

## Using and Specifying Plastic Gears

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### Abstract

For mechanical engineers, plastic gears are a powerful means of cutting drive-cost, weight, noise and wear. Plastic gears also open new opportunities for smaller, more efficient transmissions in many products. What are the payoffs when using plastic gears in place of metal? Where do they make most sense? How are they specified, and which plastics are best? These questions are timely as more engineers turn to plastic gears in higher-power, high-precision applications.

Some current examples illustrate the possibilities:

When Maytag engineers designed their new washer transmission around plastic gears, they effectively eliminated the noise of steel gears; saved 13 pounds and did away with 42 parts compared with a previous metal gearbox (See Figure 1). Gears injection-molded from unfilled and fiberglass-reinforced Celcon® acetal copolymer maintain their strength and tight tolerances even in an oil-bath transmission. They also demonstrate the long-term durability essential in an appliance expected to have a long service life.



**Figure 1.** The pioneering dual drive washer transmission from Maytag uses spur gears molded in Celcon copolymer.

Hewlett-Packard and molder UFE took plastic gears to new standards of manufacturing quality in the DeskJet 660 color printer (Figure 2). Acetal copolymer cluster gears were specified to comply with the high-quality standards of AGMA (American Gear Manufacturers Association) Quality Class Q9. The accuracy was necessary for precise paper movement to prevent “banding” – obvious skipped lines or overprinting. For 48-pitch gears, 1.25 inches in diameter, AGMA Class Q9 denotes Total Cumulative Error (TCE) of just 0.0015 inch, and Tooth-To-Tooth (TTT) error of 0.00071 inch.



**Figure 2.** Hewlett-Packard took plastic gears to AGMA class Q9 quality standards to give its new color printer precise paper motion.

To improve the reliability of the “World Washer” manufactured in several countries, Whirlpool Corporation introduced a splined clutch or “splutch,” containing a spline and gears molded in acetal copolymer (Figure 3). The low-wear epicyclic gear assembly lasts four-times the projected life of the washing machine with a 20% reduction in the number of moving parts when compared with earlier designs using metal gears.

Gears are critical, complex drive components that directly affect function and reliability. Engineers must therefore understand both the potential and the pitfalls of plastics, to get the most from them in gearing applications.



**Figure 3.** The Whirlpool “splutch” used molded plastic gears of Celcon and extend the life of the World Washer.

## 1. Introduction

Injection molded plastic gears have come a long way. Historically, they were limited to very low power transmissions such as clocks, printers and lawn sprinklers. Today's stronger, more consistent engineering polymers, and better control of the molding process, now make it possible to produce larger, more precise gears that are compatible with higher horsepower. For example, Whirlpool enhanced a 3/4 hp drive for another washing machine with a spin gear molded in fiberglass reinforced acetal copolymer. The molded plastic gear cost about a fifth of what the original machined metal gear cost and reduced the weight of the drive.

As the experience base with plastic gears has grown, computer aided design tools have advanced. For instance, CAD software can now optimize plastic gear designs based on temperature, moisture pickup and other environmental factors. Celanese developed P-GEAR, the Plastic Gear Evaluation and Research tester, specifically to gear resins in different service environments. The new data will allow design engineers to more accurately predict gear performance. Better predictions mean faster, shorter design cycles since the development phase may be approached with greater confidence.

## 2. Injection Molded Plastic Gears

Typically, gears are a means of positively transmitting uniform motion with constant drive ratios. Thermoplastic and thermosetting polymers have long provided alternatives to metals in low-powered, unlubricated geartrains. Gears machined from phenolics and other thermosets can be used at higher operating temperatures, and they are more resistant to lubricants that are generally

required. However, injection molded thermoplastic gears have better fatigue performance, and unlike those manufactured from thermosets, can cut manufacturing costs significantly compared with metal gears. Thermoplastics are now finding their way into applications demanding lubricated drives, higher horsepower and higher AGMA quality standards.

For drive designers, thermoplastic gears offer multiple advantages over metal and thermosets. They enabled the maker of a gearmotor drive for a convalescent bed to eliminate powder metal gears and reduce parts count from three to two. The acetal gears reduced noise, improved durability and cut total drive costs by one-third when compared with the original design.

