A Practical Guide for Molding Better Plastic Geared Transmissions

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Abstract

Plastic gears and transmissions require a different design approach than metal transmissions. Different tools are available to the plastic transmission designer for optimizing his geared product, and different requirements exist for inspection and testing.

This paper will present some of the new technology available to the plastic gear user, including design, mold construction, inspection, and testing of plastic gears and transmissions.

Comparing Plastic to Metal

One of the most profound differences between a molded plastic gear and its metal counterpart is the way it is made. Almost all metal gears are cut. Plastic gears are molded. The few metal gears that are not cut, i.e. powder metal and forged gears, require approaches very similar to the ones outlined here for plastic. In many ways plastic gear manufacturers are leading the industry into new levels of accuracy, design freedom and total gear inspection. With wire EDM, spur gear cavities can be cut with accuracies to 100 μ-inches. However, since this is a non-generative process, cutting errors can occur anywhere. Therefore, the entire pattern of the internal gear cavity must be inspected rather than just a few representative teeth as is usually done with metal gears. Just setting up cavities and plastic gears on inspection equipment designed for metal gears can be daunting. The molded plastic gears must also be inspected over the entire pattern since shrinkage abnormalities and molding anomalies can occur at any location. The advantage of molded gears is that any specific gear that can be drawn in CAD can usually be molded. The challenge is to measure and adjust the molded gear for its unique shrinkage and molding anomalies. Metal gear applications might someday benefit from this type of full profile inspection and comparison to the generative process.

There are other differences between plastic and metal gears. Some of these differences are due to their different methods of manufacturing. Since metal gears are cut or ground to shape, they can be expected to have highly concentric features due to the turning operation. Precision diameters are not too difficult to maintain. Shrinkage compensation is not required in their manufacture.

Plastic gears are molded. Concentricity of the bore to the tooth geometry is one of the most difficult features to maintain. Tooth geometry itself can be more precise than the average metal gear since a wire EDM generated gear cavity is inherently more accurate than a cavity made with a hob-cut electrode (Ref. 1). Also, engineering plastics tend to have high but very consistent and repeatable shrink from that cavity. This shrinkage must always be considered and compensated for in molded plastic. Diameter tolerances will almost always be greater for plastic gears than for metal.

Plastic materials are much weaker than metal, but they also have strengths not found in metal. Built in lubrication, ultra-light weight, low noise, and low cost, are all attributes of molded plastic gears.

These fundamental differences confound the traditional logic for gear design and manufacture. Gear tolerances and ratings are based on metal gear construction. These standards are not ideally

Fig. 1—A spur gear being cut by wire EDM.

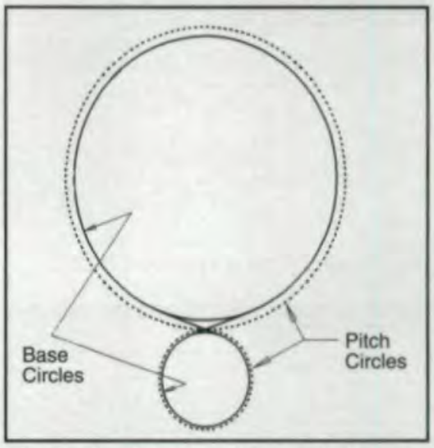

Fig. 2—Involute geared transmissions are ideally equivalent to crossed-axis belt drives.

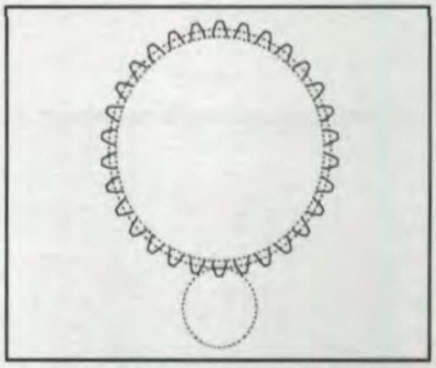

Fig. 3—Defining the tooth thickness and drawing the involute form.

Fig. 4—A partially constructed gear is rotated about the pitch circle of its mate to form the outline of the mate.

