® 900SP	Low viscosity, proprietary lubricant, improved thermal stabilizing system
	Silicone	Delrin® 500SC	20% Silicone concentrate, typically let down to 1% or 2%

Table IV
Zytel® Nylon Resins—Common Compositions for Gears

Product Composition		Product Grade	Description
Unmodified, General Purpose		Zytel® 101L	General purpose, lubricated[1] PA 66
		Zytel® 103HSL	General purpose, heat stabilized, lubricated[1] PA 66
		Zytel® 101F	General purpose, internally lubricated[1] PA 66
		Zytel® 42A	High viscosity PA 66
		Zytel®151L	General purpose, lubricated[1] PA 612
		Zytel® 153HSL	General purpose, heat stabilized, lubricated[1] PA 612
Nucleated		Zytel® 132F	Nucleated, internally lubricated[1] PA 66
Toughened		Zytel® ST801	Super tough PA 66
		Zytel® 408L	Toughened, lubricated[1] PA 66
Reinforced	**Glass**	Zytel® 70G33L	33% Glass reinforced PA 66
		Zytel® 77G33L	33% Glass reinforced PA 612
	Kevlar™	Zytel® 70K20HSL	PA 66 Reinforced with 20% Kevlar™ aramid resin

[1] Lubrication in these grades is used as a processing aid only. It is not intended to improve friction and wear properties.

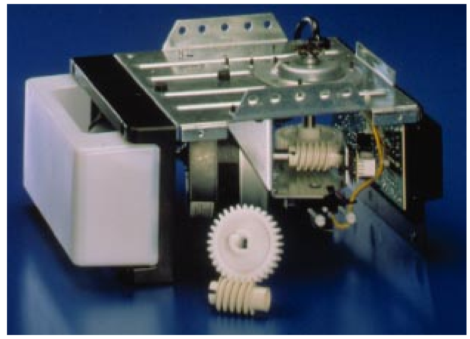
The impressive performance of Delrin® and Zytel®.

To give you a sense of the performance characteristics of these highly functional polymers for gears, important mechanical properties and durability test results are provided. Of course, this information offers a selection guideline only. More property data is provided in the DuPont Design Guides for Delrin® and Zytel®.

Mechanical Properties.

A selection of mechanical properties is presented for some of the most commonly used Delrin® resins in Table V.

Delrin® acetal resin and Minlon® mineral-reinforced nylon resin



The Chamberlain Group's ceiling-mounted garage door openers use an injection molded worm made of Minlon® 10B40 and a worm gear molded from Delrin® 100. Delrin® and Minlon® provide the requisite mechanical strength and excellent compatibility for low friction and wear. The lubricated gears run quietly and perform flawlessly in tests involving 25,000 open/close cycles (the equivalent of 15 years of service). They also cost less than the glass-reinforced nylon and steel gears they replaced.

Table V
Mechanical Properties of Various Delrin® Acetal Resins

Product Description / Properties	Unmodified, General Purpose			Enhanced Crystallinity	Toughened		Glass Reinforced	Lubricated		
								Teflon®		Internal Chemical
	100P	500P	900P	511P	100ST	500T	525GR	520MP	510MP	500AL
Tensile Strength at Yield MPa (kpsi) ASTM D638	67 (9.7)	68 (9.9)	69 (10.0)	72 (10.4)	45 (6.5)	53 (7.7)	151[1] (21.9)[1]	54 (7.8)	61 (8.9)	66 (9.6)
Elongation at Yield, % ASTM D638	23	15	11	11	35	15	NA[2]	12	10	10
Elongation at Break, % ASTM D638	80	40	25	33	>150	75	3	14	13	30
Flexural Modulus MPa (kpsi) ASTM D790	2,790 (410)	3,100 (450)	3,240 (470)	3,300 (480)	1,130 (160)	2,250 (330)	8,000 (1,160)	3,100 (450)	3,160 (460)	2,970 (430)
Izod Impact, notched J/m (ft-lb/in) ASTM D256	120 (2.3)	75 (1.4)	69 (1.3)	73 (1.4)	NB	128 (2.4)	96 (1.8)	32 (0.6)	27 (0.5)	58 (1.1)
Izod Impact, unnotched J/m (ft-lb/in) ASTM D256	NB[3]	NB[3]	1,630 (30.6)	NB[3]	NB[3]	NB[3]	1,100 (20.6)	720 (13.5)	950 (17.8)	2,350 (44)

[1]Values are tensile strength at break, since these materials do not yield.
[2]NA means not applicable.
[3]NB means no break occurs.

