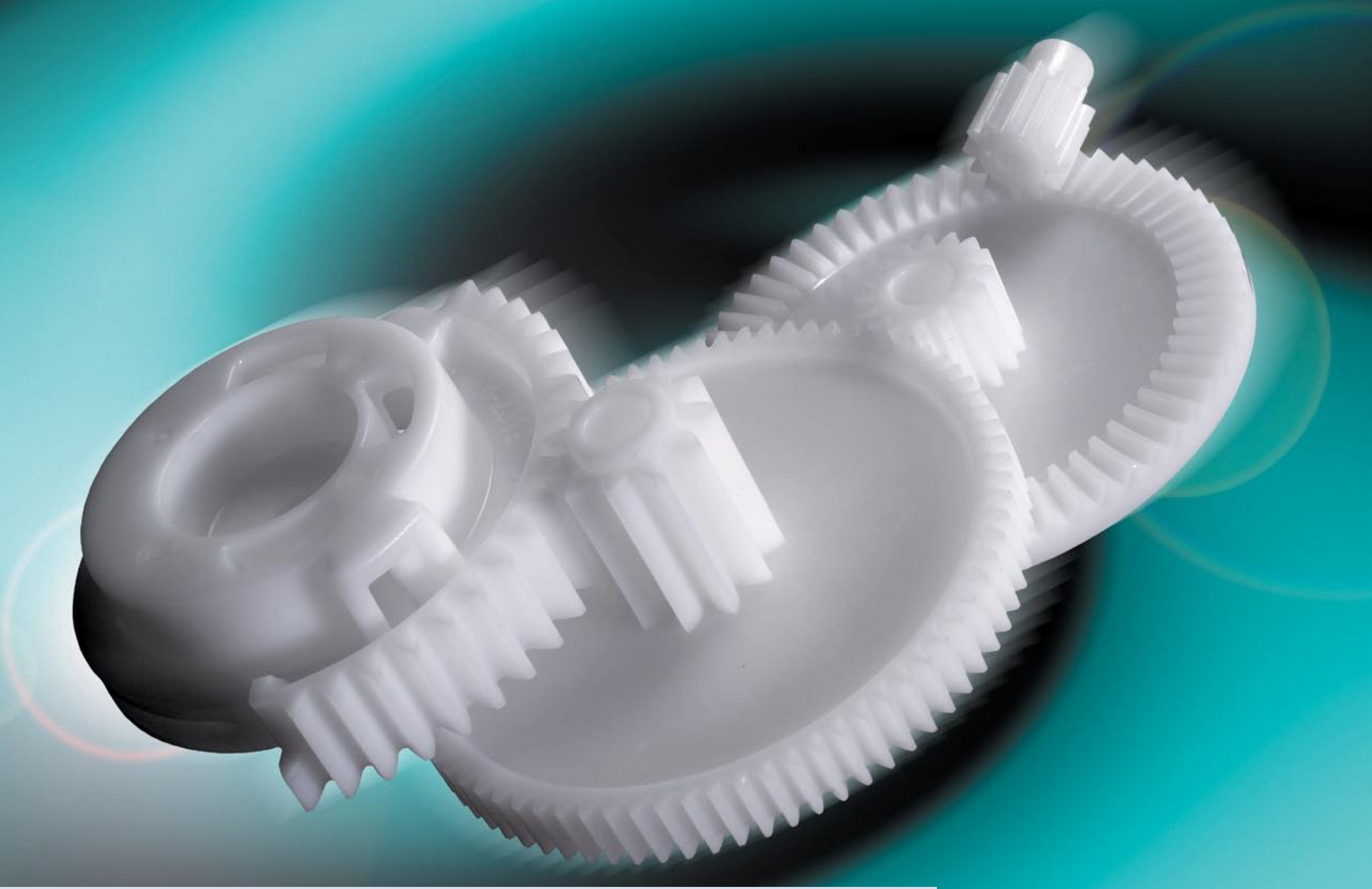


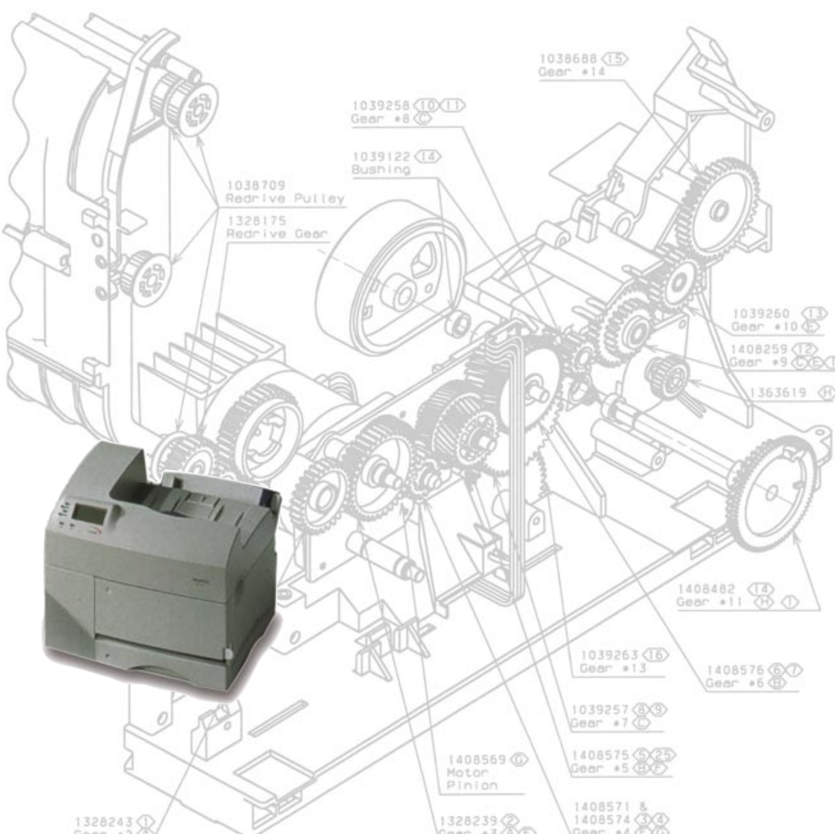
More skillful solutions from DuPont.

Engineering Polymers for High Performance Gears

DuPont
The miracles of science™

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.



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 40 years in hundreds of diverse products, including windshield wipers, windowlifts, speedometers, rotary pumps, appliances, power tools, clocks, and office automation equipment.

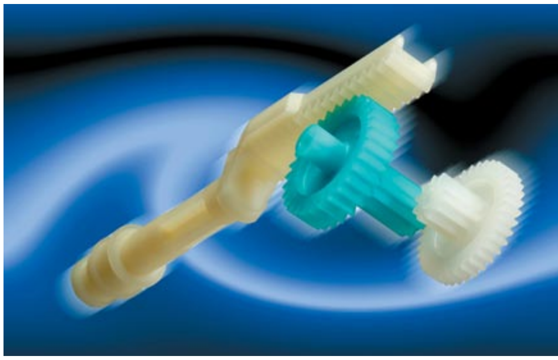
No other supplier today offers more high-performance polymers for gears and more expertise—from design consultation to molding assistance—to streamline material selection. With the recent introduction of additional grades to many product families, DuPont offers a wider range of solutions than ever before.

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® as well as unmodified Hytrel® thermoplastic polyester elastomer are available for high-shock applications.



DuPont polymers for gears at a glance.

Delrin® acetal resin (POM)

The most widely used DuPont resin for gears, Delrin® provides strength and stiffness without the need for glass fiber reinforcement. In addition, Delrin® offers 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.

Zytel® nylon resin (PA)

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 performance polyamide resin

Compared with other nylons, Zytel® HTN exhibits enhanced retention of mechanical properties with exposure to moisture, chemicals, and elevated temperatures. Zytel® HTN grades are available in both PPA and PA types.

