Gear Design:

Multipoint Properties are Key to Selecting Thermoplastic Materials

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Management Summary

The palette of thermoplastic materials for gears has grown rapidly, as have the applications themselves. Designers need to be aware of key properties and attributes in selecting the right material.

Introduction

Thermoplastic gear applications have expanded from low-power, precision motion into more demanding power transmission needs, even in such difficult environments as automotive engine compartments. Thermoplastics have supplanted metals in a number of applications, beginning historically (as might be expected) with the replacement of die cast metal gears. The range of applications has expanded as thermoplastics have proved their worth, and they are now increasingly specified for a growing number of more demanding applications.

While thermoplastic gears can be made by traditional gear machining methods, the majority of them are made by injection molding. With well-designed tooling, millions of gears at very tight tolerances can be turned out cost-effectively. Also attractive is the ability for part consolidation, including the molding of gear shaft and gear as a single unit, as well as one-piece compound gear units, where two or more spur or helical gears make up the design.

Regardless of the gear geometry or how it is manufactured, determining which of the many available materials to use is generally one of the first steps in the design process. Importantly, the material gives the gear its physical properties and greatly affects its usability for a given application. For example, in a high-temperature environment, a metal gear would traditionally be selected. In recent years, high-temperature, internally lubricated thermoplastic compounds have become available, providing designers with alternative material options. This can potentially offer savings in production by reducing the manufacturing steps involved. These compounds can also provide lubrication without the need for external oil or grease, avoiding problems from deterioration of lubricants over time and eliminating the need for maintenance and recurring application of oils or greases.

Finding Data on Thermoplastic Gear Materials

Historically the resins of choice for many thermoplastic gears were either neat polyamide (nylon) or neat polyoxymethylene (POM or acetal). As the available palette of materials has grown, and the weight, cost, corrosion resistance, low inertia, and noise advantages of thermoplastic gears have become more clear, interest has grown in thermoplastics for more demanding applications. In particular, the applicability of thermoplastics has been expanded by the development of specialized formulations that include reinforcement and internal lubrication.

Despite the availability of new thermoplastic compounds, however, designers can find themselves hampered by a scarcity of load-carrying and wear performance data, at least when compared to the large amount of easily accessible material performance information on metals. Granted, a certain amount of the design process used for metal gears can be carried over to thermoplastic gear design. However, simple interpolation of material data from metal to plastic does not work, largely because of the differences between the long-term mechanical and thermal behavior of thermoplastics versus metals.

Limitations of Single-Point Data

When choosing materials for a given application, single-point data can provide a place to begin. Such data are readily available across a range of materials and are typically displayed on a material supplier's technical datasheet. Attributes such as tensile strength, flexural modulus, and impact strength offer a snapshot of a material's performance—but single-point data do not provide the whole picture. The reason lies in the inherent characteristics of thermoplastics. Over a given temperature range, the physical and mechanical properties of a thermoplastic will change more significantly than do those of a metal. For example, tensile strength and stiffness (modulus) will decline with increasing temperature. Single-point data does not capture these types of changes.

Data-Development Initiatives

Because real-world gear designs depend on multivariate data, GE Plastics set out to establish performance and processing attributes for some of its specialty compounds in relation to gear design across appropriate ranges of environmental conditions found in gear applications. The dynamic variable differs by attribute, but most are time- or temperature-related (among these are stiffness, tensile strength and coefficient of thermal expansion). Whatever the attribute, in a performance application such as gear design, engineers need to know how a

Table I—Common resins used for thermoplastic gears. Almost all can be modified for flame retardancy and can be reinforced with glass, carbon fibers or lubricants. Several have been alloyed with other resins to create an application-specific set of characteristics.

Resin	Common Abbreviation	Key Resin Features
Polycarbonate	PC	High impact Good dimensional stability
Polyphenylene Oxide	PPO	Low specific gravity Good dimensional stability Low moisture absorption
Polyoxymethylene (Acetal)	POM	Low wear factor Superior friction resistance
Polyamide (Nylon) 6,6	PA66	Good chemical resistance Low specific gravity
Polyphenylene Sulfide	PPS	High strength High heat resistance Good chemical resistance Hydrolytic stability
Polyphthalamide	PPA	Good chemical resistance High heat resistance
Polyetherimide	PEI	High heat resistance Good dimensional stability High strength

Table II—Conventional single-point data for two grades of two different resins—a high modulus PPS and a lower modulus PA66. While this captures a number of resin attributes, it does not reflect some important dynamic data about, for example, tensile strength versus temperature (see Figures 1 & 2).