Compared with lower viscosity grades (the 500 and 900 series), the high-viscosity 100 series resins, such as Delrin® 100P, offer significantly greater elongation and impact strength with little change in flexural modulus or tensile strength. The toughened resins exhibit greater impact strength than Delrin® 100P with lower modulus and tensile strength. Glass reinforced Delrin® 525GR offers a significant increase in modulus and tensile strength with reduced elongation.

Property data for Zytel® resins is provided for dry as molded (DAM) and 50% relative humidity (RH) equilibrated samples in Table VI.

Immediately after molding, nylon parts contain less than 0.3% moisture, but gradually begin to absorb water from the atmosphere and approach near equilibrium levels at 50% RH (PA 66: up to 2.5%; PA 612: up to 1.3%). The water content in nylon slowly cycles with seasonal variations in RH.

Toughening and glass reinforcement of Zytel® have effects on mechanical properties similar to those noted for the same modifications of Delrin®. The Zytel® PA 66 nylon resins have higher modulus and tensile strength than the comparable PA 612 resins when dry (DAM), but at 50% RH show similar properties.

Durability.

Friction and wear properties (tribological characteristics) are highly dependent on the configuration of the gear train, choice of gear materials, service requirements, and molding conditions.

Table VI
Mechanical Properties of Various Zytel® Nylon Resins
(Dry as Molded/Conditioned to 50% Relative Humidity)

Properties \ Product Description	Unmodified, General Purpose		Toughened	Glass Reinforced	
	101L PA 66	151L PA 612	ST801 PA 66	70G33L PA 66	77G33L PA 612
Tensile Strength at Yield MPa (kpsi) ASTM D638	83/59 (12.0/8.5)	61/52 (8.8/7.4)	52/41[1] (7.5/6.0)[1]	186/124[1] (27/18)[1]	165/138[1] (24/20)[1]
Elongation at Yield, % ASTM D638	5/25	7/30	NA[2]	NA[2]	NA[2]
Elongation at Break, % ASTM D638	60/≥300	60/250	60/210	3/4	3/4
Flexural Modulus MPa (kpsi) ASTM D790	2,830/1,210 (410/175)	2,030/1,240 (295/180)	1,690/860 (245/125)	8,970/6,200 (1300/900)	8,270/6,200 (1,200/900)
Izod Impact, notched J/m (ft-lb/in) ASTM D256	53/112 (1.0/2.1)	43/69 (0.8/1.3)	910/1,070 (17.0/20.0)	117/133 (2.2/2.5)	128/133 (2.4/2.5)
Izod Impact, unnotched J/m (ft-lb/in) ASTM D256	NB[3]	NB[3]	NB[3]	1,330/1,490 (25/28)	1,330/1,330 (25/25)

[1]Values are tensile strength at break, since these materials do not yield.
[2]NA means not applicable.
[3]NB means no break occurs.

Plastic gears may mate with gears of the same or a different plastic composition or with metals like brass, aluminum, or steel. Plastic gear wear is notably affected by the surface roughness of mating metal gears. Gear wear may be reduced by adding internal lubricants to the polymer. Gears molded with DuPont Teflon® fluorocarbon lubricated resins are especially effective in combating wear against steel.

The effect of molding on tribological characteristics can be demonstrated by increasing the mold temperature. Higher temperatures lead to higher levels of crystallinity, which in turn improves wear performance.