Minlon® mineral-reinforced nylon resin (PA)

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

Hytrel® thermoplastic polyester elastomer (TPC-ET)

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, Rynite® PET, and Thermx® PCT thermoplastic polyester resins

Crastin® PBT, Rynite® PET, and Thermx® PCT are selected for strong, stiff gears in environments where a high degree of dimensional stability is required. The broad thermoplastic polyester product offering allows a range of service temperature requirements to be met.

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® parts and shapes

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

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.

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.

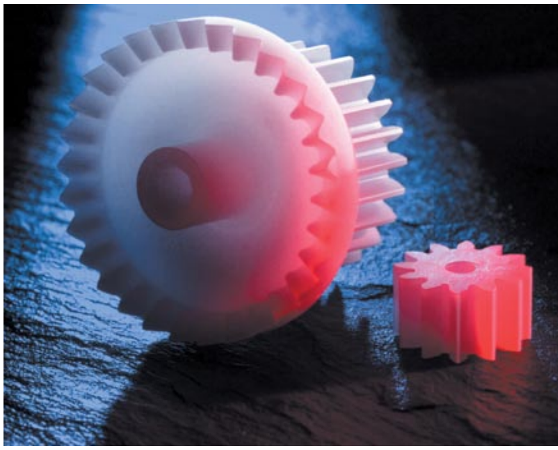
Durability. In low-stress environments, plastic gears typically offer longer lasting performance than their metal counterparts. Unmodified Delrin® and Zytel® both exhibit excellent friction, wear, and mechanical properties which can be enhanced by modifications. Selection of modifications should be based 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®, Zytel® HTN 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.

Zenite® LCP liquid crystal polymer resin

Two mating oval gears molded from Zenite® LCP precisely meter motor oil or other automotive fluids flowing through a hand-held electronic meter. 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.



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 1** presents the DuPont polymer families for gears along with applicable modifications, reinforcements, and lubricants. Recently introduced compositions are highlighted.

Table 1. DuPont Engineering Polymers for Gears

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

Key: ■ = available grades
▲ = new composition since 2000

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

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

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.

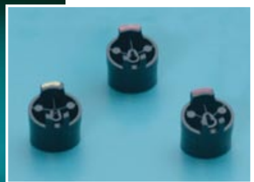
Table 2. Principal Effects of Resin Modifications on Gear Properties

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



Gears and other moving parts made of Delrin® fight wear, and provide dimensional stability in high moisture environments as well as chemical resistance.

Delrin® 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 3** and **4**.

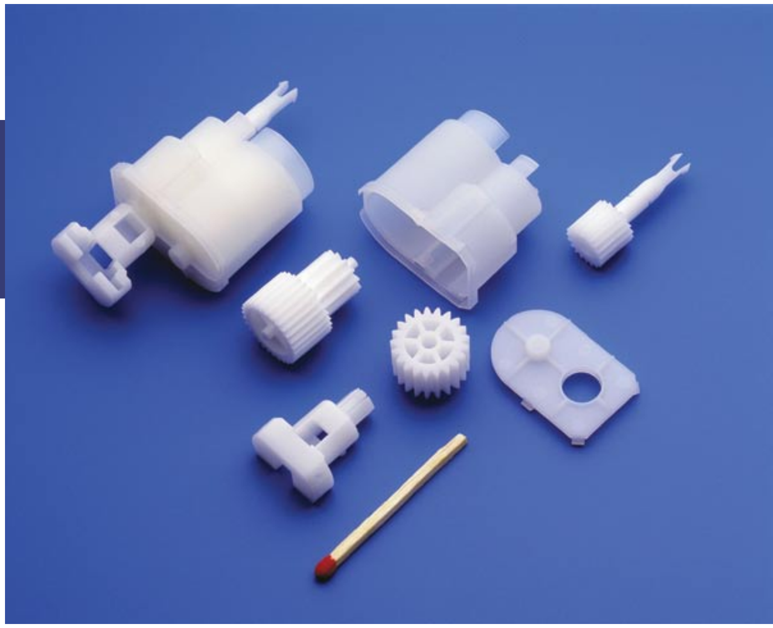
Delrin® acetal resin and Zytel® HTN high performance nylon resin

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 3. Delrin® Acetal Resins—Common Compositions for Gears

Product Composition		Product Grade	Description
Unmodified, General Purpose		Delrin® 100P	High viscosity homopolymer, tough
		Delrin® II100	High viscosity homopolymer, tough, excellent flex fatigue and creep resistance
		Delrin® 500P	Medium viscosity, homopolymer
		Delrin® 900P	Low viscosity, high flow, homopolymer
Enhanced Crystallinity		Delrin® 111P	High viscosity, homopolymer, enhanced crystallinity
		Delrin® 311DP	Medium-high viscosity, homopolymer, enhanced crystallinity
		Delrin® 511P	Medium viscosity, homopolymer, enhanced crystallinity
Toughened		Delrin® 100ST	High viscosity, homopolymer, super tough
		Delrin® 100T	High viscosity, homopolymer, toughened
		Delrin® 500T	Medium viscosity, homopolymer, toughened
Reinforced	**Glass**	Delrin® 525GR	Medium viscosity, 25% glass reinforced
		Delrin® 510GR	Medium viscosity, 10% glass reinforced
Lubricated	**Kevlar® aramid**	Delrin® 100KM	High viscosity, modified with Kevlar® aramid resin, good abrasion resistance
	Teflon® PTFE	Delrin® 100TL	High viscosity, 1.5% Teflon® PTFE micropowder
		Delrin® 500AF	Medium viscosity, 20% Teflon® PTFE fibers
		Delrin® 520MP	Medium viscosity, 20% Teflon® PTFE micropowder
		Delrin® 500MP	Medium viscosity, with Teflon® PTFE micropowder and advanced lubricant
		Delrin® 500TL	Medium viscosity, 1.5% Teflon® PTFE micropowder
	Internal Chemical	Delrin® 100AL	High viscosity, advanced lubricant system, low squeak
		Delrin® 500AL	Medium viscosity, advanced lubricant system, low squeak
		Delrin® 911AL	Low viscosity, high flow, advanced lubricant system, excellent dimensional stability
		Delrin® 500CL	Medium viscosity, chemical lubricant
	Silicone	Delrin® 500SC	20% Silicone concentrate, typically let down to 1% or 2% in most grades of Delrin®

A specially formulated grade of Delrin® with Teflon® PTFE helps assure long gear life in these input, output and cluster gears, with a smooth and easy to use mechanism for adjusting window blinds.



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® 12T 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 well 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.

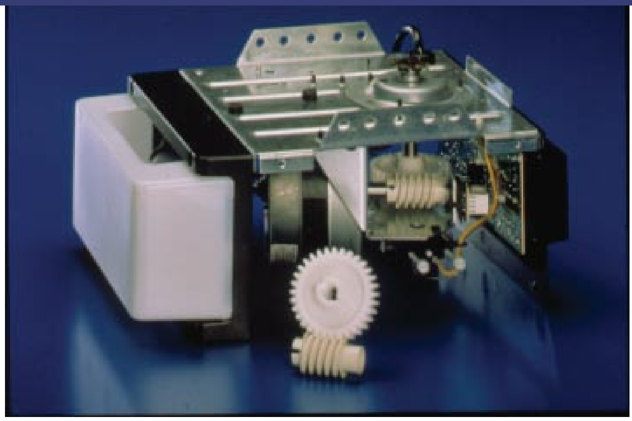
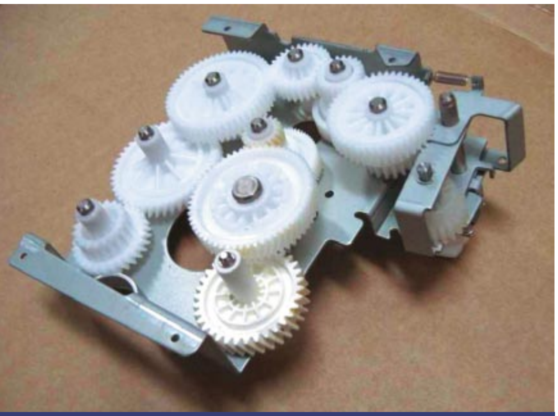