Injection molding is fast and economical compared with hobbing teeth in metal blanks. Plastic gears usually can be used as-molded and require no finishing. Consequently, they have a significant cost advantage in production quantities. The cost of plastic alternatives can be one-half to one-tenth that of stamped, machined or powder metal gears, depending on the manufacturing technique. For example, the manufacturer of a damper actuator for heating, ventilating and air-conditioning systems calculated that 14 acetal copolymer gears in the geartrain cost half as much as comparable metal gearing (Fig. 4).



**Figure 4.** Plastic gears molded from Celcon® acetal copolymer made an HVAC actuator quieter and less expensive.

Plastic gears are also inherently lighter than metal. The specific gravity of steel is 7.85, while the specific gravities of glass-reinforced nylon 6/6 and low-wear acetal copolymer are close to 1.4. Differences in specific gravity alone, however, are not direct indicators of weight saving. For example, to transmit the same power, plastic gears must usually be larger than metal gears. However, once tradeoffs in size and power are made, plastics can lend

themselves to smaller, lighter drivetrains as well as innovative gear designs that may not be possible in metal. One case is split-path planetary drives that are rarely considered by designers because they demand greater numbers of expensive metal gears. With inexpensive plastic gears, compact, split-path transmissions can actually be less costly than with multi-stage, single-branch spur drives.

### 3. Quiet and Smooth Performance

Plastic gears are less prone to corrosion than typical metal gears, and have inherently low coefficients of friction to minimize wear. Lower friction also means less horsepower wasted in heat. Maytag estimates its cooler-running plastic transmission reduced heat rise by 10 to 15% when compared with previous metal drivetrains. Greater efficiency can be important in light of anticipated future US Department of Energy standards for appliances.

Plastic gears provide the opportunity to cut drive noise by reducing dynamic loading. Gear misalignment and small tooth errors create tiny impacts resulting in running noise. However, lower modulus plastic gear teeth deform to compensate for the inaccuracies, and their softer material absorbs impacts, often making plastic gears quieter than more costly metal gears that are one or two AGMA classes higher in quality. In the home healthcare bed mentioned earlier, acetal gears reduced operating noise significantly.

### 4. Design Flexibility

The most powerful advantages of plastic gears may be the design opportunities they afford. Gear geometries overlooked by designers accustomed to metal are often easy to mold in plastic, and they can reduce drive size, weight and cost. For example, a common arrangement of two external spur gears with a large ratio demands a wide center distance. However, the same ratio can be achieved in a smaller space by replacing an external gear with an internal gear that, while tough to machine in metal, is easy to mold in plastic.

Low-cost, low-wear plastic gears may also allow designers to reconsider the axiom: The Fewer Parts, The Better. Split power paths in parallel or non-parallel axis drives can indeed have more parts, but they afford advantages in space, weight, efficiency and cost. Plastic gears impose no special restrictions on gear ratios, and the required accuracy can be achieved with today's molding machines and materials.

The higher the performance requirements for the drive, the more complicated the up-front design effort required to make plastic gears work. The state-of-the-gear-art has advanced to where plastic gears are now in drives ranging from 1/4 to 3/4 hp. Future applications may take them between 1 and 10 hp in the near-term and up to 30 hp in the long-term.

Horsepower limits for plastic gears vary with the polymer, depending upon the modulus, strength, wear and creep characteristics that change with temperature. Nevertheless, plastic gear limits can be defined in terms of contact stress, velocity and temperature for dry running gears. For lubricated gears, fatigue strength and temperature are the critical issues.

Plastic geartrains are generally built around involute gear technology. This system is very forgiving of the center distance shifts inherent to plastic gears. Conversely, plastic gears are not satisfactory in non-involute systems that are center-distance sensitive. In particular, many non-parallel axis systems are not based on involute technology and are difficult to manufacture with plastic gears.

Bevel gears are an exception as they are non-involute but often made of plastics. The low modulus of plastics makes them relatively forgiving of the alignment and manufacturing errors that are inherent in mass-produced bevel gears. Crossed axis helical worm gears that make point-contact when new are good candidates for plastic at low loads. Their capacity is increased by initial wear that produces a line contact. Involute face gears have a line contact and are preferred to worm drives at higher power levels.

### 5. Lubricated versus Unlubricated

In the past, plastic gear applications were typically ircooled, either unlubricated or greased. As engineering resins now move into drives with higher horsepower and greater precision, the drive designer faces the choice of oil- or grease-lubricated or unlubricated gearboxes. The decision to lubricate or not lubricate, and the choice of a lubricant, are key factors for the drive designer to consider.

