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New Opportunities with Molded Gears

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TECHNICAL PAPER

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Abstract

Molded gearing includes plastic and powder metal injection molded gears as well as powder metal sintered gears. Near-net forged gears may also share some unique similarities and opportunities as well. This type of manufacturing offers some particularly intriguing opportunities for the gear designer, and also some challenges not usually encountered with cut gears. The challenges are often related to the mechanical properties of the material. Proper steel, cut and hardened correctly, is hard to beat for strength. Ordinary attempts to replace steel gears with the molded variety are usually doomed to failure.

On the other hand, molded gears can offer some material properties not achievable with cut gears, including unique advantages in weight, noise, modulus, self-lubrication, magnetism, chemical resistance, and most appealing low cost. The challenge is to make them survive the demands put upon them. For instance, thermoplastic gears, when placed under continuous high load, will melt. This is a phenomenon not shared with any metal counterpart. The goal must be to make a weaker material appear stronger. The unique tools that are available to the molded gear designer are concentrated in the method of manufacture. When the proper mold is constructed and combined with the optimized molding process, a remarkably consistent and uniform gear can be continuously manufactured. The construction of this molded tooling can be almost completely CAD based. Traditional gear cutting processes are almost never used to develop the mold cavities.

Unique tooth geometry that might be difficult or even impossible to achieve with cut gears can be applied to molded gears matter-of-factly. This paper will investigate two types of gears that we have designed, molded, and tested in plastic. The first is an asymmetric mesh, the second is an orbiting transmission. The asymmetric gears have dissimilar 20° and 48° pressure angles while the orbiting gear set works with a 65° pressure angle. Both transmissions have higher load potential than traditional design approaches.

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New Opportunities with Molded gears

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Molded gears share some very basic similarities with cut metal gears, principally the involute gear shape and a need for precise design, manufacturing, and inspection. They also diverge from cut metal gears in some very significant ways. The design of the gears and mold tool construction usually does not require or employ any traditional gear cutting techniques. Spur gear molds are almost invariably made utilizing a wire Electrical Discharge Machine (EDM) which is capable of producing any 2-dimensional and even some slightly 3-dimensional shapes with surface accuracy on the order of a single micron. Helical cavities are cut using electrode EDM's. These electrodes can be made with end mills having gear profiles wire EDM'd into their cutting edges, or by using high-speed surface generation on a 4-axis CNC mill. The difficulty of using traditional gear cutting techniques is most often due to the required physical geometry of the cavity. Since most molded gears will shrink from the mold, the mold cavity must be adjusted for enlarged base pitch, tooth thickness, major, and minor diameters. Form grinding electrodes is an option, but standard hob generation is almost never suitable. Additionally, very few electrodes will be needed to generate the mold cavities. Gear houses tend to shy away from such small jobs that will only infrequently be repeated.

Still, the options left open to the molded gear designer are quite extensive To achieve an effective transmission design, every available tool and resource is usually required. First of all is the design of the gears themselves. As with many design constraints, space is usually at a premium with large expected loads. The danger with molded plastic gears especially is heat. Plastic gears melt, and as temperature increases, their modulus of elasticity decreases and they get even weaker. Constant duty cycles under heavy loading is one of the most difficult designs to achieve successfully with plastic molded gears. Using exotic materials with higher heat capacity brings along its own set of problems. Quite often these materials will be brittle, or difficult to mold accurately, or just too expensive to be cost competitive with high speed gear cutting. Most successful plastic gear designs will be molded with basic engineering thermoplastics such as nylon or acetal.

Molded Gear Design

One of the biggest opportunities for the molded gear designer is the design of the gears themselves. Since the spur tooling can be generated with wire EDM, any 2-dimensional shape that can be drawn, can usually be produced, and even adjusted mathematically for shrinkage before being cut. There are only 8 variables required to completely describe a symmetrical spur gear mesh design. Figure 1 is a screen dump of our design approach to this task.