Table 4. Zytel® Nylon Resins—Common Compositions for Gears

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® E51HSB	High molecular weight PA 66, heat stabilized
		Zytel® 151L	General purpose, lubricated[1] PA 612
Toughened		Zytel® ST801 AHS	Super tough PA 66
Reinforced	**Glass**	Zytel® 70G33L	33% Glass reinforced, lubricated[1] PA 66
		Zytel® 77G33L	33% Glass reinforced, lubricated[1] PA 612
		Zytel® HTN51G35HSL	35% Glass reinforced, high performance PPA resin, heat stabilized
	Mineral	Minlon® 12T	36% Mineral reinforced, toughened PA 66
Lubricated	**Kevlar®**	Zytel® 70K20HSL	PA 66 reinforced with 20% Kevlar® aramid fibers
		Zytel® HTNWRF51K20	PPA reinforced with 20% Kevlar® aramid fibers
	Teflon® PTFE	Zytel® WRF403	30% Glass reinforced PA 66 with Teflon® PTFE micropowder
		Zytel® HTNWRF51G30	30% Glass reinforced PPA with Teflon® PTFE micropowder
		Zytel® HTNWRF51MP20	PPA with 20% Teflon® PTFE micropowder
	Other	Zytel® WRF101A	PA 66 lubricated with silicone oil
		Zytel® WRF500	PA 66 with Teflon® PTFE and Kevlar® aramid

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



Low wear/low friction grades like Delrin® 500AL work well in this printer gear train and provide low squeak and grease-free operation.

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 5**.

Compared with lower viscosity grades (the 500 and 900 series), the high-viscosity 100 series resins, such as Delrin® 100P and 111P, 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.

Many grades of Delrin® are modified with special additives to further enhance wear and friction performance. In most cases, these are only moderate changes in the major mechanical properties of the base acetal resin, except for those that contain high levels of other additives.

The effects of temperature on stiffness are shown in **Figure 1**, page 11, where the Tensile Modulus of several grades of Delrin® are plotted versus temperature.

Property data for Zytel® resins is provided for dry as molded (DAM) and 50% relative humidity (RH) conditioned samples in **Table 6.**

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.

Zytel® HTN grades have the highest strength and modulus under DAM and 50% RH conditions, and have the greatest property retention after humidity aging.

Wear and friction additives affect mechanical properties of Zytel® resins to various extents, depending on the specific lubricant and quantity.

Table 5. Mechanical Properties Of Various Delrin® Acetal Resins

5A. Standard Grades of Delrin®														
Delrin® Grade				General Purpose							Toughened		Glass Reinforced	
				100P	111P	II100	311DP	500P	511P	900P	100ST	100T	510GR	525GR
Property	Method	SI Unit	Eng Unit											
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa	kpsi	70 (10.2)	72 (10.4)	71 (10.2)	73 (10.6)	70 (10.1)	73 (10.6)	71 (10.3)	41 (5.9)	52 (7.5)	95* (14)	145 (20.3)
Yield Strain	ISO 527	%	%	22	20	25	15	17	12	13	30	25	NA	NA
Strain (Nominal Strain or Strain at Break*)	ISO 527	%	%	45	35	40	35	30	25	23	>50	>50	4.3*	3
Tensile Modulus	ISO 527	MPa	kpsi	2900 (420)	3200 (465)	3100 (450)	3300 (480)	3100 (450)	3400 (490)	3300 (479)	1400 (203)	1900 (276)	5500 (8000)	9400 (1360)
Flexural Modulus	ISO 178	MPa	kpsi	2600 (377)	2900 (420)	2800 (405)	3100 (450)	2900 (420)	3100 (450)	3000 (435)	1100 (160)	1700 (245)	4800 (700)	8500 (1230)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m²	kJ/m²	14	11	15	10	9	8	8	90	25	5	8
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m²	kJ/m²	NB	270	NB	300	300	260	200	NB	NB	50	50
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C	°F	93 (200)	100 (212)	98 (210)	103 (217)	94 (201)	107 (225)	94 (201)	60 (140)	72 (160)	164 (327)	172 (342)
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	%	1.1 (0.61)	1.1 (0.61)	1.0 (0.56)	1.1 (0.61)	1.1 (0.61)	1.0 (0.56)	1.2 (0.68)	1.3 (0.72)	1.2 (0.68)	0.7 (0.39)	0.35 (0.19)
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	%	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.0 (0.56)	1.2 (0.68)	1.4 (0.78)	—	1.0 (0.56)	1.0 (0.56)

ISO mechanical properties measured on 4 mm bars. Tensile properties measured at 50 or 5 mm/min.
Test temperatures are 23°C.
NA indicates not applicable. NB indicates no break.
Properties measured on natural (not pigmented) samples.

* Values for Stress at Break and Strain at Break at 5 mm/min.

Figure 1. Delrin® Grades for Gears—Tensile Modulus versus Temperature

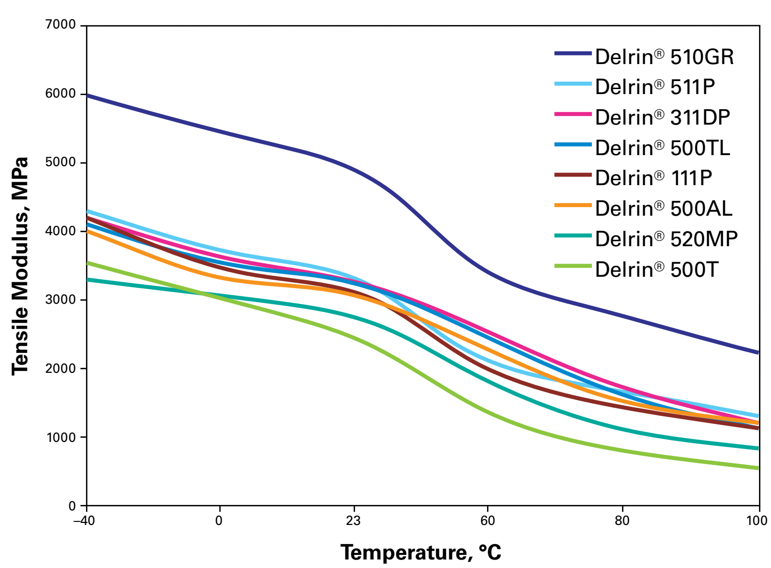


Table 5. Mechanical Properties Of Various Delrin® Acetal Resins (continued)

5B. Wear and Friction Grades of Delrin®													
Delrin® Grade				**100AL**	**100TL**	**500AL**	**500AF**	**500CL**	**500MP**	**500P + 500SC 10:1**	**500TL**	**520MP**	**911AL**
Property	**Method**	**SI Unit**	**Eng Unit**										
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa	kpsi	70 (10)	71 (10.3)	65 (9.4)	50 (7.3)	67 (9.7)	70 (10.2)	66 (9.6)	71 (10.3)	53 (7.7)	70 (10.1)
Yield Strain	ISO 527	%	%	18	25	11	10	15	12	20	13	13	9
Strain (Nominal Strain or Strain at Break*)	ISO 527	%	%	45	33	23	14	25	17	38	20	15	22
Tensile Modulus	ISO 527	MPa	kpsi	3000 (435)	3000 (435)	3000 (435)	2800 (405)	3100 (450)	3300 (480)	2900 (420)	3300 (480)	2800 (406)	3300 (480)
Flexural Modulus	ISO 178	MPa	kpsi	2800 (405)	2800 (405)	2800 (406)	2500 (360)	2900 (420)	3200 (460)	2900 (420)	3100 (450)	2700 (390)	3200 (46)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m^2	kJ/m^2	9	9	7	3	8	5	6	6	4	5
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m^2	kJ/m^2	250	150	170	40	350	125	260	170	70	150
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C	°F	97 (205)	95 (205)	97 (207)	92 (195)	90 (194)	100 (212)	95 (205)	100 (212)	94 (201)	103 (215)
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	%	1.1 (0.61)	1.1 (0.61)	1.2 (0.66)	1.1 (0.61)	1.1 (0.61)	1.0 (0.56)	1.0 (0.56)	1.0 (0.56)	1.0 (0.56)	1.0 (0.56)
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	%	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.1 (0.61)	1.0 (0.56)	1.0 (0.56)	1.0 (0.56)	0.97 (0.54)	1.0 (0.56)

ISO mechanical properties measured on 4 mm bars. Tensile properties measured at 50 or 5 mm/min.
Test temperatures are 23°C.
NA indicates not applicable. NB indicates no break.
Properties measured on natural (not pigmented) samples.