For plastic gears running in an oil bath, the oil facilitates removal of frictional heat and allows higher load capacity. Unlubricated and greased gears are aerodynamically cooled and therefore run hotter with lower load capacity. Unlubricated gearsets are often molded in different materials for reduced coefficient of friction (COF). Acetal copolymer is often mated with nylon 6/6 or polybutylene terephthalate (PBT). The combinations have much lower COFs than any of these materials working against themselves. Unlubricated plastic gears often have lubricants such as PTFE, silicone or graphite compounded into the polymer. While these additives reduce friction, the COF is still higher than that of greased gears.

Generally, the load capacity and life of lubricated plastic gears is governed by bending fatigue at the tooth root. Unlubricated gears, which run hottest with the lowest load capacity, often fail by wear or overheating on the tooth flanks.



Greased gears will occasionally fail by wear if the grease does not stay in the mesh.

While engineering resins can resist oils and greases, lubricants must be carefully chosen because some can cause dramatic changes in gear properties and dimensions. For example, extreme pressure oils are unnecessary with the low contact pressures found in plastic gearing, and some can chemically attack plastics. Likewise, the choice of resin for the application is important. PTFE and other low-friction additives compounded in the material of plastic gears may have little or negative value, if the gears are oiled or greased.

Plastic gears also lend themselves to applications where grease or oil is unacceptable, such as food processors or computer printers. Without the need to seal a gear box housing, unlubricated gearboxes are generally far less expensive than those designed to contain grease or oil. While unlubricated gears simplify transmissions, plastic gears can nonetheless operate with and benefit from lubricants when necessary. Whirlpool Corp. incorporated a plastic helical spin gear in the Design 2000 washer and the fiberglass-reinforced acetal copolymer gears maintained tensile and impact strength in SAE60 oil.

Oil bath or grease lubrication enables drive designers to exploit the added strength of glass-reinforced plastic gears without excessive wear. A major automotive supplier, for instance, eliminated squeaks and wear in motorized car seats by replacing metal seat adjuster gears with those molded in acetal copolymer compatible with lubricants.

Self-lubricating plastic gears also lend themselves to geartrains where the use of grease must be avoided such as the Hewlett-Packard printer or K'Nex motorized toy where oil or grease leaks cannot be tolerated.

## 6. Application Requirements

Horsepower limits for plastic gears vary with the resin, depending upon the modulus, strength, and creep characteristics which all change with temperature. Nevertheless, plastic gear limits can be defined, in terms of contact stress, velocity and temperature for dry running gears. For lubricated gears, fatigue strength and temperatures are the critical issues.

Plastics are naturally more prone to dimensional creep than metal, and creep in plastic gears depends on duty cycle and temperature. Consequently, molded gears are best used in applications without static loads. If static loads cannot be avoided, plastic gears must be designed to operate properly after teeth have deflected due to creep.

The operating speed of plastic gears obviously impacts operating temperature. However, rapid-loading rates can also affect material properties. For some materials, the faster a tooth is loaded, the higher the effective modulus and strength. Higher temperature reduces the modulus and strength of most plastics and accelerates creep. These effects must be considered in the design process, and studies to quantify them are just beginning.

Gear load analysis is complicated, regardless of gear material, and gear design remains an area of special expertise. Gears also usually demand more precision than commonly molded parts, so their tooling can be expensive. A good plastic gear design, however, saves money in reducing trial-and-error mold iterations. For the project engineer, building a drive with plastic gears ideally should start with a team including a gear designer, molder, tool builder and resin supplier, all experienced with gears.

The team needs the most complete application information available to create the most detailed gear specification possible. Ambient temperature, lubrication and duty cycle impact gear life and drive performance. A housing material that matches the thermal and moisture expansion of plastic gears can help maintain precise center distances. However, plastic housings cannot dissipate heat as well as metal. Gear swelling due to moisture absorption in some resins can also stall tight-meshed gears. CAD tools can help designers allow for worst-case tolerances. Universal Technical Systems in Rockford, IL, is one supplier of such CAD tools.