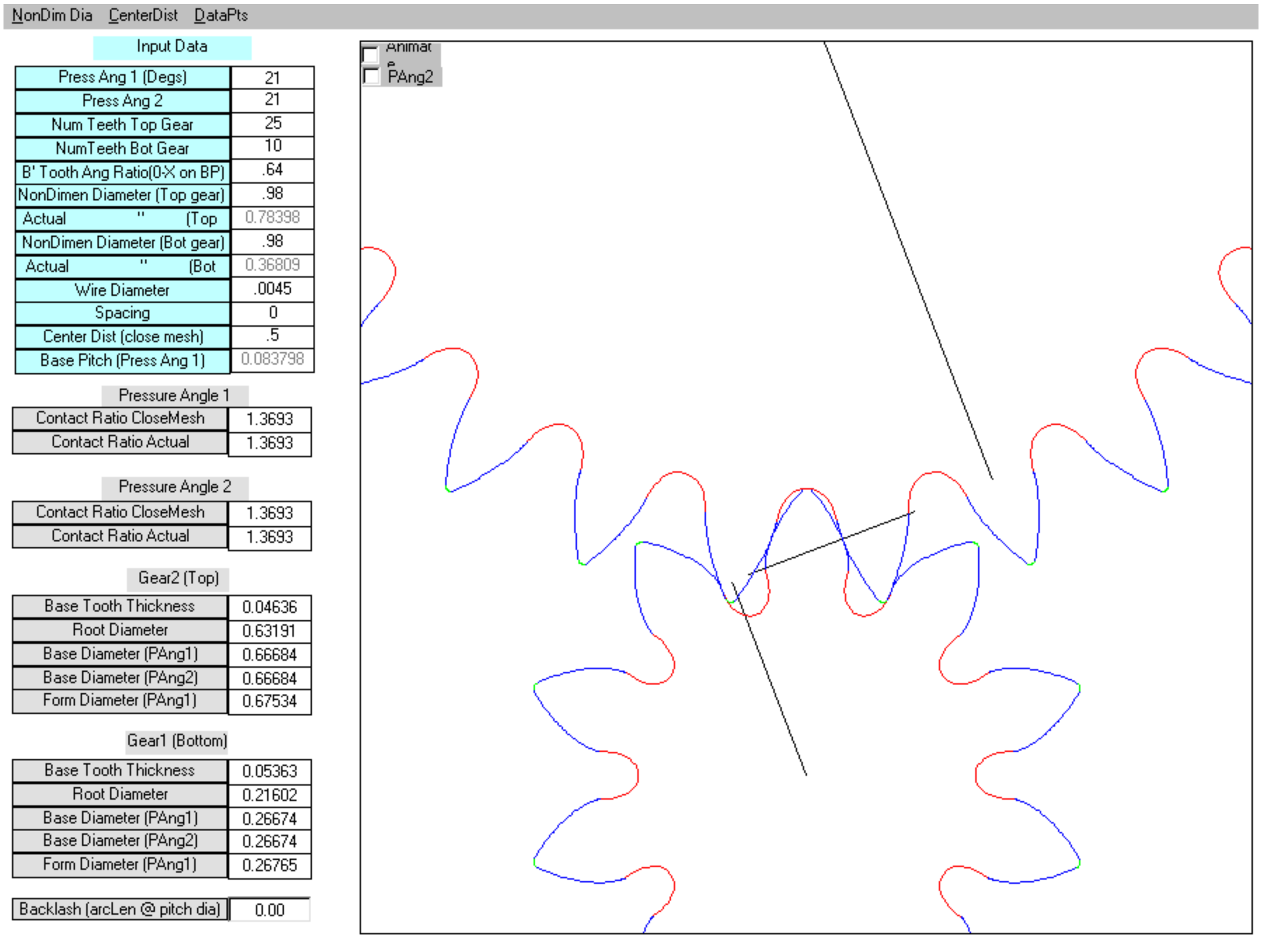


Figure 1 Typical spur gear design

The input data field in the upper left-hand corner of Figure 1 shows the required information to complete this design. For symmetric gears the operating pressure angle will be the same in both directions. The numbers of teeth in each gear is followed by the tooth thickness of one of the gears. In this case tooth thickness is defined as a non-dimensional ratio to the base pitch of the drive pinion. The outside diameter of both gears is required as well as the wire diameter of the EDM that will cut the cavities. This will cause the tips of each gear to be rounded, which will affect both the contact ratio and the formation of the mating gear's root geometry. Finally, either center distance of the mesh or the base pitch is required to physically size the gears. With these minimum inputs the rest of the gear features are produced by generation from the principal features.