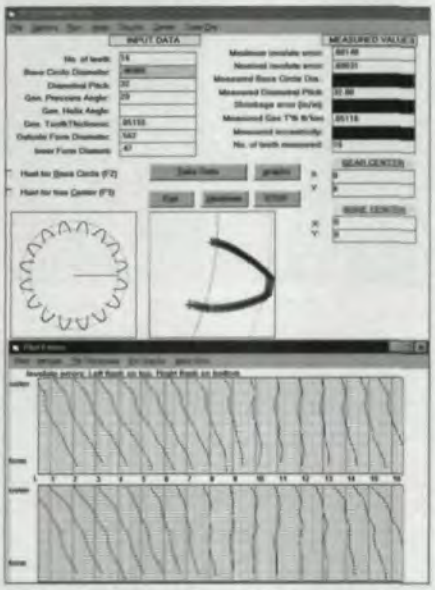

Fig. 5—Best fit inspection results.

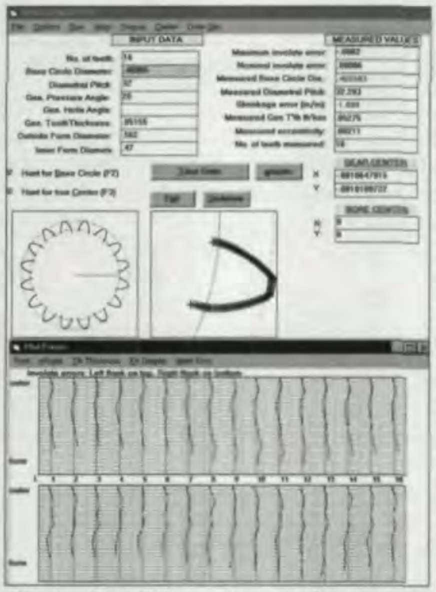

Fig. 6—Best fit inspection results, compensating for shrinkage error.

descriptive of plastic gear geometry. Design calculations are based on metal material properties and do not accurately predict plastic gear function and life. Even the plastic material properties supplied by resin vendors do not accurately define the real material parameters of a plastic gear as it is moving into and out of mesh at a high rate of speed. Traditional plastic properties are based on long term phenomena.

Designing Plastic Gears

Customarily, metal gears are designed and defined with respect to their cutting process by the basic rack method, and many plastic gear designers use a similar approach. The defined pitch circle of a metal gear describes the set-up distance with the gear to its cutting tool. Such things as addendum modification refer to additional cutting tool set-up features required to produce the desired gear shape. The 'whole depth' of a gear really refers to how far the cutter plunges into the gear blank. However, in plastics we don't need this definition scheme, and many times it only causes confusion and misinterpretation.

A great benefit of the basic rack method is that it allows families of gears to be cut that will all mesh properly with each other in any combination. However, plastic gears are usually designed for specific high-volume applications. We are trying to make as rugged a gear set as we can; therefore we waste no time trying to make these gears generally suitable for a range of applications. The approach outlined below is a method for maximizing the function for a specific transmission.

Almost all plastic spur gears these days are molded from cavities cut with wire Electrical Discharge Machining (EDM) as pictured in Figure 1. Kleiss and Hoffmann (Ref. 1) have written on the process, its application, and its accuracy. Wire EDM can trace any two-dimensional construction directly from a Computer Aided Drawing (CAD) file to a machined part. Therefore, any geometry that can be represented in CAD can essentially be applied to the mold cavity.

The importance of this difference is profound. Plastic gears are not dependent on metal gear tooling to create their geometry. The gear designer is free to create the perfect mathematical gear on paper and transfer that geometry to the gear through wire EDM. One method of doing this is to let the gears essentially design themselves through their meshing conditions.

Involute geared transmissions are ideally equivalent to the crossed-axis belt drives in Figure 2. The gear teeth cause the same rotational effect using the same path of transmission. The driver pushes the driven through the path defined by the belt coming off one drum or base circle, crossing the pitch point and moving to the base circle of the other drum. Many of the features of the crossed belt drive are exactly described with gear nomenclature such as base circle, pitch circle, pressure angle, and base tangent length. Khiralla (Ref. 2) thoroughly describes this geometry of motion as well as the mathematical construction of the involute.

With these facts in hand, one can relatively size the drums per the reduction ratio of the intended gear set. Absolute size is unimportant at this stage since the final gears can be scaled to fit the intended volume. Next, the designer must select a base tooth thickness and draw the involute tooth form on one gear, as shown in Figure 3, as well as the distance to separate the gears, which will fix the working pressure angle. The outside diameter of the gear is set arbitrarily at this point.

Now that one gear has been defined in the above fashion, the rest of the construction will be self-generating. The partially constructed gear is rotated about the pitch circle of its mate, and the outline of its mate is formed as in Figure 4. The tip of that gear is cut off at a reasonable length and then the second gear is in turn rotated about the pitch circle of the first to outline the root of that gear. With this complete, the two gears are fully described at their maximum material condition. In order to account for eccentricity and molded tolerances, the teeth can be additionally thinned, or the gears can be pulled slightly apart to allow for necessary clearance. The outside diameters can be toleranced minus from this maximum material condition to eliminate the possibility of interference.