DuPont has conducted a number of studies to provide comparative information on the friction and wear characteristics of a variety of polymer resins. Given the complexity of friction and wear studies, it is necessary to verify performance by testing the chosen material in a prototype part under simulated operating conditions.

High Sliding Wear.

Gear wear will increase with contact pressure (load) and increased sliding velocity. Because worm gears generally have a high degree of sliding contact, as opposed to primarily rolling contact, wear should be investigated as a failure mode.

In one test, a modified ASTM D3702 thrust washer of Delrin® was rotated against two unlubricated countersurfaces at various loads and velocities in order to measure both break-in and equilibrium wear. Equilibrium wear is the constant wear rate experienced after initial break-in wear has occurred. The results of this test were used to develop three-dimensional plots of equilibrium specific wear rate ($\dot{W}_S$)—as defined by DIN method 50324—versus pressure × velocity (PV) and velocity (V). In an effort to provide practical design guidance, the data is presented at potential operating PV ranges, as opposed to describing a PV limit. This test is most applicable to worm or helical gears.

Two examples of these three-dimensional plots are provided in Figures 1 and 2 for Delrin® 520MP against steel and Delrin® 500AL against itself. The plots show that wear is dependent on operating pressure and velocity. Lubricated grades like Delrin® 520MP and 500AL are less dependent on these parameters than nonlubricated compositions.

To help simplify the data from three-dimensional plots, comparisons are presented in Tables VII and VIII for various Delrin® resins against steel and against themselves at two PV conditions.

Delrin® acetal resin

Delrin® 100 is used in mixer gears manufactured by E.G.S. of Germany. Delrin® was selected because of its good impact strength, low coefficient of friction, and high stiffness. The switch to Delrin® means improved productivity, a low reject rate, and cost reductions as the result of parts consolidation.

Figure 1. Delrin® 520MP Against Steel: Equilibrium-Specific Wear Rate

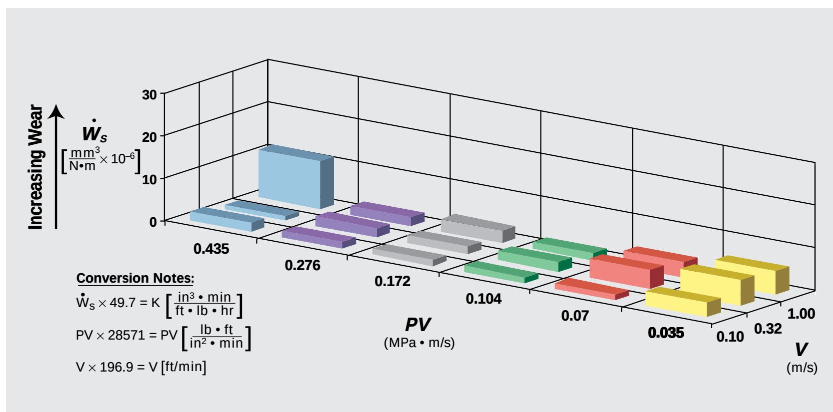
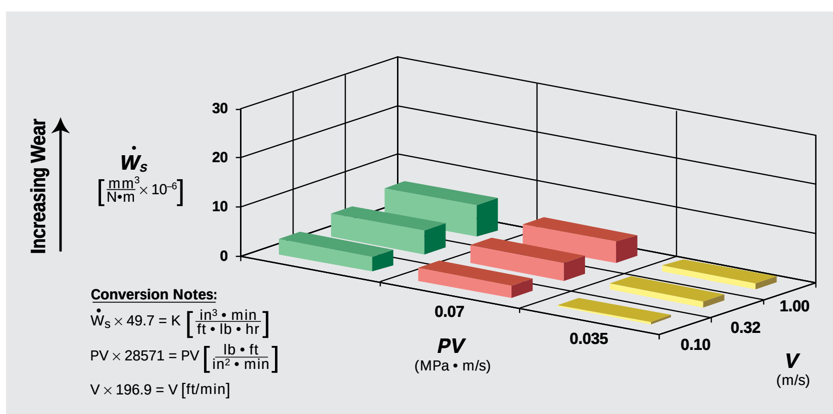