	ASTM Method	Unit	High Modulus PPS	Lower Modulus PA66
Specific Gravity	D792	g/cm^3	1.69	1.03
Mold Shrinkage	D955	%	1–3.5	18–23
Water Absorption (24 hours)	D570	%	---	0.20
Tensile Strength (Break)	D638	MPa	146	53
Tensile Modulus	D638	MPa	12,888	2,172
Tensile Elongation (Break)	D638	%	1.5	27
Flexural Strength	D790	MPa	200	76
Flexural Modulus	D790	MPa	11,000	2,320
Notched Izod Impact	D256	J/m	85	59
Heat Deflection Temperature (1.82 MPa)	D648	°C	269	78
Flammability	(UL94)	---	V-0 @ 1.5 mm	HB @ mm

thermoplastic compound's performance varies with time and temperature. Similar data is available for some of the more common engineering resins used in gearing, but our efforts concentrated on internally lubricated and glass fiber-reinforced compounds. In support of this effort, GE Plastics created a new laboratory specifically for developing performance data to support gear design in engineering thermoplastic materials.

In relation to gears, the new lab generates thermoplastic material performance data at multiple temperatures and loads, and it can also measure gear accuracy and gear performance characteristics, including wear, friction, noise generation, and allowable tooth stress. In addition, the laboratory develops injection molding production parameters for tooling design and processing. Resins tested to date include compounds based on polycarbonate (PC), polyphenylene oxide (PPO), polyoxymethylene (POM or acetal), polyamide (PA), polyphenylene sulfide (PPS), polyphthalamide (PPA), and polyetherimide (PEI) (see Table I).

Comparing Single-Point to Multivariate Data

While space precludes the inclusion of specific data for a broad range of resins suitable for gears, we can compare single-point data with dynamic data ranges for two contrasting resins as a means of illustrating how multivariate data contain more useful information than single-point data. The first resin is a relatively high-modulus, internally lubricated, 30 percent glass fiber-reinforced polyphenylene sulfide; the second is a relatively low-modulus, low-wear PA66. (Important note: These data apply to two specific formulations. One advantage of thermoplastics is that they can be compounded, alloyed, or mixed using multiple resins, additives and processing or performance aids. Differing formulations result in differing performance and processing characteristics. Thus, it is important to know precisely the formulation to which a given data set applies. It is equally important to refrain from extrapolating data from known formulations to resins with similar descriptions, as generic descriptions such as "30 percent glass-filled" may not capture complete formulation details.)

There are two key conclusions to be drawn from this comparison of single-point data (Table II) and dynamic or multipoint data (Figures 1 and 2). First—and this is the main point—is that each type of thermoplastic resin may exhibit very different material behaviors (in this case, as a function of temperature) across a given application's operating environment. Second, different thermoplastics can exhibit widely different performance for a given parameter. While these two material examples show very different performance characteristics, both have been successfully used in gearing, albeit in very different applications.

Key Parameters Studied

For a material to be successfully used in a gear application, it must meet several basic requirements. First, it must be strong enough to carry the transmitted load, both in a static position and as a repeated cyclic event. Second, it should not prematurely wear or cause wear on its mating gear. It must meet both of these requirements over the entire operating range of the application. Third, it should be dimensionally stable over the expected operating conditions of the application. A fourth requirement that is often missed is that the material should lend itself to a repeatable manufacturing process. Any test regimen selected should have these basic requirements in mind. Based on these general gear design requirements, as well as our experience with customer projects, we have gathered extensive data on the following performance properties:

- Load Carrying Capability
  - o Tensile strength
  - o Tensile creep
  - o Tensile fatigue
  - o DMA (Shear)
- Wear
  - o Gear wear testing
  - o Thrust washer wear testing
  - o Dimensional stability
- Dimensional Stability
  - o Coefficient of thermal expansion
- Processing
  - o Thermal conductivity
  - o Shear rate vs. viscosity
  - o Specific heat
  - o Mold shrinkage