This self-generating construction technique allows the designer to maximize the gear action for the plastic mesh. Teeth can be made longer to increase the working range of engagement or thicker to increase tooth strength. Attention must still be paid to traditional gear concerns such as contact ratio and tooth strength. Khiralla and Colbourne (Ref. 3) describe mathematics for these calculations, although very little practical validation of tooth strength mathematics exists for plastic gear teeth.

A further advantage of this technique is that the CAD geometry can be used to compare molded gear features either optically or with a scanning Coordinate Measuring Machine (CMM).

Plastic Gear Shrinkage

The next critical step in plastic gear manufacture is mold development. This requires estimating shrinkage for the plastic gear geometry, a feature that has caused many potentially acceptable plastic transmissions to perform inadequately or fail. Kleiss (4) wrote about the effect of plastic gear shrinkage and thermal expansion. Since that paper, further work has shown the authors that it is definitely incorrect to presume that plastic gears shrink isotropically, or in more common terms like a photographic reduction. The authors have found that plastic gear shrinkage is indeed much more fascinating.

There are two aspects of plastic gear shrinkage, macroscopic and local. The body and major features of a simple symmetrical plastic gear will have one approximate shrinkage value. This would include such features as the outer diameter, root diameter, base, and pitch circles. Local shrinkage around the individual gear tooth has a totally different shrink rate. The major effect of these differing shrink rates is that tooth thickness does not shrink nearly as much as other gear features. In some cases, it can actually expand from the mold due to local effects. This is most profound in unfilled crystalline materials such as acetal and nylon.

Inspection

Due to the non-uniform shrinkage phenomenon of plastic gears, traditional inspection techniques fail. One cannot simply measure the major diameter of the molded gear to determine shrinkage and then roll-test the gear against a master gear to ascertain form. The entire gear must be inspected for its actual material condition. One possible method is to scan the entire involute geometry and perform a best fit of that geometry to the intended shape as shown in Figure 5. The traces in this figure are representations of tooth form errors with respect to perfect geometry. The general trend of the negative slope indicates shrinkage error, while the slope variation of the traces around the gear indicate gear eccentricity. These effects are compensated for in Figure 6, showing the gear to have significant runout with a shrinkage error of .009 inches per inch. The tooth thickness of the measured gear is also much larger than specified.

The plastic gear user can perform an inspection very similar to the one shown by comparing the molded gear geometry to the CAD geometry developed in the design phase. Once this shrinkage has been correctly accounted for, simple gear roll testing with a known master can be used to maintain quality and form in the production environment.

Testing

The authors' personal experience indicates that no matter how thoroughly the components of a plastic transmission are designed and measured (cases, gears and shafts), it is impossible to predict plastic geared transmission torque capacity, smoothness, noise and life expectancy without actually testing the assembled transmission. The best way to conduct this functional test is by using a transmission dynamometer that directly measures input and output shaft torques and angular position/velocity. It is also beneficial to instrument the transmission case with an accelerometer. Spectral analysis of the input and output torques and/or velocities will reveal poor tooth geometry, while a spectral analysis of the accelerometer data will reveal poor

Fig. 7—A simple dynamometer for testing transmissions.

Fig. 8—Transmisison testing device with computer controlled air cylinder and load cell.

tooth geometry and indicate the vibratory power available to generate noise. A comparison of the input to output power (transmission efficiency) will find misaligned shafts, gears that are jamming due to oversizing or miscut roots, and incorrectly identified material among other deficiencies

The dimensions of plastic parts are subject to subtle changes during production. For example, mold cleaning and recutting, changes in molding compounds and/or process can cause these changes.

The authors have found it beneficial to periodically test production units of transmissions on a dynamometer. By comparing the dynamometer "signatures" of production units with the development units, they have detected significant changes in part geometry that component inspection missed.

Transmission dynamometers can be simple or complex. Many transmissions are DC motor powered. DC motor current is a good indicator of torque, and back EMF wave shape can indicate speed. By gearing a second motor to the output, a complete simple dyno test can be configured. Figure 7 shows an example of this kind of tester. An accelerometer was also used. This test found an interfering root geometry condition that component testing missed. A complex tester is shown in Figure 8. It consists of a computer controlled air cylinder and load cell that applies an arbitrary load function to a slider crank transmission. This tester found that the torque capacity of an existing transmission was considerably less than believed. ○

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