Figure 2. Delrin® 500AL Against Itself: Equilibrium-Specific Wear Rate



In Table VII, the break-in and equilibrium wear of Delrin® against steel at both PV conditions show that Delrin® 500P is slightly better than Delrin® 500. All of the lubricated compositions in this table are significantly better than Delrin® 500 and 500P. Delrin® 500AF offers the lowest wear and coefficient of friction (COF) values. Delrin® 500AF, 520MP, and 510MP are all very low in break-in wear.

Wear of plastic against plastic is generally much greater than wear of plastic against steel; therefore, the results represented in Table VIII are for significantly lower PV conditions. The data for

Table VII
Specific Wear Rate and Coefficient of Friction—Delrin® Against Steel

Product Composition		Product Grade	Break-in Wear	Equilibrium Wear			
			PV = 0.104	PV = 0.104 (P = 0.33 MPa V = 0.32 m/s)		PV = 0.172 (P = 0.55 MPa V = 0.32 m/s)	
			Wear, $\dot{W}_s$	Wear, $\dot{W}_s$	Dyn. COF	Wear, $\dot{W}_s$	Dyn. COF
Unmodified, General Purpose		Delrin® 500	22.5	15.5	0.39	26.0	0.43
		Delrin® 500P	13.5	8.5	0.37	5.4	0.34
Toughened		Delrin® 500T	10.5	10.0	0.54	4.0	0.47
Lubricated	**Teflon®**	Delrin® 500AF	2.1	1.4	0.19	0.7	0.16
		Delrin® 520MP	2.0	2.2	0.17	1.9	0.18
		Delrin® 510MP	2.6	1.8	0.20	1.3	0.20
		Delrin® 500TL	8.1	1.6	0.27	2.0	0.21
	Internal Chemical	Delrin® 500AL	5.2	3.8	0.23	1.5	0.18
		Delrin® 500CL	6.0	2.0	0.20	3.6	0.21

Metric Units—Specific Wear Rate $\dot{W}_s = \frac{mm^3}{N \cdot m} \times 10^{-6}$

Conversion Notes: P(MPa) × 145 = P(lb/in²)
V(m/s) × 196.9 = V(ft/min)

Table VIII
Specific Wear Rate and Coefficient of Friction—Delrin® Against Itself
(Wear of Washer Test Surface Only)

Product Composition		Product Grade	Break-in Wear	Equilibrium Wear			
			PV = 0.035	PV = 0.035 (P = 0.11 MPa V = 0.32 m/s)		PV = 0.070 (P = 0.22 MPa V = 0.32 m/s)	
			Wear, $\dot{W}_s$	Wear, $\dot{W}_s$	Dyn. COF	Wear, $\dot{W}_s$	Dyn. COF
Unmodified, General Purpose		Delrin® 500	>600	26.0	0.42	885	0.50
		Delrin® 500P	>600	16.1	0.44	503	0.48
Lubricated	**Teflon®**	Delrin® 520MP	3.21	0.08	0.29	0.44	0.20
		Delrin® 500TL	78.7	7.04	0.34	11.7	0.30
	Internal Chemical	Delrin® 500AL	6.43	1.23	0.30	3.72	0.23
		Delrin® 900SP	1.55	1.15	0.33	2.96	0.23
	Silicone	Delrin® 500P with with 1% Silicone	24.8	7.85	0.33	19.7	0.20
		Delrin® 500P with with 2% Silicone	2.01	0.52	0.30	0.60	0.18

Metric Units—Specific Wear Rate $\dot{W}_s = \frac{mm^3}{N \cdot m} \times 10^{-6}$

Conversion Notes: P(MPa) × 145 = P(lb/in²)
V(m/s) × 196.9 = V(ft/min)

Delrin® resins against themselves demonstrates that Delrin® 500 and 500P resins have the greatest wear of the compositions tested. The other compositions, which include special internal lubrication systems, are all significantly better than the unmodified resins, and 2% silicone in Delrin® 500P is markedly better than 1%. Although the differences among Delrin® 500P with 2% silicone, 520MP, 500AL, and 900SP are slight, Delrin® 900SP exhibits the lowest break-in wear. Delrin 520MP shows the lowest equilibrium wear under these conditions.