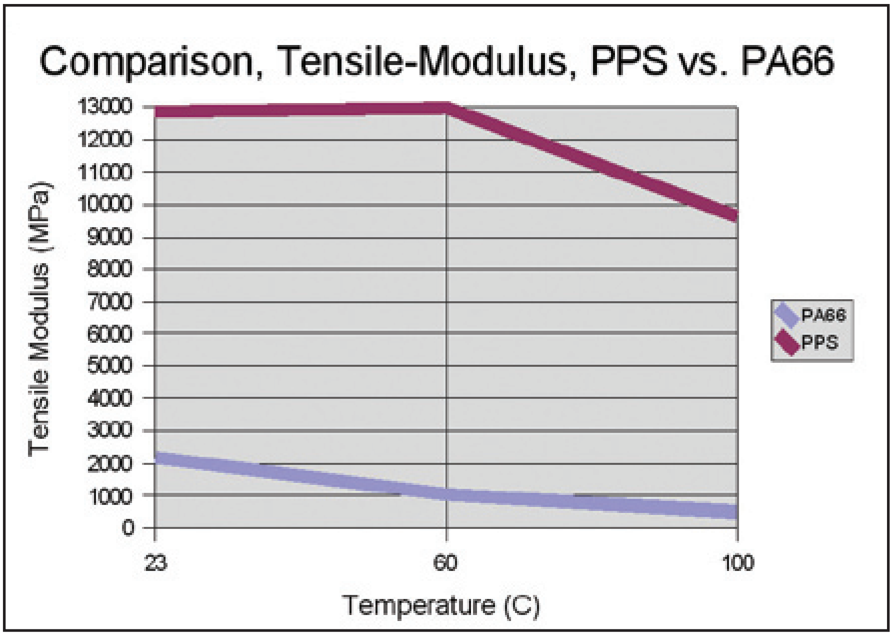


Figure 1—Comparison of tensile modulus for one grade of PA66 versus one grade of PPS resin. Note the changes in material behaviors as the temperature increases. This shift in performance with temperature is not captured by the single-point data in Table II. Resin grades were selected for maximum contrast and represent only one attribute. Do not use for general engineering purposes, as these data reflect only a range of values obtained in a specific series of testing at GE for specific grades (PPS = GE's LNP Lubricomp OFL-4036 specialty compound; PA66 = GE's LNP Lubriloy R specialty compound).

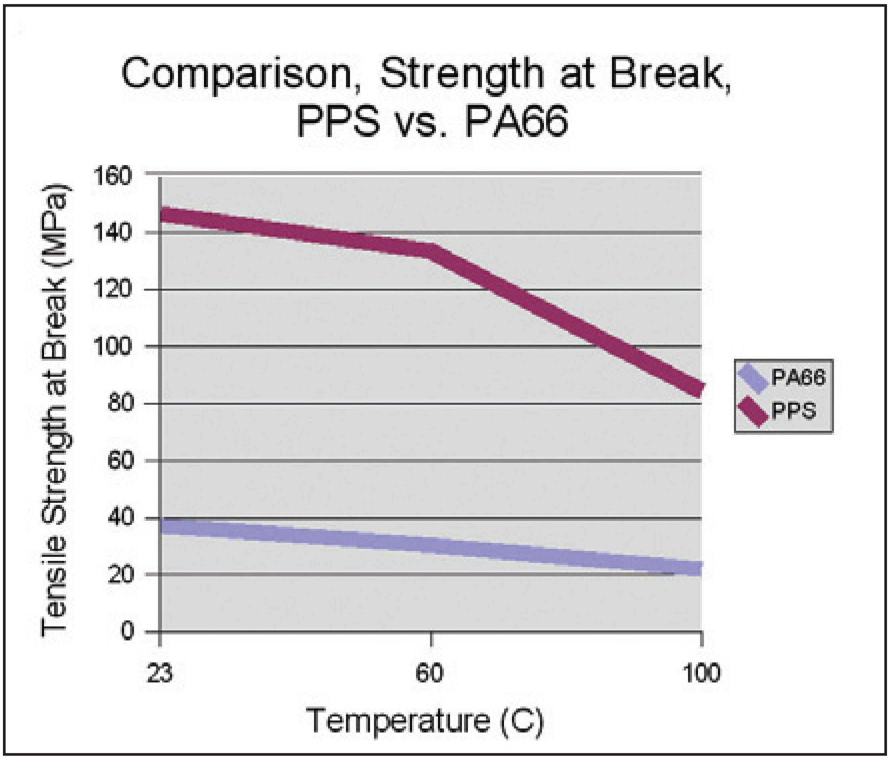


Figure 2—Comparison of tensile strength for the same grades of PA66 and PPS in Figure 1. Again, note the fact that these dynamic data capture differences in material properties for each resin grade versus temperature, similar to Figure 1. Single-point data at room temperature would not convey the shift in performance with temperature change. Resin grades were selected for maximum contrast and represent only one attribute. Do not use for general engineering purposes, as these data reflect only a range of values obtained in a specific series of testing at GE for specific grades.

