Advantages of Direct Gear Design For Automotive Polymer Gear Drives

By Alexander L. Kapelevich and Thomas M. McNamara

Direct Gear Design, a development process where gear parameters are primary and tool parameters are secondary, maximizes performance of plastic gearing by compensating for polymer property limitations.

INVENTION OF THE GEAR-GENERATING MACHINING process that uses the gear rack shape tooling cutting edge (as shown in Figure 1) established basic principles of traditional gear design. Parameters of the tooling gear rack such as the profile (or pressure) angle, addendum, whole depth, and fillet radius proportions are standardized and used as input gear design parameters. Selection of the standard gear rack becomes a starting point and foundation of gear design. This made the gear design indirect depending on pre-selected, typically standard, basic gear rack parameters.
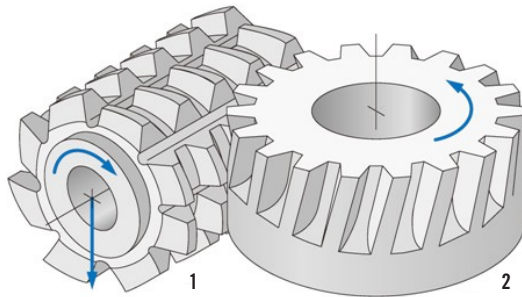

Figure 1: Gear-generating machining process; 1) hob cutter, 2) gear blank

Major benefits provided by the traditional gear design approach include an availability of standards and software, ability to use one tooling rack for generation of gears with different numbers of teeth, potential gear interchangeability, and low tooling inventory. At the same time, this gear design method imposes significant limitations on the gear parameters and restrains the gear drive performance.

Polymer gears are typically fabricated by an injection molding process (as shown in Figure 2), which does not use the rack type tooling. In addition, there is a clear trend to gear customization in general, especially in plastic gear drives. Polymer gears are not interchangeable and are designed spe-
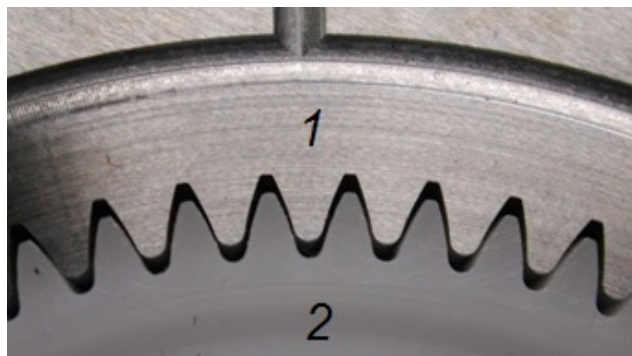
cifically for a particular application. This practically diminishes all benefits of traditional gear design for polymer gears. Nevertheless, the majority of polymer gears are designed traditionally based on the rack tooling generation of the gear profile. The traditional design approach does not allow for optimizing gear tooth geometry of polymer gears in all applications including automotive.

DIRECT GEAR DESIGN®

An alternative Direct Gear Design method [1] defines the gear tooth geometry without using standard generating rack tooling profiles. It is an application-driven gear geometry development process with a primary emphasis on performance maximization and cost efficiency without concern for any predefined tooling parameters. This means that the gear parameters are primary and the manufacturing process and tool parameters are secondary. This is the essence of Direct Gear Design.

Two involutes of the base circle, the arc distance between them, and tooth tip circle describe the gear tooth (Figure 3).
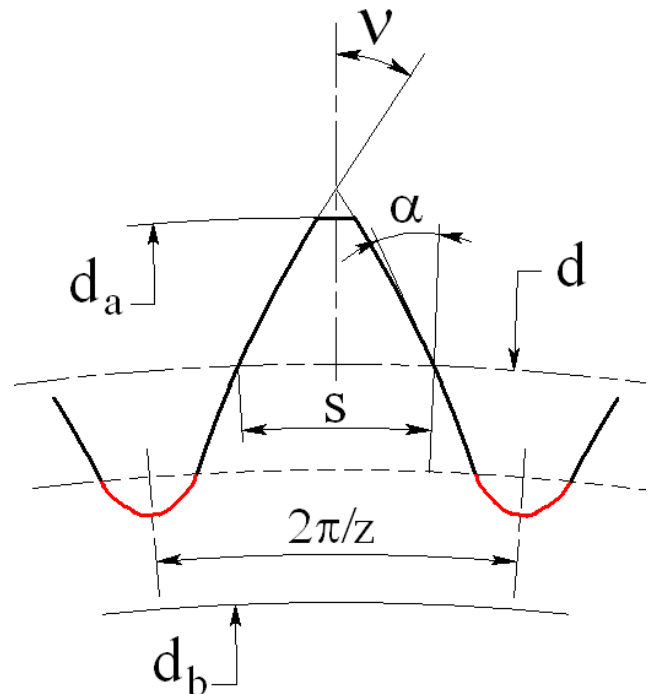

Figure 2: Plastic gear injection molding process; 1) tooling cavity, 2) gear

Figure 3: Tooth profile (the fillet portion is red); d_b = base circle diameter, ν = involute intersection profile angle, d = reference circle diameter, α = profile angle at reference diameter, S = circular tooth thickness at reference diameter, d_a = tooth tip circle diameter

The equally spaced teeth form the gear. The root fillet between teeth is not in contact with the mating gear teeth. However, this portion of the tooth profile is critical because this is the area of maximum bending stress concentration.

The profile angle α at the reference diameter d is:

$$\alpha = \arccos(d_b / d)$$

<div align="right">Equation 1</div>

and the circular tooth thickness S at the reference diameter d is:

$$S = d \times (inv(v) - inv(\alpha))$$

<div align="right">Equation 2</div>

where $inv(x) = \tan x - x$ is the involute function.

