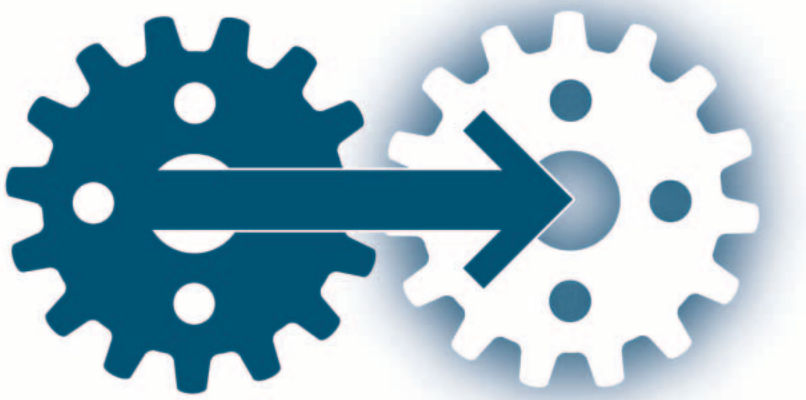
SUCCESSFUL PLASTIC GEAR CONVERSIONS



ARE YOU THINKING OF CONVERTING, BUT STILL SITTING ON THE FENCE BETWEEN METAL AND PLASTIC GEARING? THE FOLLOWING ARTICLE MAY PROVE TO BE THE TIPPING POINT TOWARD PLASTICS.

By Richard R. Kuhr

The conversion of a steel gear set to plastic is not a slam-dunk operation. A gear designer who is proficient in designing steel gears may be reluctant to dive into the design of plastic gears. The properties of plastic make it quite interesting. Nothing stays the same. Time, temperature, and humidity can change the properties of plastic materials. Size, strength, impact resistance, and deflection are all influenced.

Plastic data sheet specifications are readily available from the manufacturer or Web services. They are a good place to start the material evaluation. However, they only tell you a part of the story. They do not offer fatigue data over a range of temperatures. What is needed is actual fatigue data obtained by testing gears. Ask the material supplier and molder for assistance in material selection. Your molder may be very helpful in suggesting materials that yield the best selection based on fatigue testing, material cost, and accuracy.

There are a number of steps in the conversion process. Here are some suggestions to aid in plastic conversion success. Knowledge of how to avoid the conversion pitfalls can save valuable time and money.

Conversion Incentives

Converting to plastic gears can offer a reduction in weight, noise, and cost. There are also benefits of lubricity, chemical resistance, and shock resistance. These are powerful incentives. An awareness of property differences is necessary to avoid trouble. A robust balance between material properties and the required duty cycle is needed.

Along with the consideration of material property differences, it is prudent to consider added benefits that may be possible in the conversion process. For instance, injection molding offers the advantage of combining separate parts into one. Parts integration will reduce inventory and assembly costs. Also, other functions can be added. Using plastic in a spring function, a snap fit or a cam action may eliminate a component and enhance the function of the part. Since the molding operation produces finished parts, secondary operations are not necessary.

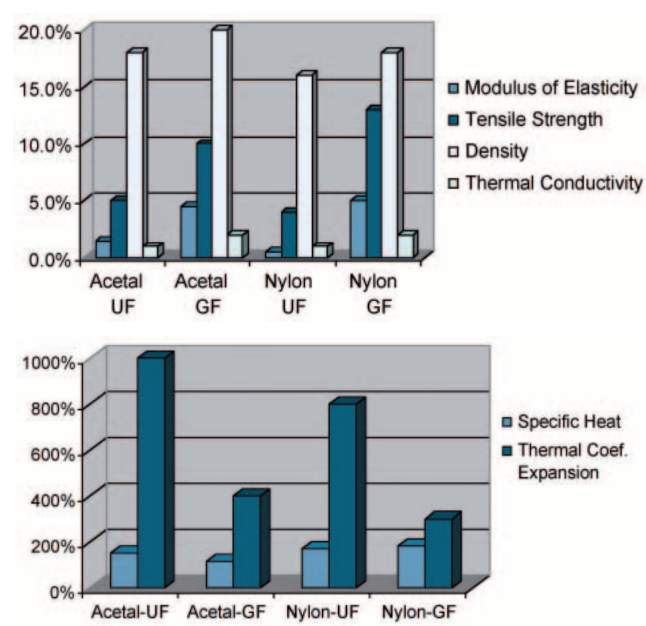
Plastic gears allow a number of lubrication options. Eliminating external lubricants is possible. This option would take advantage of the natural lubricity resulting from the mating gears molded from resins like acetal and nylon. More rigorous applications may use internal lubricants such as silicon and PTFE. External grease is commonly used and offers excellent wear resistance, even just as an initial application. These value-added options can easily justify the conversion process.