Figure 3—Gear with broken teeth.

Figure 4—Gear with melted teeth.

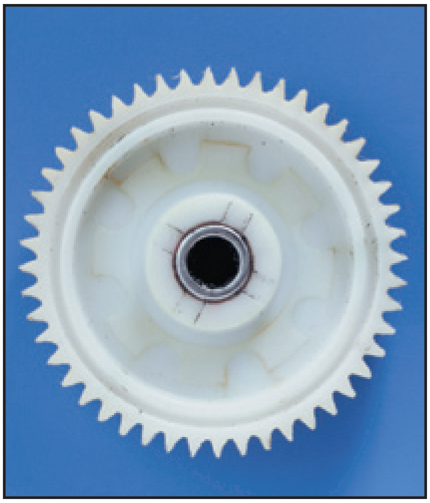


Figure 5—Thinned gear teeth.

Load Carrying Capability
(Bending Stress)

When evaluating the load carrying capability of a gear tooth, it is useful to know a material's strength characteristics. Even though the applied load is bending the tooth, the primary stress is on the side of the tooth in tension, and this is the location of most tooth failures due to overload (Fig. 3). For this reason we suggest looking at tensile strength and modulus as opposed to flexural strength. Tensile strength tests can be run at a variety of temperatures and can reveal information on a material's strength and ductility (toughness).

To assess the effect of the repeated nature of the load application in a gear set, some form of fatigue data is important. Flexural fatigue is a common test, but tensile fatigue testing can also be useful. Flexural fatigue testing requires a unique sample configuration, but the current ASTM standard (D671-93) has been withdrawn by ASTM and has not been replaced. Tensile fatigue tests can be run on the same type of sample used for other tensile tests, and tensile fatigue testing also better mimics the stress application seen in a one-directional gear-on-gear wear test currently being run by GE Plastics. Fatigue failures in gears can look like overload failures (tooth breakage at root), or can lead to thermal failures as the repeated flexing of the tooth leads to hysteresis heating and material flow (Fig. 4).

While it's typical to consider the cyclic nature of gear loading in most applications, many applications require the gear to hold a load in a fixed position for some period of time. In these situations it will be important to understand the material's creep performance—that is, its tendency toward permanent deformation. Under constant load, thermoplastic materials will exhibit varying degrees of permanent deformation, dependent on applied loading, resin type and reinforcement type. If, in a particular application, a gear is holding a load (that is, the teeth are under constant load), the teeth under load could deform permanently, potentially leading to increased noise, loss of conjugate action or outright tooth failure due to interference.

Figure 6—Tensile strength vs. temperature.	
Rationale	The physical properties of thermoplastics typically vary with temperature, so it is appropriate to test a target material across a range of temperatures that will be encountered in a given application.
Test Method	ASTM D638. Under controlled thermal conditions, the test specimen is pulled until it breaks. By measuring the force required to break the specimen, as well as the distance it stretches before breaking, this test produces a stress-strain diagram that is used to determine tensile strength, elongation and tensile modulus.
Representative Data	See Figures 1 and 2, above

Wear Behavior

Tribological factors are highly important in all gear applications. A material's wear and friction characteristics are important to understand, because they can affect such critical factors as gear tooth life, tooth mesh and backlash, noise generation, and gear train efficiency. Self-lubricating properties and enhanced wear resistance are primary reasons that many designers switch to plastic gears. Consequently, the wear factor and coefficient of friction of a given resin are key properties to understand.

Even if the material data suggest that a particular material is strong enough to carry the applied load for the number of cycles expected in the application, another concern is wear of the gear set. The removal of material from the active flank of a gear tooth can dramatically limit the life of the gear, since a thinner tooth may not support the design load of the application (Fig. 5). Wear behavior is influenced by the materials/fillers used in the gear pair, environmental conditions and contaminants, and the load condition of the application.