## 7. Design

Gear resin selection requires the appliance designer to focus on resin performance at the high end of the operating temperature range planned for the drive. However, higher temperatures lower both the modulus and strength of gear resins. They increase creep rate and introduce thermal expansion into precision parts. Fortunately, the temperature response of engineering resins is well understood, allowing designers to predict the effect on their gears. The advantages of plastic gears are becoming more obvious as major manufacturers look to cut cost and increase reliability. Along with a range of compatible engineering resins, there is also ample expertise available about the design and manufacture of plastic gears. With the right material and some help, designers can realize the powerful potential of plastic gears in a wider range of appliances. Plastics also change the rules of gear and drive design. The designer of a metal pinion gear would normally limit the aspect ratio to one or less. With plastics, an aspect ratio of two or three may be acceptable as full tooth contact may be achieved.

Plastic gears can require tip relief unnecessary in metal gears. The lower mesh stiffness of plastic teeth requires more backlash than found in metal gears. A Hunting Ratio considered desirable in many metal gear trains to equalize wear may accelerate wear with plastic gears. The guidelines for metal gear design must be examined carefully before applying them to plastic gears. Rack tooth form remains a convenient way to define and generate gear teeth in metal or plastic. Standard metal gear profiles can provide a starting point for plastic gears, although there are some plastic profiles that are preferred. The most common profile systems is described in ANSI/AGMA 1006-A97, "Tooth Proportions For Plastic Gears." Most profiles are based on a 20 degree pressure angle and a working depth of two over the diametral pitch or two-times the module. However, standard tooth profiles are a starting point for plastic gears. The profile needs to be optimized for a material with a lower modulus, greater temperature sensitivity and different coefficients of friction and wear than metal. Plastic gears commonly have greater working depths than metal gears, sometimes up to 35% greater. This allows for variations in effective center distance due to thermal, chemical and moisture expansion. The designer of plastic gears should strive for a full root radius to not only reduce stresses at the root but also to enhance resin flow into the teeth during injection molding that reduces molded-in stresses and more uniformly removes heat from the plastic during solidification resulting in a more stable geometry.

Designers of plastic gears should also pay special attention to shaft attachment. Bore tolerances naturally impact true center distances, sometimes resulting in loss of proper gear action. A simple press-fit demands extra molding precision for a secure mount without over-stressing the plastic. A press-fit knurled or splined shaft can transfer more torque but also puts more stress on the gear hub. Insert-molded hubs grip better but during molding, as the plastic shrinks onto the shaft, they can induce residual stresses. Ultrasonic insertion of a knurled shaft produces the lowest residual stresses. In some cases, a single- or double-D keyed shaft prevents slippage and minimizes distortion with assembly. However, if torque is high, these can become loose. For high torque applications, splined assemblies are preferred.

## 8. Plastic Selection

A fundamental misconception in plastic gear design is that, whatever the resin, "It's just plastic." The choice of a gear resin demands careful study. Inexpensive commodity resins generally lack the fatigue life, temperature resistance, lubricant resistance, and dimensional stability required for quality plastic gears in all but the most primitive applications.

However, many of today's engineering resins provide the necessary performance for working gear trains. They also have the consistent melt viscosity, additive concentrations and other qualities essential to consistent, accurate molding.

It is generally easier to mold high-quality gears with resin containing minimal additives than with highly filled blends. The specifier should call for only as much glass or mineral filler or lubricant additives as is actually needed. If external lubrication is required, the drive designer, resin supplier and lubricant supplier should work together to select an appropriate lubrication system.

Crystalline resins generally have better fatigue resistance than amorphous plastics, and most gear applications have utilized the crystalline resins, nylon and acetal. Nylon 6/6 was used successfully, for example, in a lawn mower cam gear. Nylon, both with and without glass reinforcement, continues to serve in many gear and housing applications. Acetal copolymer provides long-term dimensional stability and exceptional fatigue and chemical resistance over a broad temperature range.

Other resins have found limited gear success. ABS has good dimensional stability and low shrink out of the mold, but its fatigue characteristics make it suitable for only lightly loaded gears and short service life. Liquid Crystal Polymer (LCP) has exceptional dimensional stability and fills the most intricate molds. To date, LCP has been used for only small precision gears under light loads, such as tiny wristwatch gears.