Physical Differences Abound

When considering a conversion to plastic, a new mindset is required. Just start with the assumption that everything is different and everything changes under different conditions. Not to mention that there are more than 1,000 acetal resins and 5,000 nylon resins to choose from. Consider a comparison of the basic parameters of steel and two commonly applied resins, acetal and nylon. The differences in the mechanical properties soon stand out as major design influences (Figure 1). The modulus of elasticity is less than 5 percent that of steel. The tensile strength is in the 5 to 15 percent range of steel, depending on whether the resin is unfilled or fiber filled. Glass or carbon fibers are used for filled materials.

The thermal properties also impact the design. The difference in specific heat indicates that more energy is required to heat plastic resins per unit of mass. However, the specific heat per unit of volume indicates that plastic materials will heat up three to five times more than metal for the same energy input. But the thermal conductivity is only 1 to 2 percent that of steel. That means your plastic gear teeth want to hold on to the heat that is generated in the mesh because of the lower conductivity.

Figure 1 — Plastic properties compared to steel



Heating of the teeth reduces the gear strength and increases the tooth deflection.

The coefficient of thermal expansion of plastic resins range from three to 10 times that of steel. The difference in expansion rates of the individual gears and the gear housing for plastic gears will have a greater impact on plastic gear design than that of steel gears.

Plastics differ from steel in that they are much more viscoelastic. Depending on temperature, rate of load application, time, and the resin itself, plastic will exhibit a combination of solid and liquid properties. With increasing loads plastic resins move through an elastic response followed by primary deformation, then secondary deformation, and then tertiary deformation, followed by rupture. Plastic gears are designed to operate in the elastic zone to avoid any creep response. The duty cycle should not have high sustained overloads that subject the gear teeth to creep.

The temperature effects on steel gears are usually not significant in their normal working ranges. Heat can be removed by the coolant system. However, the effect of temperature is much more pronounced in plastic resins. They are a major consideration in material selection and in design options. The chart at right (Figure 2) illustrates the range of the modifying factor that is applied to the ambient allowable bending stress. The chart is normalized to 1.0 at 23 degrees centigrade. It shows the upper and lower ranges that apply to typical acetal gear resins. Specific resins will have their unique line within this range. Other resins will have their unique factors. The temperature noted is the mesh temperature.

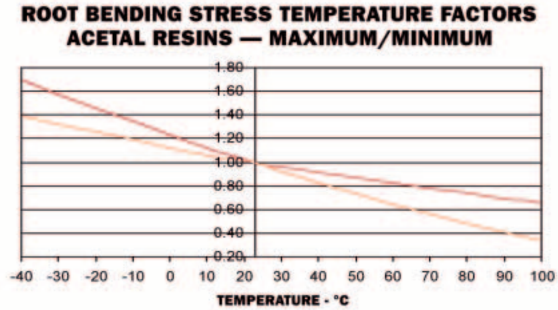


Figure 2 — Plastic properties compared to steel

Temperature is a dominant change agent. The design parameters of allowable shear stress, elastic modulus, impact resistance, and size all have their unique temperature response.

Moisture absorption also impacts these properties, especially in nylon resins. The data sheets for nylon are published under two different conditions. One is "dry as molded" and the other is "conditioned." The conditioned material has been allowed to absorb moisture in a controlled state such as 23 degrees centigrade at 50 percent relative humidity. Moisture reduces the tensile strength properties but improves the impact resistance of nylon.