Low Sliding Wear.

DuPont measured tooth wear in spur gears, each made of a different Delrin® resin. The gears were driven by a steel pinion at equivalent torque and speed. In Figure 3, compositions containing Teflon® (Delrin® 500AF, 520MP, and 510MP) show the least wear, followed by chemically lubricated Delrin® 500AL and the resins without any internal additive or lubricant, Delrin® 500T and 500P.

In the same test, sensitivity to load of the three Delrin® resins containing Teflon® was also measured. Each resin was compared at two different initial contact stress levels. As shown in Figure 4, greater initial contact stress causes more wear.

Figure 3. Unlubricated Wear of Gear Teeth—Delrin® Against Steel

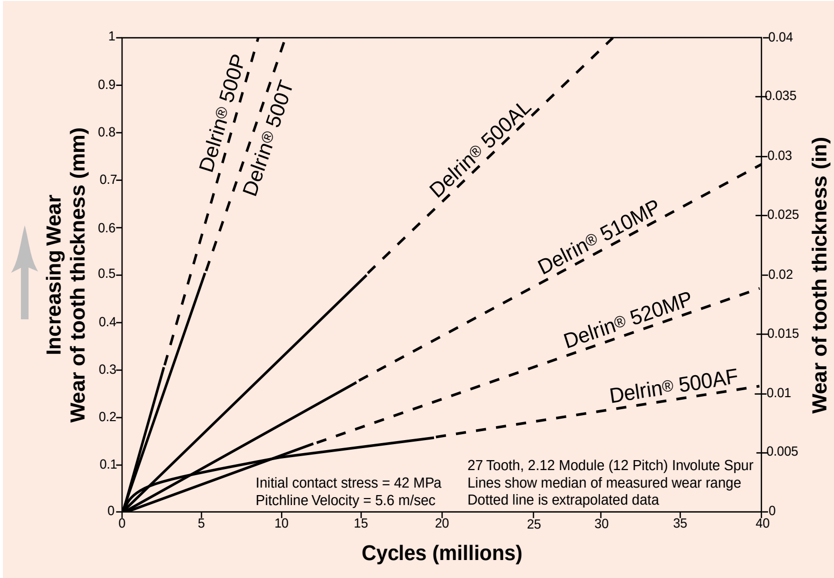
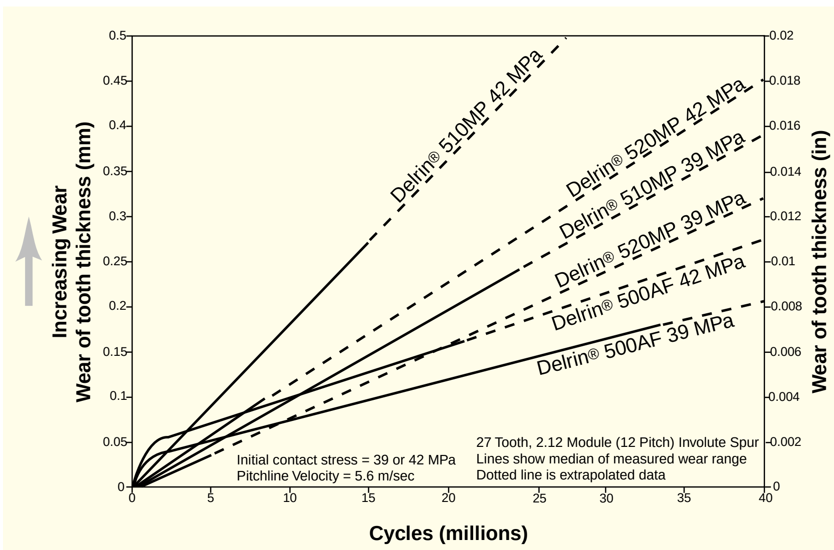


Figure 4. Sensitivity to Load—Delrin® Against Steel



Zytel® nylon resin

In small appliance engines manufactured by Briggs & Stratton, the cam gear and lobes are insert molded around a steel camshaft using Zytel® 103HSL. Chosen for its high-temperature toughness and oil resistance, Zytel® reduces noise at the cam/lifter interface and provides greater cost efficiency.