* Values for Stress at Break and Strain at Break at 5 mm/min.

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.

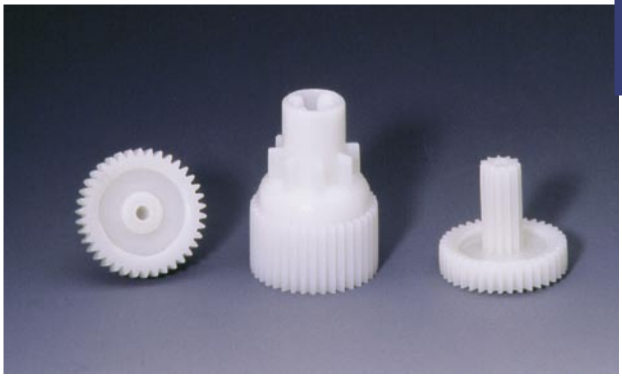


Table 6. Mechanical Properties of Various Zytel® Nylon Resins

6A. Standard Grades of Zytel®										
Zytel® or Minlon® Grade			101L PA 66		151L PA 612		E51HSB PA 66		70G33L PA 66	
Properties	**Method**	**Units**	**DAM**	**50% RH**	**DAM**	**50% RH**	**DAM**	**50% RH**	**DAM**	**50% RH**
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa (kpsi)	82 (11.9)	55 (8.0)	62 (9)	54 (7.8)	84 (12.2)	55 (8.0)	200* (29)	140* (20.3)
Yield Strain	ISO 527	%	4.5	25	4.5	18	4.3	29	NA	NA
Strain (Nominal Strain at Break or Strain at Break*)	ISO 527	%	25	>50	17	>50	35	>50	3.5	5
Tensile Modulus	ISO 527	MPa (kpsi)	3100 (45)	1400 (200)	2400 (348)	1700 (247)	3100 (450)	1200 (174)	10500 (1520)	8000 (1160)
Flexural Modulus	ISO 178	MPa (kpsi)	2800 (410)	1200 (174)	2100 (304)	1440 (208)	2800 (410)	—	9300 (1350)	6205 (900)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m²	5.5	15	3.5	4	7	21	13	17
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m²	NB	NB	NB	NB	NB	—	85	100
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C (°F)	70 (158)	—	62 (144)	—	70 (158)	—	252 (486)	—
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	1.0 (0.55)	—	1.1 (0.61)	—	—	—	0.18 (0.10)	—
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	1.1 (0.61)	—	1.2 (0.66)	—	—	—	0.83 (0.46)	—

6A. Standard Grades of Zytel® (continued)								
Zytel® or Minlon® Grade			77G33L PA 612		12T PA 66		HTN51G35HSL PPA	
Properties	**Method**	**Units**	**DAM**	**50% RH**	**DAM**	**50% RH**	**DAM**	**50% RH**
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa (kpsi)	168* (24.4)	140* (20.3)	80* (11.6)	58* (8.4)	220* (31.9)	210* (30.5)
Yield Strain	ISO 527	%	NA	NA	NA	NA	NA	NA
Strain (Nominal Strain at Break or Strain at Break*)	ISO 527	%	3.2	3.2	18	40	2.4*	2.5*
Tensile Modulus	ISO 527	MPa (kpsi)	9500 (1380)	7900 (1150)	4900 (710)	2000 (290)	12000 (1740)	12000 (1740)
Flexural Modulus	ISO 178	MPa (kpsi)	8200 (1190)	7000 (1015)	4500 (650)	1800 (260)	10500 (1520)	10500 (1520)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m²	13	12	9	15	12	11
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m²	80	90	210	330	70	55
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C (°F)	200 (392)	—	80 (176)	—	264 (507)	—
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	0.17 (0.09)	—	0.64 (0.36)	—	0.15 (0.08)	—
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	1.1 (0.63)	—	0.65 (0.36)	—	0.54 (0.30)	—

ISO mechanical properties measured on 4 mm bars. Tensile properties measured at 50 or 5 mm/min.
Test temperatures are 23°C.
NA indicates not applicable. NB indicates no break.
Properties measured on natural (not pigmented) resins.

* Values for Stress at Break and Strain at Break at 5 mm/min

Table 6. Mechanical Properties of Various Zytel® Nylon Resins (continued)

6B. Wear and Friction Grades of Zytel®							
Zytel® or Minlon® Grade			**WRF101A**	**WRF403**	**WRF500**	**70K20HSL**	
Properties	**Method**	**Units**	**DAM**	**DAM**	**DAM**	**DAM**	**50% RH**
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa (kpsi)	85 (12.3)	185 (26.8)	90 (13)	110 (16)	85 (12.3)
Yield Strain	ISO 527	%	4	NA	NA	NA	NA
Strain (Nominal Strain at Break or Strain at Break*)	ISO 527	%	10	2.8	4.5	5.2	7.2
Tensile Modulus	ISO 527	MPa	3300 (480)	10300 (1500)	4300 (620)	5300 (769)	3500 (510)
Flexural Modulus	ISO 178	MPa	2900 (420)	9200 (1330)	4200 (610)	4900 (710)	3300 (478)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m²	3	13	6	6	9
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m²	50	80	50	50	65
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C (°F)	70 (160)	250 (482)	190 (374)	222 (432)	—
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	—	—	—	—	—
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	—	—	—	—	—

6B. Wear and Friction Grades of Zytel® (continued)					
Zytel® or Minlon® Grade			**HTNWRF51G30**	**HTNWRF51K20**	**HTNWRF51MP20**
Properties	**Method**	**Units**	**DAM**	**DAM**	**DAM**
Tensile Strength (Yield Stress or Stress at Break*)	ISO 527	MPa (kpsi)	190 (27.2)	107 (15.5)	55 (7.9)
Yield Strain	ISO 527	%	NA	NA	NA
Strain (Nominal Strain at Break or Strain at Break*)	ISO 527	%	2.6	3.2	2.3*
Tensile Modulus	ISO 527	MPa	10300 (1500)	5300 (770)	2900 (420)
Flexural Modulus	ISO 178	MPa	9300 (1350)	5000 (730)	2700 (390)
Notched Charpy Impact Strength	ISO 179/1eA	kJ/m²	10	4	3
Unnotched Charpy Impact Strength	ISO 179/1eU	kJ/m²	60	20	20
Deflection Temperature, 1.8 MPa Load	ISO 75-1/-2	°C (°F)	260 (500)	180 (356)	130 (266)
CLTE, Parallel, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	0.15 (0.08)	0.44 (0.24)	0.69 (0.38)
CLTE, Normal, 23–55°C (73–130°F)	ISO 11359-1/-2	E-4/C (E-4F)	0.58 (0.32)	0.58 (0.32)	0.66 (0.37)

ISO mechanical properties measured on 4 mm bars. Tensile properties measured at 50 or 5 mm/min.
Test temperatures are 23°C.
NA indicates not applicable. NB indicates no break.
Properties measured on natural (not pigmented) resins.