In this case, the outside diameters of the gears are designed to 98% of the theoretical maximum diameter possible. A slight undercut is generated by the gear to the pinion. This gives the effect of a bonus tolerance on contact ratio, since the contact ratio will not begin to decrease until the gears have separated beyond the undercut condition. Tooth thickness can be adjusted visually and then checked with traditional methods to assure balanced strength. Working pressure angles can be increased or decreased to optimize any particular feature. Similar results can be attained with shaper cut gears, but accuracy will not be equivalent to the wire EDM, and physical limitations of cutters will limit attainable features. Figure 2 shows some of the possibilities with this method of design.

As is readily apparent in Figure 2, design freedom does not necessarily result in good design, but the potential for unique solutions is obvious. Internal as well as external gear sets are equally feasible. Two unique designs utilizing this approach will now be presented. These designs were tooled, molded and tested.

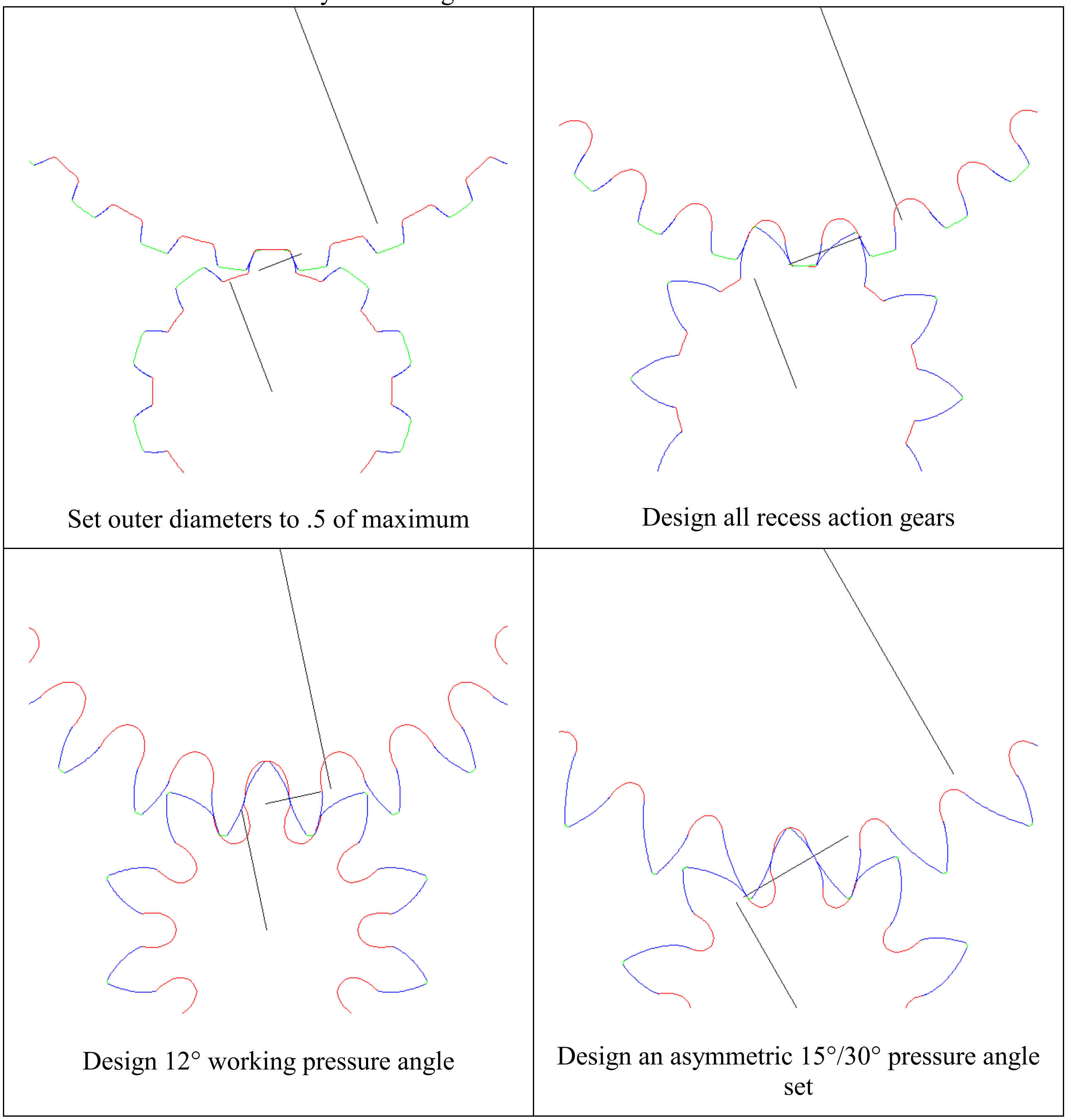


Figure 2 Possibilities for unique gear design

Internal Orbiting Gear Set

A constant goal in gearing is to produce higher reduction gear sets with greater torque capacity. One method that has been utilized consists of orbiting a notched wheel about fixed pins, the wheel having one or less fewer indentations than the pins. Therefore, with each orbit of the wheel, the bolt hole pattern cut into its face will advance angularly. An output bolt pattern can couple this rotation from the orbiting gear to an output shaft on the reference axis (Figure 3). Transmissions of this design are in production today. They have high load capabilities and high efficiency, but must be machined with very high accuracy to effect smooth torque transfer, and they also must have excellent bearing systems.

An alternative approach is to design involute gears for the orbiting set rather than use circular arcs. This has the advantage of letting the involute geometry provide for smooth rotary transmission in the low tolerance environment of plastic molding. An additional benefit is that the torque coupling through involutes would be more effective for plastic and reduce the change of tooth deformation.

Utilizing the same approach as for external gears, an internal gear set was designed to orbit a 39 tooth gear about a 40 tooth internal gear. The design is presented in Figure 4. As with external gears, internal designs require only a few variables to completely describe the system. A one tooth difference between driver and driven gear requires a very large working pressure angle to assure clearance outside of the contact area. In this case the working pressure angle was set at 65 degrees.

The largest apparent discrepancy with this design is the less than unity contact ratio of the gears. Although this is true mathematically, the fact is that the gears are really in mesh over a much larger area of engagement than theoretically predicted, given the lower modulus of elasticity of plastic. The resultant actual contact ratio is in effect much greater than 1. The tools were made and the gears were molded as shown in Figure 5.