Two different tests have been used to characterize the wear performance of gears. Traditional wear testing is done on a thrust washer wear configuration, which places the raised edge of a rotating disc (moving sample) in contact with another material (stationary counterface). The volume of material lost during the test is recorded, and a wear factor is calculated for both the moving and stationary sample. Measurements of coefficient of friction can also be made during the test.

Versions of this test have been widely used to determine if a particular material pair “wears well” or not. Failures can be characterized as a large loss of material (high wear) or a thermal failure (material flow, “PV” or pressure-velocity failure) due to frictional heat generation.

A new type of wear test using actual molded gears has also been developed. In this test two molded gears are run together at a predetermined speed and load. Any loss of material from the face of the gears is detected as a shift in the phase angle between the driving and driven gear shafts. This phase shift is expressed as a linear value and charted against the time the gear set is running. This wear value is a combination of the loss of material from the gear tooth and any additional deflection caused by the tooth thinning or increased flank temperatures. Some might describe the value as an increase in backlash, but backlash has a specific definition in gearing that doesn’t fit this value. This same test can be used to generate fatigue curves (S-N) for a set of gears by simply running the gears at a series of loads/speeds and plotting the curves vs. cycles. Tooth wear as a factor in failure must be included. Similar tests are being adopted by the industry for application testing and validation.

Dimensional Stability

Even the best-designed gear set that uses an appropriate material for the strength and wear requirements of the application can fail if the gears cannot be held at the proper operational center distance. Two aspects of thermoplastics that can make this a challenge are changes in the size of the gear due to temperature change and moisture absorption. For most materials the thermal component will overshadow any growth due to moisture absorption. A gear designer needs to consider the gear mesh not only at a maximum and minimum material condition (as a result of runout in the finished gear), but also at those conditions as influenced by the maximum and minimum temperature in the application. Multi-point coefficient of thermal expansion data can be consulted to evaluate this effect.

Figures 6–12 discuss the testing of different gear-related parameters. In each figure, you will find (a) the rationale for considering a parameter as important to

Figure 7—Tensile fatigue.

Rationale	Fatigue tests for thermoplastics simulate cyclic loading conditions that lead to fatigue failure. These tests can be important in characterizing a material’s response in use. This test is useful because it can provide insight into a material’s performance under load conditions similar to what gear teeth see in operation. Standardized tests exist for both flexural fatigue and tensile fatigue.
Test Method	Specimens are strained under a given load at a specific frequency, generally one that does not heat the specimen. The specimen may be loaded with a strain-controlled configuration that could result in reduced stress if elongation or yielding occurs. The applied load is the same on the first loading cycle as on the last cycle.
Representative Data	Tensile fatigue of a PPO-based compound at 23°C, 24 percent relative humidity (GE’s LNP Lubriloy Z specialty compound). There was no break at the 15 MPa stress level over 1.000.E+06 cycles.

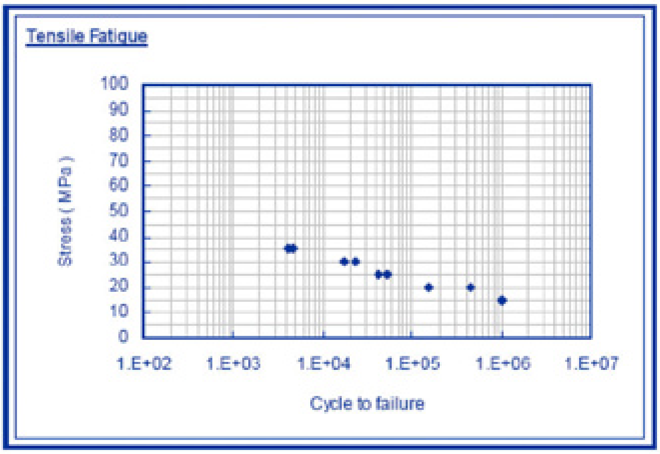


Figure 8—Tensile creep.

Rationale	Under constant load, thermoplastic materials will exhibit varying degrees of permanent deformation. This is dependent on applied loading, resin type and reinforcement type. This can be important when gears are expected to support a load for a period of time in a static position and then resume rotational operation at a later time.
Test Method	ISO 899-1. This is a method for determining the tensile creep of plastics in the form of standard test specimens under specified pretreatment conditions of time, temperature, and humidity.
Representative Data	Tensile creep of a flame-retardant polycarbonate resin grade (GE’s LNP Lubriloy D-FR non-chlorinated, non-brominated flame-retardant system specialty compound), at 23°C and 60°C.