* Values for Stress at Break and Strain at Break at 5 mm/min

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.

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

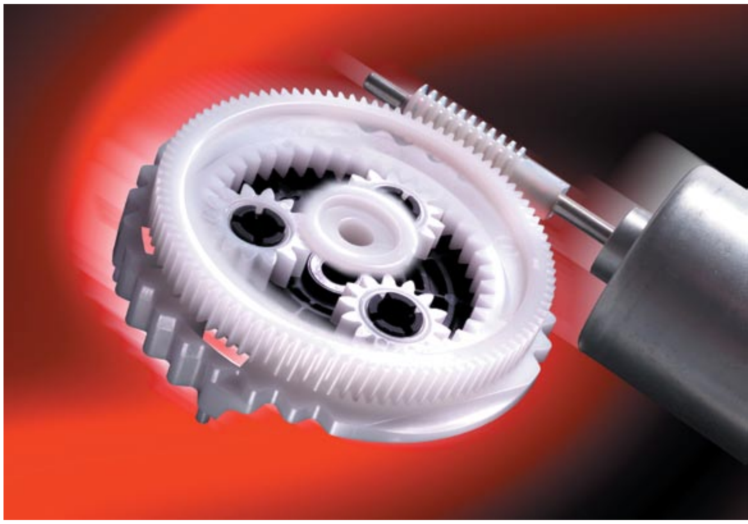
Gear wear will increase with contact pressure (load) and increased sliding velocity. Because worm gears generally have a high degree of sliding contact, as opposed to primarily rolling contact, wear should be investigated as a failure mode.

In a set of special wear tests, 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 x velocity (PV) and velocity (V). Units are also given for this equilibrium wear factor. 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 2** and **3** 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 7** and **8** for various Delrin® resins against steel and against themselves at typical operating PV conditions.

In **Table 7**, the equilibrium wear of Delrin® against steel at both PV conditions shows that even Delrin® 500P has relatively low wear against a steel countersurface. All of the lubricated compositions in this table are significantly better than 500P. Delrin® 500AF offers the lowest combination of wear and coefficient of friction (COF) values, and it will have a higher limiting PV.



Wear of plastic against plastic is generally much greater than wear of plastic against steel; therefore, the results represented in **Table 8** are for significantly lower PV conditions. The data for Delrin® resins against themselves demonstrates that unmodified acetal has the greatest wear and highest COF 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 there are differences among Delrin® 500P with 2% silicone, 520MP and 500AL, these resins have low break-in wear. Delrin® 520MP shows the lowest equilibrium wear under these conditions.

Table 9 shows similar wear and friction data for several grades of unmodified and lubricated Zytel® against a steel countersurface. Zytel® E51HSB shows the lowest wear of the unmodified PA grades. Zytel® WRF500 (an unreinforced grade) and WRF403 (with 30% glass reinforcement) both contain Teflon® PTFE and exhibit reduced wear and lower coefficient of friction.

Figure 2. Delrin® 520MP Against Steel: Specific Wear Rate at Equilibrium

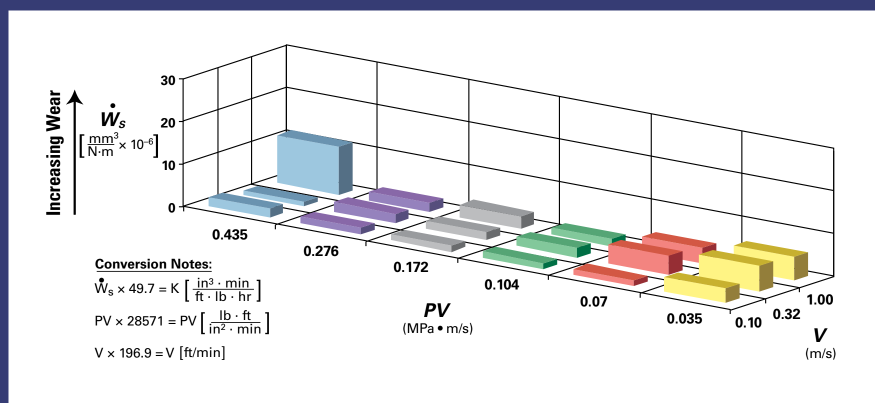


Figure 3. Delrin® 500AL Against Itself: Specific Wear Rate at Equilibrium

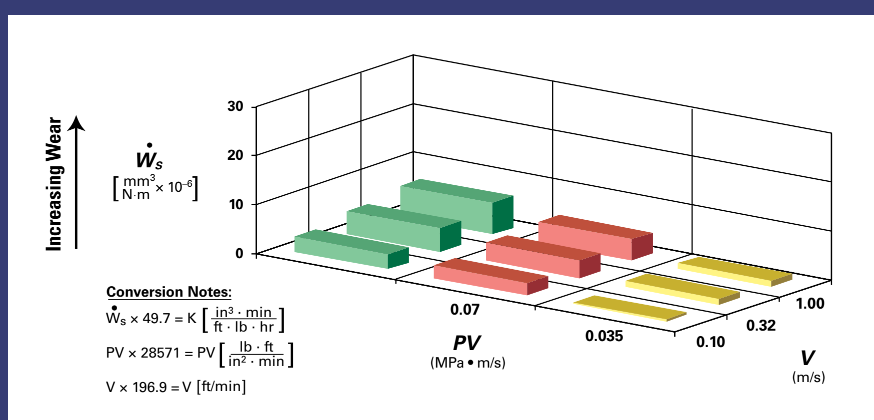


Table 7. Wear and Coefficient of Friction— Delrin® Against Steel Countersurface at PV = 0.176 (PV = 5000)

PV = 0.176 (P = 0.55 MPa, V = 0.32 m/s)
PV = 5000 (P = 80 lb/in^2, V = 64 ft/min)

Composition		Resin	Wear Rate, Equilibrium Metric Units (English Units)	Dynamic COF
Unmodified		Delrin® 511P	14 (694)	0.32
		Delrin® 311DP	3.6 (179)	0.33
		Delrin® 500P	2.7 (134)	0.42
Lubricated	Teflon® PTFE	Delrin® 500AF	1.1 (54.6)	0.16
		Delrin® 520MP	1.0 (49.6)	0.20
		Delrin® 500MP	9.7 (482)	0.21
		Delrin® 500TL	1.1 (54.6)	0.28
	Internal Chemical or Advanced Lubricant	Delrin® 500CL	7.3 (362)	0.23
		Delrin® 500AL	2.9 (144)	0.21
		Delrin® 100AL	5.9 (263)	0.25
	Kevlar® Aramid	Delrin® 100KM	3.1 (154)	0.36

ASTM D3702 Thrust Washer Testing
Metric Units of Wear (Specific Wear Rate) = mm^3/N·m x 10^{-6}
English Units of Wear (Wear Factor) = (in^3 min)/(ft·lb·hr) x 10^{-10}

PV = 0.176 (P = 0.55 MPa/V = 0.32 m/s)
PV = 5000 (P = 80 lb/in^2/V = 64 ft/min)

Table 8. Specific Wear Rate and Coefficient of Friction— Delrin® Against Self as Countersurface at PV = 0.035 (PV = 1000)

Wear of Test Sample and Countersurface Washer
PV = 0.035 (P = 0.11 MPa, V = 0.32 m/s)
PV = 1000 (P = 16 lb/in^2, V = 63 ft/min)

Composition		Resin	Wear Rate, Equilibrium Metric Units (English Units)	Dynamic COF
Unmodified		Delrin® 500P	464 (23,000)	0.3
Lubricated	Teflon® PTFE	Delrin® 520MP	0.61 (30)	0.41
		Delrin® 500MP	300 (14,920)	0.34
		Delrin® 500TL	247 (12,260)	0.45
	Internal Chemical or Advanced Lubricant	Delrin® 100AL	3.63 (180)	0.37
		Delrin® 500AL	0.48 (24)	0.25
		Delrin® 911AL	0.36 (18)	0.44
	Silicone	Delrin® 500P w. 1% Silicone	—	0.20*
		Delrin® 500P w. 2% Silicone	—	0.18*

ASTM D3702 Thrust Washer Testing
Metric Units of Wear (Specific Wear Rate) = mm^3/N·m x 10^{-6}
English Units of Wear (Wear Factor) = (in^3 min)/(ft·lb·hr) x 10^{-10}

*Measured at PV = 0.070 (P = 0.22 MPa, V = 0.32 m/s)

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.