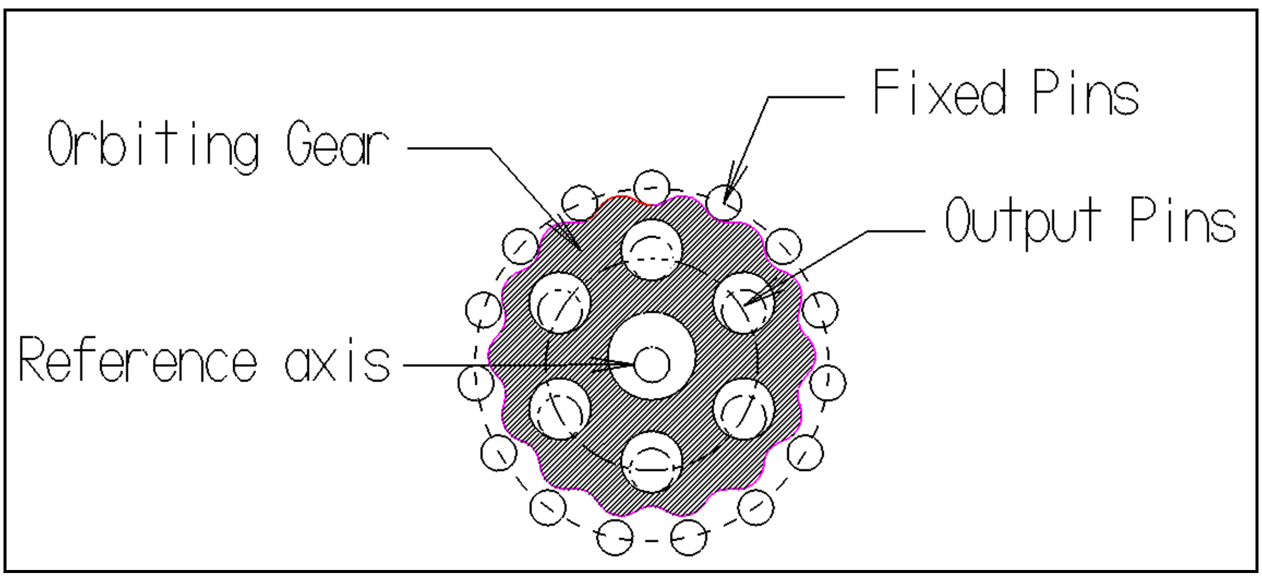


Figure 3 Orbiting gear transmission

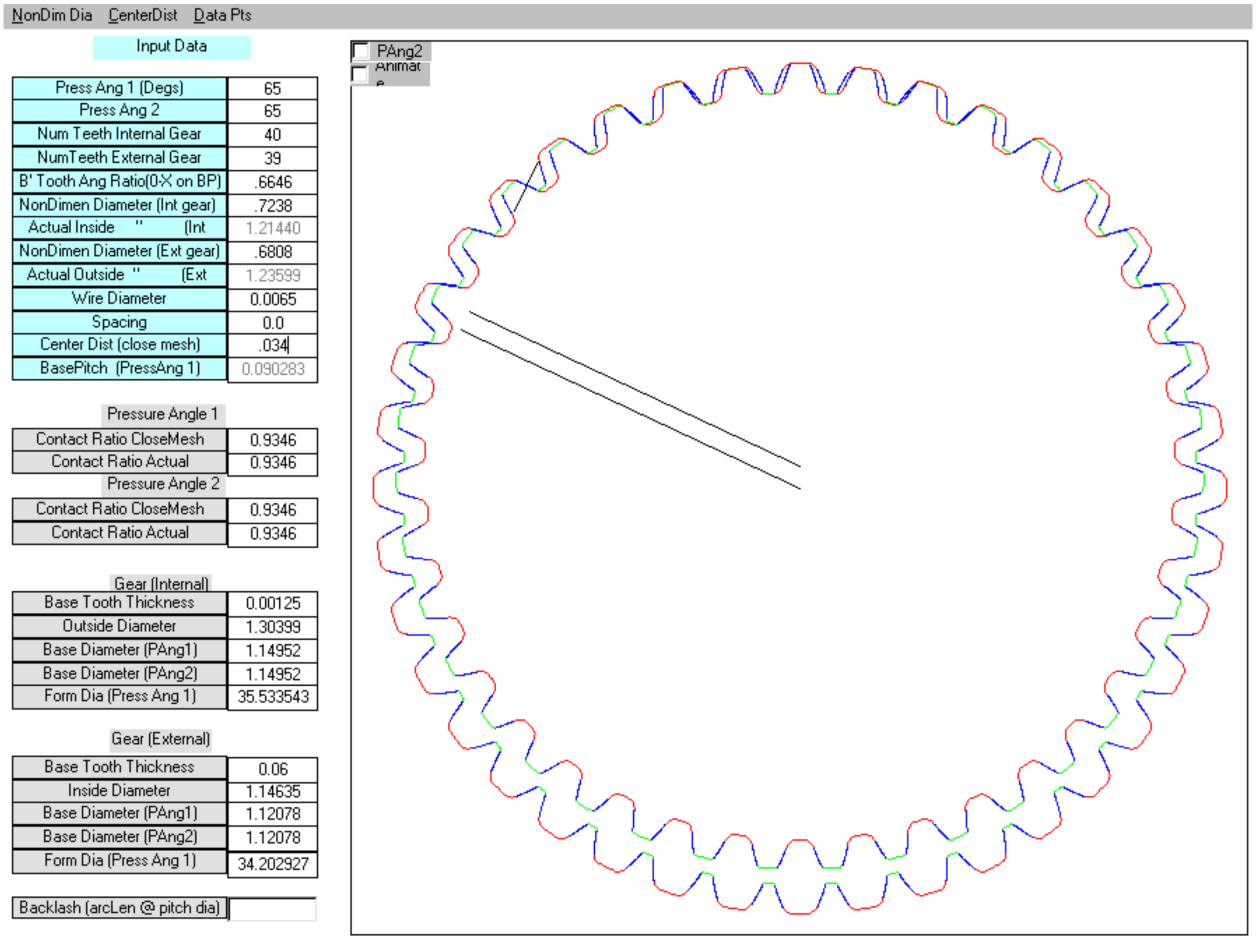


Figure 4 Internal Involute Orbiting Gear

A gear tester was constructed to determine the actual load capacity of the gears and the efficiency. The transmission mounted in that tester is shown in Figure 6.

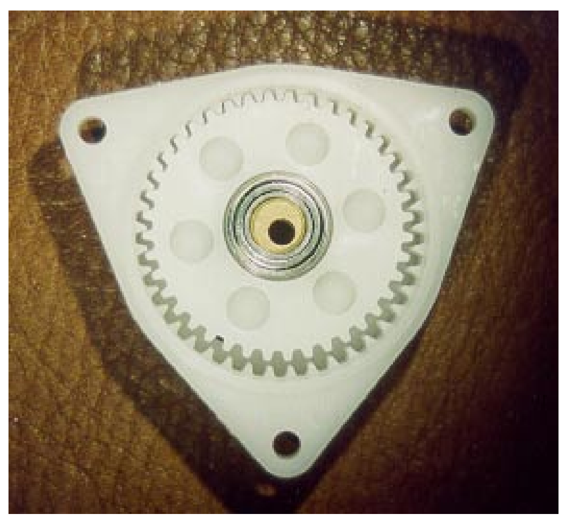


Figure 5 Involute Orbiting gears

The gear tester consists of a precision DC servomotor driving the transmission into a calibrated hysterisis brake with an attached strain gage load cell on a torque arm to accurately gauge transmitted torque. Voltages and currents are supplied and monitored with a computerized interface with torque readings and angular position recorded dynamically.