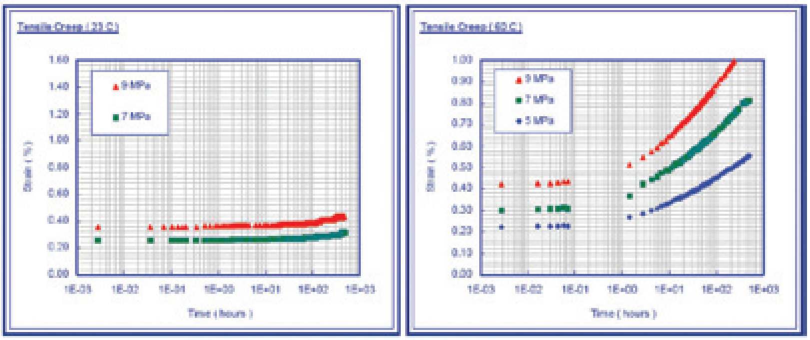


Figure 9—Wear factor.	
Test Method	Proprietary test developed by GE LNP Specialty Compounds. In this test, the plastic test sample rotates against a stationary counter face. Any pair of materials can be evaluated; however, the standard test is the thermoplastic compound of interest on 1141 cold rolled steel with a 12–16 μin finish. The weight loss of the plastic sample is converted to volume wear (W), and (W) is then used to calculate wear factor (K).
Representative Data	See Table III

Table III—Representative resin wear factor K and COF (coefficient of friction, static & dynamic) versus steel and unmodified POM. K factor is determined at 40 psi moving 50 ft./min; unit is 10^{-10} in^5-min/ft-lb-hr.

Specialty Compound Tested[1]	Wear factor (K_{moving}) at 40 psi, 50 fpm	Wear Factor ($K_{stationary}$) at 40 psi, 50 fpm	Static COF at 40 psi, 50 fpm	Dynamic COF at 40 psi, 5 0 fpm
PC[1] vs. Steel Vs. POM	60 16	0 40	0.09 0.17	0.16 0.19
POM vs. Steel Vs. POM	10 (failed)	0 (failed)	0.24 0.16	0.38 0.13
PPS vs. Steel Vs. POM	33 3	10 73	0.35 0.36	0.44 0.46
PEI vs. Steel Vs. POM	124 (failed)	3 (failed)	0.11 0.32	0.17 0.26

[1] This table reports data for the following LNP Specialty Compound resin grades: PC = GE's Lubriloy D specialty compound; POM = Lubriloy K specialty compound; PPS = Lubricomp OFL-4036 specialty compound; PEI = Ultem 4001 specialty compound.

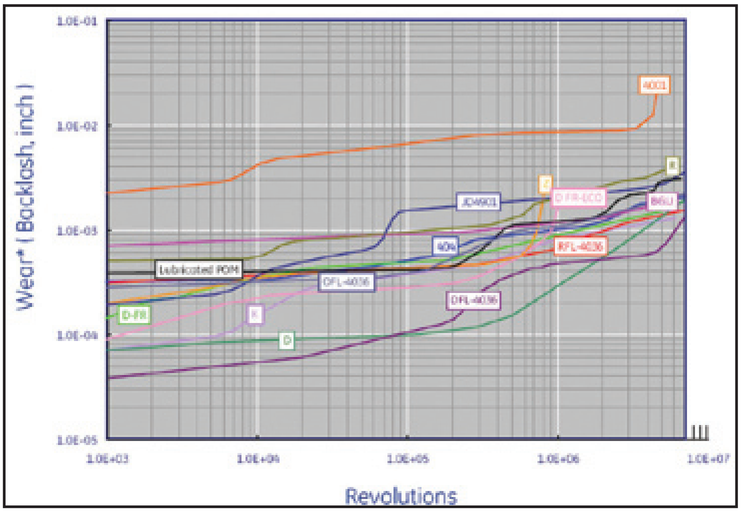
gears; (b) the test method; and (c) representative data. The data are necessarily representative because space limitations preclude inclusion of all data gathered to date for all compounds evaluated.