Table 9. Wear and Friction Zytel® Grades Thrust Washer Testing—ag Steel Countersurface at PV = 0.176 (PV = 5000)

Grade	Zytel® Material	Base	Glass	Composition	PV = 0.176 (5000) Wear Rate (Equilibrium) metric (english)	PV = 0.176 (5000) Dynamic COF
Unmodified Grades	Zytel® 101L	PA66	—	nylon 6,6 control	7.2 (360)	0.76
	Zytel® E51HSB	PA66	—	high viscosity, unmodified	4.5 (225)	0.90
	Zytel® 70G33L	PA66	33% GR	nylon 6,6 control	7.1 (350)	0.46
	Zytel® HTN51G35	PPA	35% GR	PPA control	18.7 (930	0.46
Zytel® WRF Grades	Zytel® WRF101A	PA66	—	lubricated	2.5 (125)	0.15
	Zytel® WRF500	PA66	—	PTFE + Aramid	5.8 (290)	0.27
	Zytel® 70K20HSL	PA66	—	20% Aramid fiber	2.1 (105)	0.55
	Zytel® WRF403	PA66	30% GR	PTFE	1.2 (62)	0.44
Zytel® HTN WRF Grades	Zytel® HTNWRF51MP20	PPA	—	20% PTFE	3.0 (150)	0.25
	Zytel® HTNWRF51K20	PPA	—	20% Aramid fiber	2.1 (105)	0.60
	Zytel® HTNWRF51G30	PPA	30% GR	PTFE	1.8 (69)	0.44

ASTM D3702 Thrust Washer Testing
Metric Units of Wear = $mm^3/N{\cdot}m \times 10^{-6}$
English Units of Wear = $(in^3 min)/(ft{\cdot}lb{\cdot}hr) \times 10^{-10}$

PV = 0.176
P = 0.55 MPa / V = 0.32 m/s

PV = 5000 data
P = 80 lb/in^2 / V = 64 ft/min

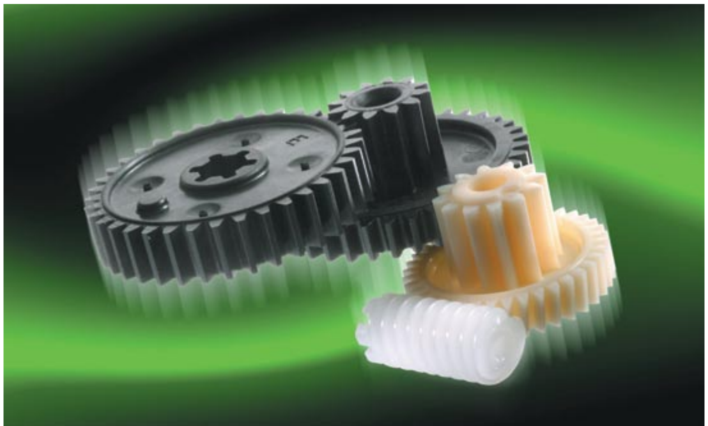


Figure 4. Unlubricated Wear of Gear Teeth

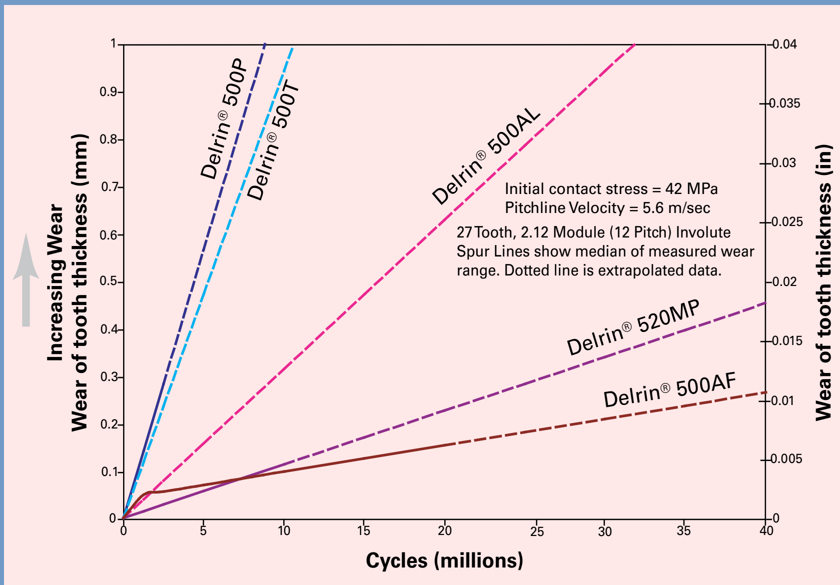
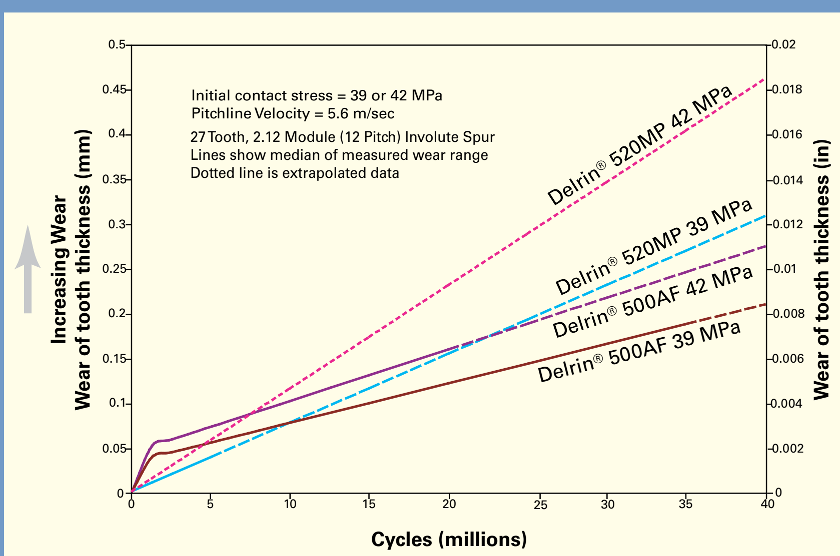


Figure 5. Sensitivity to Load



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 4**, compositions containing Teflon® (Delrin® 500AF and 520MP) 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 two Delrin® resins containing Teflon® was also measured. Each resin was compared at two different initial contact stress levels. As shown in **Figure 5**, greater initial contact stress causes more wear.