Linear polyphenylene sulfide (PPS) has exceptional temperature and chemical resistance and good fatigue life. It has been effective in other highly loaded parts molded with fine details and should prove to be a high performance gear material. Spur gears molded in PTFE lubricated linear PPS were incorporated in an automotive steering column where their coefficient of thermal expansion matches that of surrounding diecast parts. As plastic gears move into higher loads with larger gears in lubricated environments, the improved fatigue resistance, dimensional stability and high-impact strength of longfiber reinforced thermoplastics (LFRT) should make these materials leading gear candidates.

## 9. Injection Molding

For the gear molder, uniform mold flow and cooling is essential to the fabrication of accurate gears. Uniform cooling from cavity to cavity is also critical for consistent quality gears. A single-cavity mold is the best approach for precision gears, but it is rarely cost-effective for production. Multi-cavity molds can create minor differences in flow patterns and major variations from part to part.

The more mold cavities, the greater the potential variation. Four cavities are generally the maximum allowable for molding precision gears.

Three-plate tooling with small pin gates on the gear web is common for molding most small gears. However, larger gears with heavier teeth can require center diaphragm gating for better dimensional control and higher quality. Whatever the mold, gear teeth should be cut in an insert, not integral to the mold cavity. Gear designers and molders are almost guaranteed to replace the tooth profile once or twice in the gear prototyping evolution to get it right. Interchangeable ring inserts make it faster and less expensive to refine the tooth profile.

Gear resin selection requires the designer to focus on resin performance at the high end of the operating temperature range planned for the drive. Heat deflection temperatures for engineering resins range from 170°F for unfilled nylon and 230°F for acetal copolymer to 500°F for reinforced linear PPS at 264 psi. However, higher temperatures can lower the modulus and strength of gear resins. They increase creep rate and introduce thermal expansion into precision parts. Fortunately, the temperature response of engineering resins is well understood, allowing designers to predict the effect on their gears.

The initial engineering effort to design plastic gears is greater than that required with metals, if only to cope with changing properties and dimensions. The most common errors of plastic gear designers start with insufficient application specifications. The specifics of the application must be factored into detailed drawings before prototyping. The detailed drawings must contain sufficient information to manufacture the gear. The accompanying table (Figure 5) is an example of the detailed specifications for a plastic spur gear.

Problems with prototypes can also tempt gear designers to change resins -- a costly mistake given the different shrink characteristics of various plastics. It is better to rework the tooth profile than switch the material, unless it is clear that the wrong material was chosen.

To avoid the pitfalls of plastic gears and to realize their potential, expertise is available from software, gear consultants and resin suppliers. With careful design and material selection, the power transmitted by plastic gears can be significant, and the potential savings enormous.

Figure 5. Typical Print Data for A Molded Spur Gear

Part No.
Mating Gear Part No.
Material
Number of Teeth
Diametral Pitch
Module
Pressure Angle
Base Pitch
Reference Pitch Diameter
Effective Tooth Thickness @ Ref PD
Face Width
Outside Diameter
Effective Outside Diameter
Roll Angle @ Effective OD
Normal Tooth Tip Radius
True Involute Form Diameter
Roll Angle @ TIF
Root Diameter
Base Diameter
Inspection Data:
AGMA Quality No.
Measured Tooth Thickness W/Pins
Size over X Pins of 0.X in. diameter
Radial Runout (TIR)
Pitch Variation
Tooth Alignment
Master Gear No.
xx Teeth -- Class 1A
Gear Test Radius
Test Load
Tooth-to-Tooth Composite
Composite Minimum Fillet Radius
Basic Generating Rack:
Flank Angle
Tip to Reference Line
Tooth Thickness at Reference
Tip Radius

## ENGINEERED MATERIALS

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### Engineered Materials

- Celanex® thermoplastic polyester (PBT)
- Hostaform® and Celcon® acetal copolymer (POM)
- Celstran®, Compel® and Factor® long fiber reinforced thermoplastic (LFRT)
- Celstran® continuous fiber reinforced thermoplastic (CFR-TP)
- Fortron® polyphenylene sulfide (PPS)
- GUR® ultra-high molecular weight polyethylene (UHMW-PE)
- Impet® thermoplastic polyester (PET)
- Riteflex® thermoplastic polyester elastomer (TPC-ET)
- Thermx® polycyclohexylene-dimethylene terephthalate (PCT)
- Vandar® thermoplastic polyester alloy (PBT)
- Vectra® and Zenite® liquid crystal polymer (LCP)

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