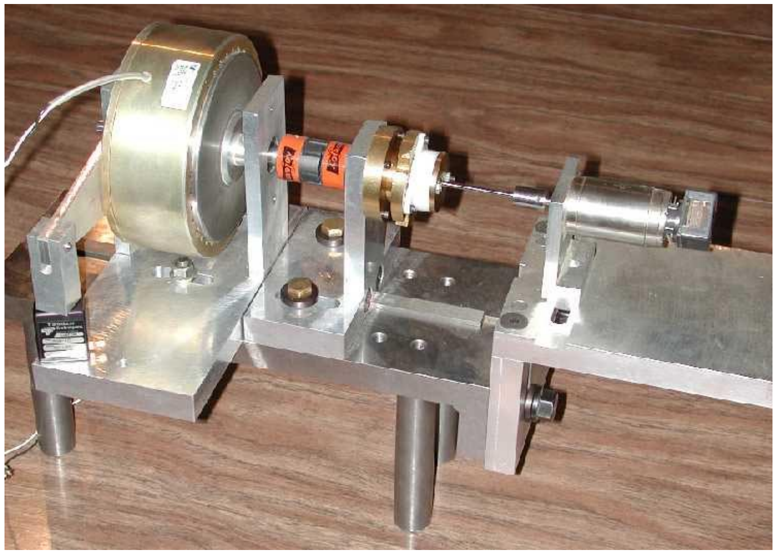


Figure 6 Orbiting Transmission Tester

Testing on this transmission proved that the gears themselves could not be failed with the available motor torque. Stall torques up to 30 in.-lbs. failed to break the transmission. Efficiency was another story. The use of bushings resulted in efficiency less that 20%. Coupling the input torque through the small motor bushing resulted in early mortality of that motor. Subsequently, ball bearings replaced bushings, the motor was de-coupled, and efficiency raised to over 70%. The conclusion made at the end of this testing was that the bearing system rather that the plastic gears became the weakest link. Further work is continuing to reduce these bearing loads and improve performance.