Fatigue

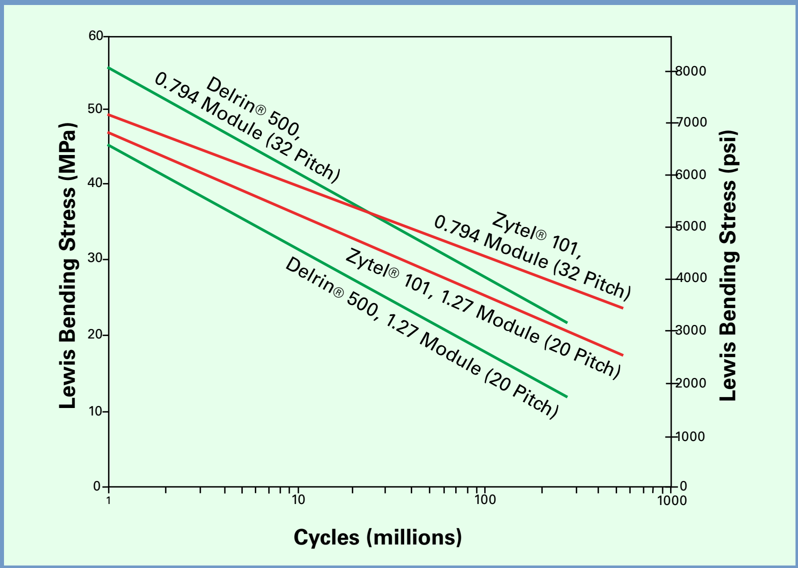
Tooth fatigue from repeated bending stress is another important failure mode for continuously or initially lubricated gears. A simple approximation of this stress may be calculated using a form of the Lewis equation. This approach assumes that only one tooth of each gear is in contact near the pitch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

$$S_b = \frac{2T}{fYMD_p}$$

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 6** 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 6. Maximum Bending Stress for Continuously Lubricated Gear Teeth



Truck external rear-view mirror provides more safety for lorry drivers. The mirror turns up to 90°. Gears molded from acetal homopolymer provide the strength and stiffness for long term durability.

Material Requirements

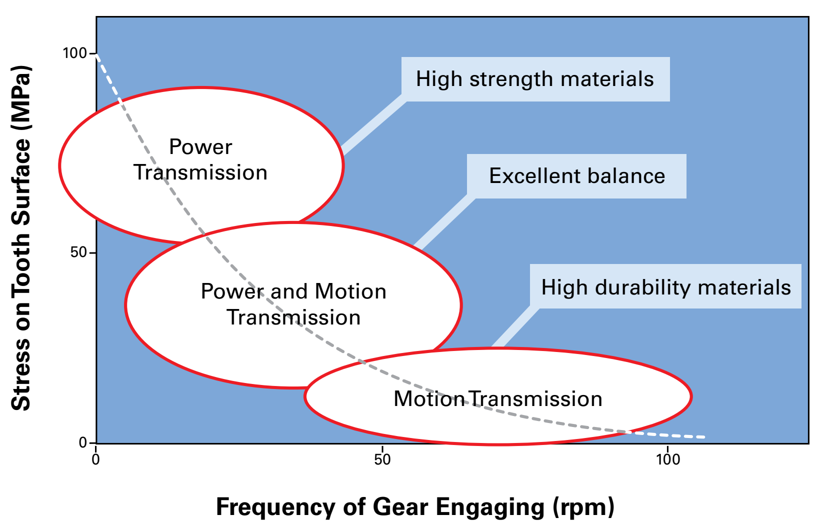
Material requirements for plastic gears fall into three categories, as illustrated in **Figure 7**, showing the relative effects of teeth surface stress and rotation speed, or frequency of gear engagement.

The highest strength materials are required for gears used in power transmission, such as power steering gears where operating temperatures are generally high, and systems are generally externally lubricated.

Materials of high durability (generally requiring internal lubrication, such as PTFE, silicone, or any of the advanced lubricant additives) are chosen for gears with motion transmission, such as in small motors and in office automation equipment, where operating temperatures are lower.

Resins with a balance of stength and long term performance properties are used in applications employing both power and motion transmission. These include automotive window lift gears, seat adjuster gears, and door actuator gears.

Figure 7. Material for Gears: Mechanical Requirements



Finite Element Analysis (FEA) Techniques Applied to Gears

Many gear designers are using computer aided techniques to help predict gear performance under varied operating conditions using known mechanical properties of plastic materials. In this example in **Figure 8**, a 40 tooth, 0.8 module gear set was modelled, with the drive gear and driven gear being identical. In actual gear fatigue life testing, the gears ran at 100 rpm at a torque of 3 N•m, with failure usually occurring in about 10 minutes. The same gears were modeled in the ABAQUS finite element program as plane stress, eight noded quads, as shown. The driven gear was fixed on its ID, while the driver had 3 N•m torque uniformly distributed on its ID. The material for this test was DuPont™ Delrin® 100P.

In a non-linear finite element analysis the load is applied in increments until the maximum load is achieved. **Figure 9** shows some of the increments. In each succeeding increment the Von Mises stresses are higher and spread out to more teeth as these teeth come in contact.

Figure 10 shows the Von Mises stresses in the test gears at maximum load, 3 N•m. The yield stress is exceeded in a few locations. When repeated stresses are in excess of the yield stress low cycle fatigue occurs, i.e., failure takes place after a relatively few cycles. This figure shows that three sets of teeth are in contact simultaneously at the maximum torque, thus a certain amount of load sharing occurs. Traditional gear formulas, created primarily to design metal gears, cannot give this information directly.

Figure 8.

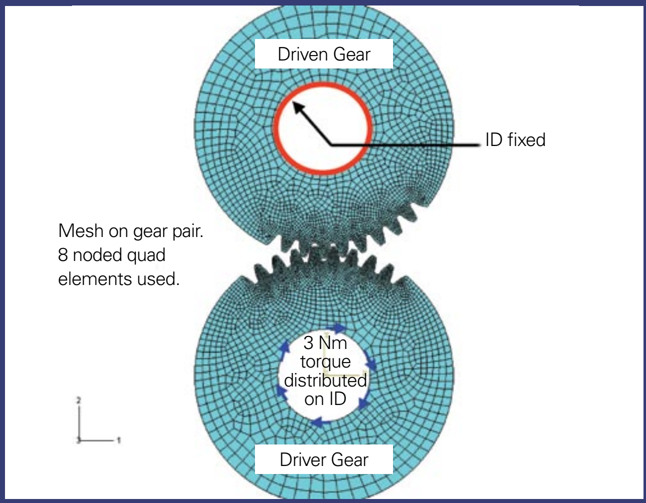
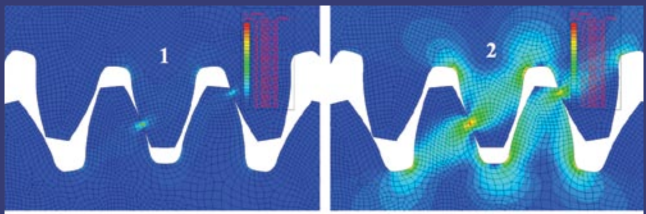


Figure 9.



The 3 Nm torque is applied in several increments. Each torque increment causes additional tooth deformation and an increase in the stresses until the full load is applied (see Figure 4).

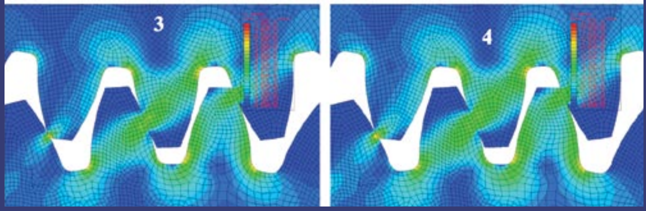
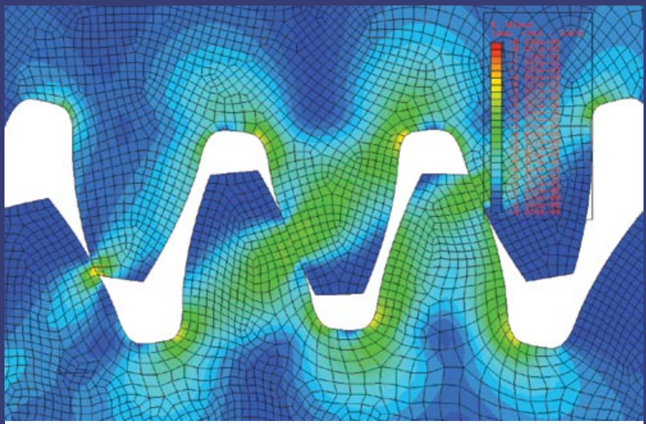


Figure 10.