Dimensional Accuracy

Typically, the mold shrinkage values given for a material have been determined by measuring the shrinkage of a 5" x 1/2" x 1/8" rectangular bar measured in accordance with ASTM D-955 test methods, or a 60 mm x 60 mm x 2 mm plaque for ISO 294 test methods. These values are usually given corresponding to the dimensions that are parallel (flow) and perpendicular (transverse) to the direction of melt flow in the part. They are normally expressed as "inch/inch" or sometimes as a percentage. These mold shrinkage values can be useful in comparing the relative shrink rate of one material to another, but they should not be treated as absolutes. Mold shrinkage can and will vary with part thickness, mold layout, processing variations, and mold temperature.

Of greater value is mold shrinkage data collected on an actual part, whether it is a simple prototype mold or a similar application. It was this approach that was

Figure 10—Actual gear wear.	
Rationale	A material's wear and friction characteristics are important to understand, because they can affect critical factors such as gear tooth life, tooth mesh and backlash, noise generation, and train efficiency. Self-lubricating properties and enhanced wear resistance are primary reasons that many designers switch to plastic gears. Consequently, the wear factor and coefficient of friction of a given resin are key properties to understand.
Test Method	Proprietary test developed by GE LNP Specialty Compounds. In this test, two mated gears are rotated by a servo motor connected to the drive gear. The gears are run at 509 rpm at 22.2 inch-pounds torque until failure or 10^6 cycles.
Representative Data	Actual gear wear of selected resin grades. Seven grades show less wear than standard lubricated POM (dark gray line). Three exhibit greater wear. The wear value shown reflects a change in the tooth thickness of the tested pair.



used to study the effect internal lubricants and reinforcements have on the overall accuracy of a gear. A series of gear cavities based on a common spur gear geometry was created to mold a range of materials. The molded sample gears were then used to study how material composition affects dimensional parameters, including:

- Warpage
- Eccentricity
- Radial composite error
- Profile and helix deviation
- Pitch deviation

Specific data are not supplied here, because the range of conditions and results generated are both too extensive for presentation and are beyond the scope of this article.

Your Design Methodology

Key to specifying materials for gear applications is a full understanding of material properties in the conditions that the gear train will see in use. The availability of multipoint data is crucial for this engineering process. As a specifier, you will be best served by working with materials experts who can provide a rich dataset—one that captures performance across the full range of end-use environments—and, further, can work with both design and manufacturing to refine the selections from a universe of outstanding material candidates.

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Figure 11—High shear viscosity.

Rationale	The screw in the barrel of an injection molding machine can create high shear as it turns, as can high pressure flow through runners and cavities in the molds themselves. This test is important for determining a variety of processing parameters.
Test Method	In this test, a capillary rheometer measures the viscosity of the resin under high shear rate conditions (>100 sec^{-1}). The material is kept at a constant temperature in the barrel as it is pushed by a piston through a capillary die at various rates of shear. The test is performed over a range of temperatures and shear rates that correspond to typical processing conditions.
Representative Data	Example of high shear viscosity data (fire retardant polycarbonate, GE's LNP Lubriloy D-FR non-chlorinated, non-brominated flame retardant system specialty compound) at three temperatures: 265, 280 and 295°C).

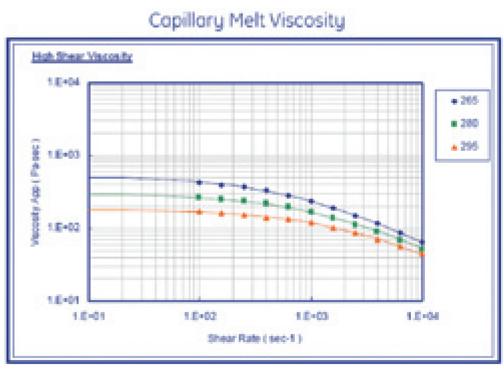

Figure 12—Coefficient of thermal expansion (CTE).

Rationale	CTE helps predict dimensional changes as a result of changes in temperature. Dimensional changes are measured in two directions, one in the flow of the resin during molding and the second across or perpendicular to that flow. The reason is that many thermoplastics, especially thermoplastics filled, for example, with glass fiber reinforcement (in which the fibers tend to align themselves along the axis of flow), can exhibit differing dimensional changes in the flow and across-the-flow directions.
Test Method	ASTM E831. In a furnace or temperature bath, a test specimen is measured at room temperature and across a specified range of temperatures, with a soaking period at each temperature of interest. The results are then graphed.
Representative Data	Coefficient of thermal expansion for a grade of PEI-based compound, measured with the flow and cross-flow ("X-flow"). Compound grade is GE's Lubricomp BGU specialty compound.