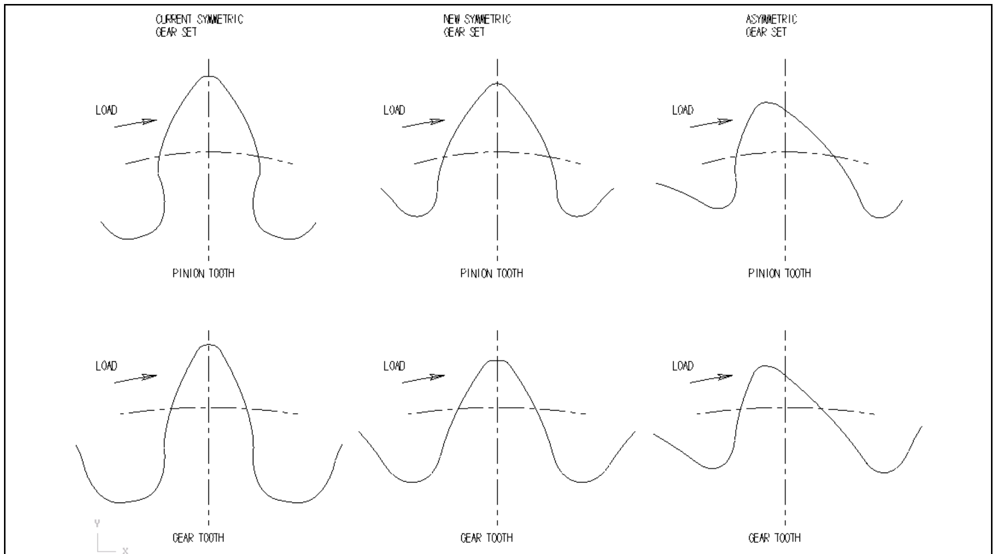
Asymmetric Gears

Another way to increase load capacity of transmissions is to modify the involute geometry. This has been standard practice in sophisticated gear design for many years. The nomenclature describing these types of gear modifications can be quite confusing, with reference to addendum modification, profile shift, etc., etc. An additional alteration that is very rarely used is to make the gears asymmetric with different profile angles for each side of the tooth.

Two sides (profiles) of the gear tooth are functionally different for most gears. The workload on one profile is significantly higher and/or for longer periods of time then the opposite one. The tooth shape must reflect this functional difference. The general idea of asymmetric teeth is to improve performance (increase load capacity, reduce noise and vibration, etc.) of the main contacting profiles by dint of degrading the opposite profiles. These opposite profiles are unloaded or slightly loaded and usually work for short duration only.

Degree of asymmetry and drive profile selection for asymmetric gears depends on the gear application. If bending stress is an issue then the low-pressure angle profile is preferable for the drive side (so called "buttress" teeth), whereas the contact stresses, noise and vibration could be significantly reduced if the drive side has a high-pressure angle.

An asymmetric gear set was designed and molded for a lawn sprinkler system. Design and testing of the asymmetric gears was conducted with comparison to current symmetric gears and the best possible symmetric gears. A summary of the three different design meshes is presented in Figure 7.



	Pinion	Gear	Pinion	Gear	Pinion	Gear
Drive side pressure angle, deg.	23.194		30		20	
Coast side pressure angle, deg.	23.194		30		48	
Operating pitch diameter, in.	.1147	.2294	.1147	.2294	.1147	.2294
Drive side base diameter, in.	.1054	.2108	.0993	.1986	.1078	.2156
Coast side base diameter, in.	.1054	.2108	.0993	.1986	.0767	.1534
Outside diameter, in.	.1443	.2538	.1398	.2488	.01352	.2472
Root diameter, in.	.859	.195	.0952	.2042	.0968	.2073
Tooth thickness on PD, in.	.0205	.0155	.0208	.0152	.0196	.0164
Tooth width, in.	.100	.095	.100	.095	.100	.095
Center distance, in.	.172		.172		.172	
Drive side contact ratio	1.48		1.08		1.157	
Coast side contact ratio	1.48		1.08		.933	

* maximum material condition profiles, backlashless mesh.