At maximum torque, 3000 N-mm, the Von Mises stresses exceed the yield strength of the material at at least one location. Since the point of yielding moves as pairs of teeth come in contact, a low cycle fatigue process is set in motion.

Figure 11. Delrin® test gear and runner system modeled using Moldflow's new solid modeling module, MPI®/3D. The gear is modeled with tetrahedral elements.

Illustrations in Figures 11–13 courtesy of Moldflow.

Injection Molding Simulation Applied to Gears

DuPont Engineering Polymers has used the Moldflow injection molding simulation software for two decades to help predict the behavior of our resins in our customers' molds. The latest modules from Moldflow, including MPI®/3D, use three dimensional tetrahedral elements for modeling "chunky" parts such as gears. The example in **Figure 11** is a gear made from Delrin® 100P, shown with the assumed runner system.

The fill time plot in **Figure 12** shows the gear during filling. The three dimensional nature of the flow front is clearly visible in this plot.

MPI®/3D predicted the total shrinkage and warpage of the gear. **Figure 13** shows that in this case most of the deformation is shrinkage with little out of plane warpage.

Figure 12. A partial fill during the filling phase shows the three dimensional shape of the flow front.

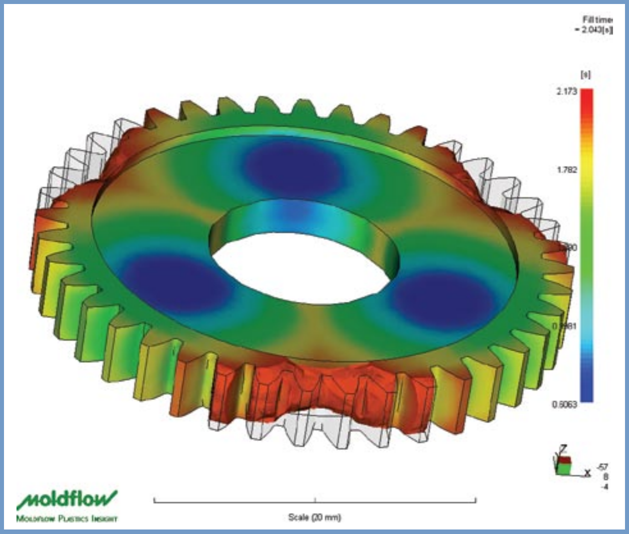
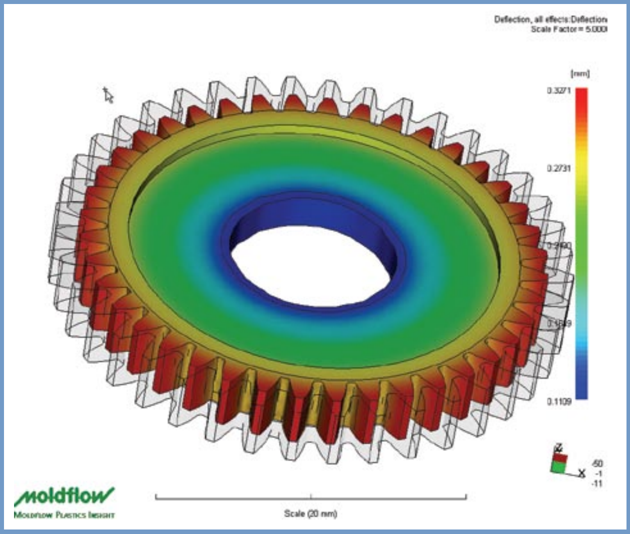


Figure 13. Total deformation due to shrinkage and warpage. In this case, out of plane warpage is minimal and shrinkage constitutes most of the deformation.

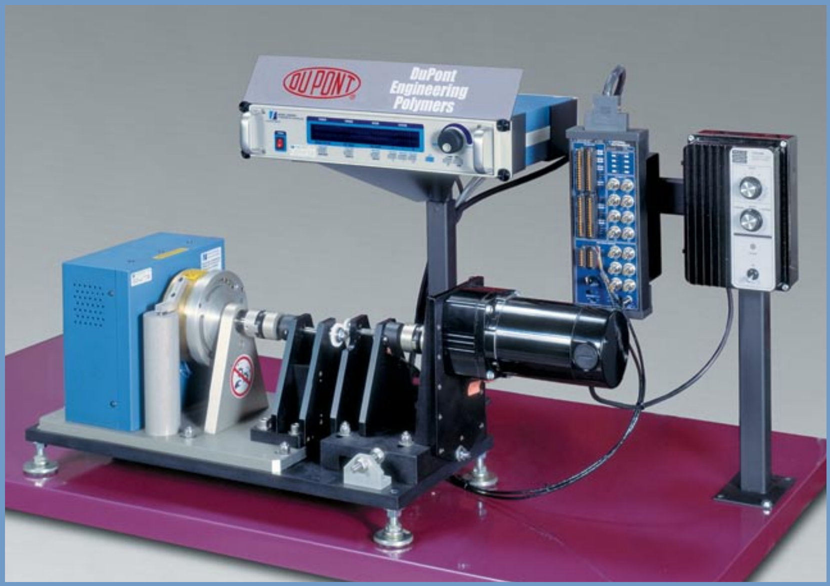


Gear Testing

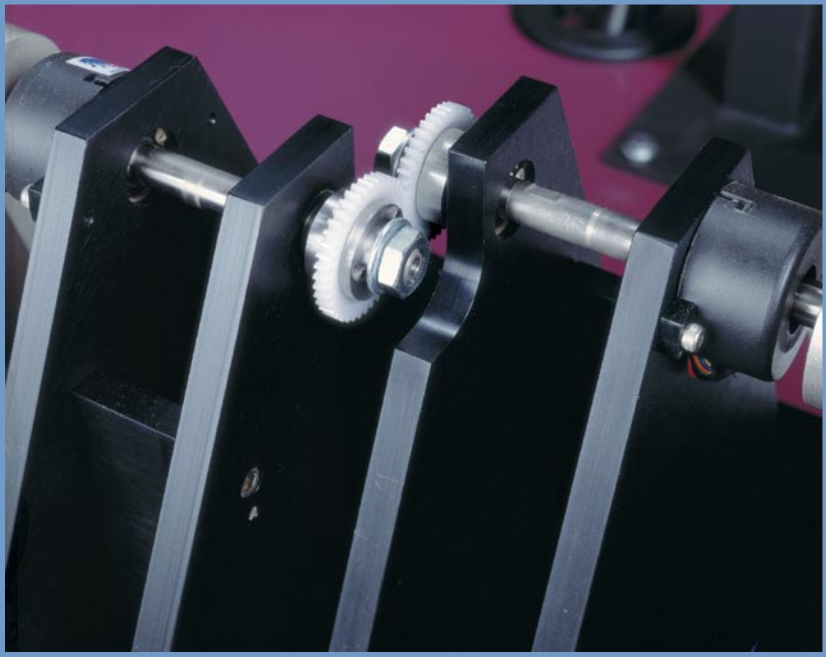
The ultimate proof of a resin's performance in gears is the way it performs in the actual end-use application. Since this is not a suitable way to evaluate a sufficient number of new resins for gears, often these resins are tested in simulated environments using various gear testers. One of the Gear Testers we have used to demonstrate capabilities is a gear dynamometer for wear testing plastic gears, as shown in **Figure 14**.

The objectives of this capability are the testing of helical and spur gears of various materials under a range of loads and speeds and the development of a database of information on the performance of plastic gears. The apparatus can test the number of cycles a molded plastic gear can survive under a sustained load before failure. It can also determine a gear's short-term failure point under increasing load. This kind of tester is a valuable tool in the development of new resins for gear applications.

Figure 14. Close-ups of Gear Dynamometer Test Apparatus



This gear tester was developed in conjunction with Winzeler Gear, Inc. and Bradley University.



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Gear inset, stylized photographs throughout provided by Winzeler Gear, Inc.

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