Plastic Gear Design

The table at right, (Table 1) outlines a basic plastic gear design process. The American Gear Manufacturers Association offers a number of publications that aid in the design of plastic gears. The AGMA standard "Tooth Proportions for Plastic Gears" ANSI/AGMA 1006-A97 suggests four different depth options. While standard tooth forms may be used successfully, an optimized plastic gear will not have standard proportions. Non-standard depths, root and tip radii, pitch, pressure angle, and tooth thickness proportions can be combined to provide superior performance.

Design Implications

What is the effect of these physical differences? The challenge is to make sure that your design considers all the thermal and hydroscopic expansion over the temperature and humidity ranges that the gear teeth will encounter. Keep in mind that the plastic materials can be affected not only by moisture but also specific chemicals, including lubricant additives. Care must be exercised to guard against harmful interactions that would degrade material properties. Differential size changes can also affect uniform motion transmission and noise generation. It is also necessary to check the design at the extreme material conditions. This includes the minimum and maximum radial play caused by the required bore clearances.

For external gears the first extreme condition is maximum material condition at minimum effective center distance. At these extremes check for minimum backlash, root clearance, and specific sliding ratio. A specific sliding ratio less than 3.00 will reduce the heat generated in the gear mesh.

The second extreme condition is minimum material condition and maximum effective center distance. Check that the profile contact ratio is greater than 1.10. Make sure the allowable bending strength check is made at the appropriate temperature that corresponds to the extreme effective center distance.

The modulus of elasticity for plastic is from 1 to 3 percent that of steel at 23 degrees centigrade. Deflection will be a major design concern. Excessive deflection will cause base pitch errors that can lead to excessive wear and noise. In addition, the modulus changes with temperature and moisture. Different grades of plastic will have unique temperature responses. For example, the modulus of elasticity of an unfilled acetal will decrease at a slower rate than an unfilled nylon. The maximum acceptable working temperature varies with the different grades. Nylon resins can operate at a higher temperature than acetal resins.

The tensile strength of all plastic varies with the temperature and moisture content. Special attention must be given to the operating design parameters

TABLE 1 — PLASTIC GEAR DESIGN PROCESS

DEFINE THE APPLICATION	
Duty Cycle	Consider start up, running, inertia and over load conditions
Motor Specification	Calculate inertia load of rotor considering motor acceleration
Ratio required	Consult the motor curves
Space	Balance outside diameter and face width for available space
Lubrication – None, internal, grease or oil	Choose the best for the application
Temperature & Humidity Ranges	Establish realistic extremes
DEFINE THE GEAR ARRANGEMENT	
Number of Stages	Sometimes more stages are more effective
Ratio Distribution	For multiple stages target minimum total volume for the ratio distribution – Vary as space requires
Gear Type/Shaft Orientation	The gear types selected will determine the orientation
Material	Multiple material grade testing may result in savings - consult your molder
Process Capability	Be aware of the tolerance and accuracy capability of the molder. These values will determine the effective center distance
PRELIMINARY DESIGN	
Choose Gear Pitch/Pressure Angle	Start with a unit load of 5-7 MPa for unfilled and 10-12MPa for filled resins. Adjust with final design iteration as required by detailed solution
Balance Bending Fatigue - Unit Load	U Unit load(MPa) = Tangential Load(N)/(Face(mm) * Module)
OPTIMIZE	
Determine Tooth Depth	Increased depth will yield increased profile contact ratio
Determine the Profile Shift	At minimum effective center distance (External Gears) and maximum material condition keep sliding ratio < 3.0 if possible
Higher Contact Ratio Goal	Produces improved load sharing and reduced noise if gears are molded accurately
Lower Sliding Goal	Lower sliding reduces heat and abrasive wear
Extreme Conditions	Check at least material condition and maximum effective center distance (External Gears). Check contact ratio
Root and Tip Radii	Full fillet root radii are preferred for tooth strength. Generous tip radii will avoid corner contact with deflected teeth
Pitch, Pressure angle & Root Clearance	Modify as necessary to aid optimization
Bending Stress Evaluation	Check with material supplier and molder gear tested allowable stresses (Material Data Sheets do not provide practical allowable stresses)

at the maximum effective center distance and minimum material condition. The profile contact ratio will be minimum reducing load sharing. The thin teeth will have the maximum bending stress. Be sure to apply the proper temperature factors that correspond to the extremes.