Static Finite Element- bending stresses*

	Current Symmetric Gear Set				New High Pressure Angle Set				Asymmetric Set			
	Pinion		Gear		Pinion		Gear		Pinion		Gear	
Torque (In*lb)	0.10		0.20		0.10		0.20		0.10		0.20	
RPM	1,000		500		1,000		500		1,000		500	
Stress (psi)	Tension	Comp-ression	Tension	Comp-ression	Tension	Comp-ression	Tension	Comp-ression	Tension	Comp-ression	Tension	Comp-ression
Von Mises	8,178 (100%)	8,692 (100%)	6,761 (100%)	7,897 (100%)	5,350 (65%)	7,540 (87%)	4,878 (72%)	7,010 (89%)	4,070 (50%)	4,937 (57%)	4,660 (69%)	3,510 (44%)
Max Principal	8,820 (100%)		7,313 (100%)		5,857 (66%)		5,394 (74%)		4,290 (49%)		5,057 (69%)	
Min Principal		-8,879 (100%)		-8,061 (100%)		-8,089 (91%)		-7,386 (92%)		-5,312 (60%)		-4,210 (52%)

* Load is applied to the drive side of the tooth in the highest point of single tooth contact

Material properties: Young's Modulus = 700,000psi; Poisson's ratio= .32

Figure 7 Design comparison tables

Gears were molded in the three different designs and tested. The results of that testing are presented below:

Standard – Parts from the Line

Peak Torque (oz-in)		Comments
1	27.4	Gearbox output gear teeth bent & broken. Final compound gear teeth broken.
2	20.6	Gearbox output gear had some bent teeth. Final compound gear teeth broken.
3	23.0	Gearbox output gear had some bent teeth. Final compound gear teeth broken.
4	24.7	Final compound gear teeth broken.
5	27.3	Gearbox output gear had bent teeth. Final compound gear teeth broken.
Avg.	24.6	

BASF N2320 - Asymmetric

Peak Torque (oz-in)		Comments
1	24.3	Gear teeth jumped when torque was applied. Gearbox output and final compound gears both bent and broken.
2	25.4	Gear teeth jumped when torque was applied. Gearbox output and final compound gears both bent and broken.
3	24.6	Gear teeth jumped when torque was applied. Gearbox output gear teeth bent. Final compound gear teeth bent and broken.
4	25.4	Gear teeth jumped when torque was applied. Gearbox output and final compound gears both bent and broken
5	26.8	Gear teeth jumped when torque was applied. Gearbox output gear teeth bent. Final compound gear teeth bent and broken.
Avg.	25.3	

BASF N2320 - 30° Symmetric

Peak Torque (oz-in)		Comments
1	28.0	Gear teeth jumped when torque was applied. Gearbox output gear teeth bent and broken. Final compound gear teeth bent.
2	26.8	Gear teeth jumped when torque was applied. Gearbox output gear teeth bent and broken.
3	25.4	Gear teeth jumped when torque was applied. Gearbox output and final compound gears both bent and broken.
4	25.8	Gear teeth jumped when torque was applied. Gearbox output and final compound gears both bent and broken.
5	26.3	Gear teeth jumped when torque was applied. Gearbox output gear teeth bent and broken.
Avg.	26.5	

These tests show the effect that varied pressure angles, and symmetry have on the peak torque the gears. The measured range of peak torque is from 20.8 to 28.8 oz-in. Although the final two tests with the 30° symmetric gears and the asymmetric gears did not have a substantial increase in peak torque, they did not immediately break like the other units. Instead, these units jumped teeth before breaking which is a desirable feature resulting in clutch ratcheting rather than gear failure.

Conclusions

Molded plastic gearing truly fits into the realm of an emerging new technology. Given the novel process of design, tooling, and molding, these gears can be improved in function to compensate for their material properties an environment. As in any physical application, modifications result in trade-offs. One optimizes geometric features for the intended application. In plastic gear the design need not be marginalized by the limits of metal gear cutting.