Fatigue.

Tooth fatigue from repeated bending stress is another important failure mode for continuously or initially lubricated gears. A simple approximation of this stress may be calculated using a form of the Lewis equation. This approach assumes that only one tooth of each gear is in contact near the pitch point and carries the entire load.

$$S_b = \frac{2\,T}{f\,YMD_p}$$

where S_b = Bending stress

T = Gear torque

f = Gear face width

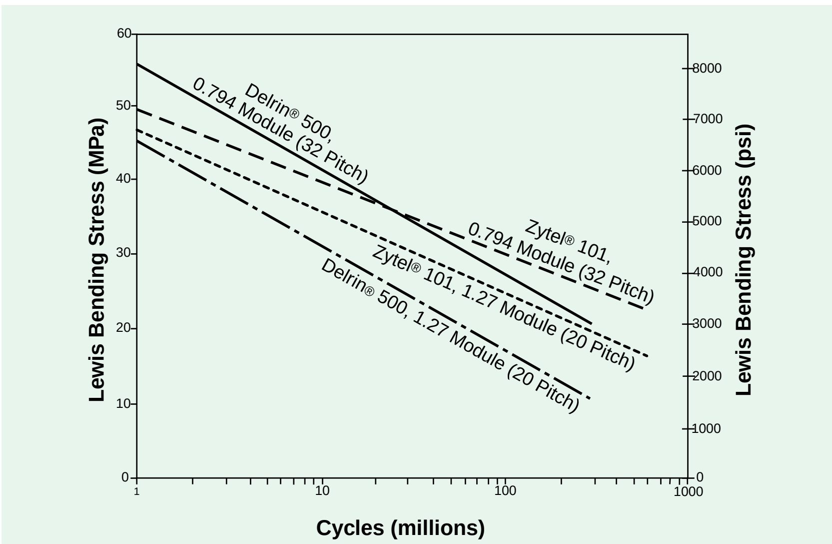
Y = Lewis form factor for plastic gears, loaded near the pitch point

M = Module (pitch diameter in millimeters (mm) ÷ number of gear teeth)

D_p = Pitch diameter

In one gear-life test, tooth bending stress was calculated on continuously lubricated gears using this formula to plot cycles (gear revolutions) to failure. The plotted bending stress presented in Figure 5 has been reduced by 25% to provide an acceptable safety margin. Lines are presented for 20- and 32-pitch gears of both Delrin® 500 and Zytel® 101.

Figure 5. Maximum Bending Stress for Continuously Lubricated Gear Teeth



Delrin® acetal resin

Zanussi IMD of Italy uses Delrin® 500 in its gears for vending machine grinders. Delrin® was selected because of its dimensional stability at higher temperatures and lower noise. The gears made of Delrin® are quieter than the metal parts they replaced.

Make DuPont part of an ideal solution.

When you involve DuPont early in the process as part of your gear design team, you have access to a wealth of resources:

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Zytel® nylon resin

Black and Decker's cordless PowerDriver screwdrivers have a planetary gear transmission with two stages, each using three gears of Zytel® 101L. The gears run against metal sun gears and a zinc ring gear. Zytel® offers quiet operation, excellent durability, and precision molding. It replaces metal in the second-stage gears at a lower cost.

Gear photo insets throughout provided by Winzeler Gear, Inc.

For more information on DuPont Engineering Polymers for gears, call: 1-800-441-0575

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