Injection molded gears offer a unique design opportunity. Gear molds will be specialized and a significant investment. Prior to making that investment, the advantages of gear design optimization should be evaluated. Optimization aimed at increasing the strength and decreasing the potential for noise generation are common goals. Performance improvements of 25 percent over standard proportions are typical. The Plastic Gear Design Process summary chart (Table 1) points to the variables that lead to that optimization.

Accuracy Implications

Be prepared to take another look at the accuracy grade specified for your gears. While it is possible to mold AGMA Q12 gears, it may not be practical or necessary in the materials of your choice. It would not be uncommon to see an accuracy grade level one or two levels below the metal gear specification satisfy the conversion process. The reason is that the resiliency of plastic tends to mask errors that would be problems with metal gears.

Also note that the common inspection method in the gear molding industry is double flank composite inspection. A gear qualified as a Q12 by double flank composite inspection may well not meet that accuracy grade when measured by single flank or analytical methods.

As more and more emphasis is being placed on the reduction of noise, more attention is being paid to the advantages of analytical inspection, especially in the tool qualification and development stages.

Material selection will impact gear quality. Unfilled gears can attain higher accuracy levels and process capability values more consistently. For example, glass filled test specimen bars exhibit transverse thermal expansion rates of four to five times their axial values. This will affect part size and gear accuracy, especially helical leads. Accurate prediction of fiber orientation and tight process controls are required for consistent accuracy from cavity to cavity, and shot to shot.

Duty Cycle Effects

The definition of the duty cycle needs to take into account all the issues that relate to the material properties. For plastic gears, anything that affects temperature needs to be included. Speed, load, load duration, time between load cycles, and housing design can all cause temperature changes. Since the plastic gear teeth have more difficulty releasing heat, the accurate definition of these elements is even more important.

The lower thermal conductivity of plastic highlights the significance of whether the load is continuous or intermittent. An intermittent load cycle can allow time for the mesh temperature to decrease between cycles. Continuous cycles raise the temperature to an equilibrium condition which can be much higher than the intermittent temperature rise.

Any prescribed test cycle required for validation or approval should also allow for a temperature rise test similar to the actual duty cycle. External cooling may be required for accelerated testing. The more the test cycle exceeds the actual requirements, the more total cost is added to the solution.

Environmental Considerations

Plastic gears have more environmental influences than metal gears. In addition to the temperature effects already discussed, the moisture in the environment influences a number of material properties on nylons. For example, PA66 is hydroscopic to the point of absorbing water up to 9 percent of the gear mass. The modulus of PA66 conditioned at 23°C and 50 percent relative humidity could be half of what it is in the dry condition. There may be other external influences. Oils, greases, and other chemicals that come in contact with the gears should be checked for potential interaction.

Cost Implications

The cost reduction gained from the use of injection molded gears compared to using metal gears is one of the primary incentives associated with plastic gears. A density ratio of six to one is a major reason. Also, the injection molded contour is extremely material efficient. The cost is lowered as the number of mold cavities is increased. The use of automated part handling, including packing, further reduces the cost. Tight mold processing controls allow for reduced labor content. Although injection molds may represent a more significant initial cash outlay, the return is in the lower tooling cost per part, due to the large quantity of parts available from the mold. Also, the mold turns out a finished product with no need for any secondary operations.

A prototype tool is sometimes requested for design validation. One option that can effectively reduce time to market and total cost is the use of a pull-ahead tool. In this situation the prototype mold is made as one cavity in a mold body that can be used for the final production mold. One of the advantages is that whatever technology gain is gleaned from the prototype can quickly be applied to the production tool.

The application of total cost accountability can have a substantial payback. Often there is a rush to withhold resources on the front end of a new development. Reality points to the conclusion that the expenditure of 60 minutes of quality design effort on the front end will easily save 60 hours of trouble at the end of that development cycle.

Conclusions

The application of plastic conversions is still in the early stages of development. Power densities are rising. Accuracy is increasing. Refinements of crowning and profile modification are adding to the noise reduction goals. High temperature and high strength plastic resins are now making greater impact on the size and range of application. Thinking beyond the constraints of a "metal mentality" will yield greater innovation and added value in the future.

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