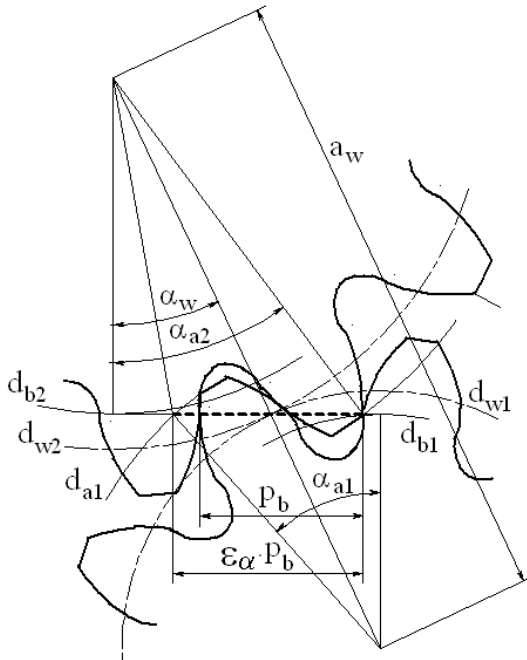Two gears can be engaged in the gear mesh if they have an identical base pitch p_b (see Figure 4).

Figure 4: Gear mesh; p_b = base pitch, a_w = center distance, α_w = operating pressure angle, ε_α = operating contact ratio

The operating pressure angle is:

$$inv(\alpha_w) = \frac{1}{1+u}(inv(v_1) + u \times inv(v_2) - \frac{\pi}{z_1})$$

<div align="right">Equation 3</div>

where $u = d_{b2}/d_b1 = z_2/z_1$ – gear ratio,
z_1, z_2 = numbers of teeth of mating pinion and gear.

The center distance a_w is:

$$a_w = \frac{d_b(1+u)}{2\cos(\alpha_w)}$$

<div align="right">Equation 4</div>

The operating contact ratio ε_α is:

$$\varepsilon_\alpha = \frac{z_1}{2\pi}(\tan\alpha_{a1} + u\tan\alpha_{a2} - (1+u)\tan\alpha_w)$$

<div align="right">Equation 5</div>

GEAR GEOMETRY OPTIMIZATION

Gear Efficiency Maximization
In gear transmissions, almost all inefficiency or mechanical losses are transferred into heat, reducing gear performance, reliability, and life.

This is especially critical for plastic gears. Plastics do not conduct heat as well as metal. Heat accumulates on the gear tooth surface, leading to premature failure.

Spur gear efficiency is defined as:

$$E := 100 \cdot \left[1 - \frac{f}{2 \cdot \cos(\alpha)} \cdot \frac{(H_1)^2 + (H_2)^2}{H_1 + H_2}\right]\%$$

<div align="right">Equation 6</div>

where: H_1 and H_2 are the maximum specific sliding velocities (Figure 5) of the pinion and the gear; f is the friction coefficient.
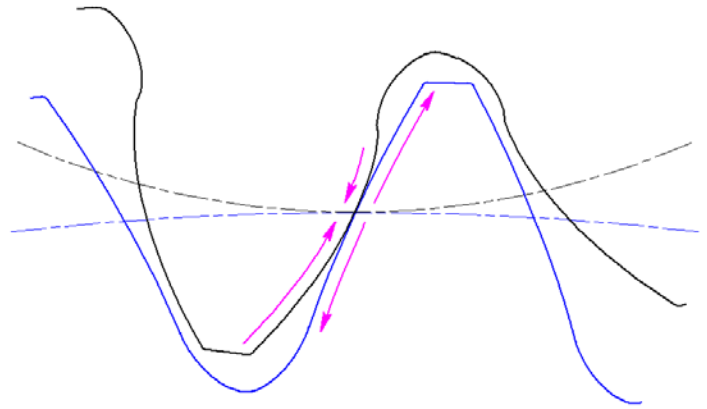

Figure 5: Gear mesh efficiency maximization

In Direct Gear Design, the gear efficiency is increased by equalizing the maximum specific sliding velocities for both mating gears $H_1 = H_2$ (Figure 5). Then, the spur gear efficiency is:

$$E_{max} = 100 \times [1 - \frac{1}{2}f\pi\varepsilon_\alpha(\frac{1}{z_1} \pm \frac{1}{z_2})]\%$$

<div align="right">Equation 7</div>

where: a sign "+" for external gear mesh and a sign "-" for internal gear mesh.

Unlike in traditional gear design, this can be done without compromising gear strength or stress balance.

Bending Stress Balance
Mating gear teeth should be equally strong. Direct Gear Design defines the optimum tooth thickness ratio S_{w1}/S_{w2} (Figure 6), using FEA and an iterative method, providing a tooth bending stress difference of less than 1 percent. If the gears are made out of different materials, the bending safety factors should be balanced.

Fillet Profile Optimization
In traditional gear design, the fillet is defined by a trajectory of the cutting tool's edge. This results in a large radial clearance and small fillet radii in the area of maximum bending stress.

In Direct Gear Design, a fillet profile is optimized in order to minimize the bending stress concentration [1]. The initial fillet profile is a trace of the mating gear tooth tip. An optimization process is based on a finite element analysis (FEA) and a random search method (Figure 7). This optimization process sets up a center of the fillet and connects it with the FEA nodes on the fillet. Then it moves all the nodes along the beams and calculates the bending stress. The nodes cannot be moved above the initial fillet profile because it will lead to interference with the mating gear tooth. The process analyzes successful and unsuccessful steps, altering the fillet profile to reduce the maximum bending stress. This process continues for a certain number of iterations, resulting in the optimized fillet profile.
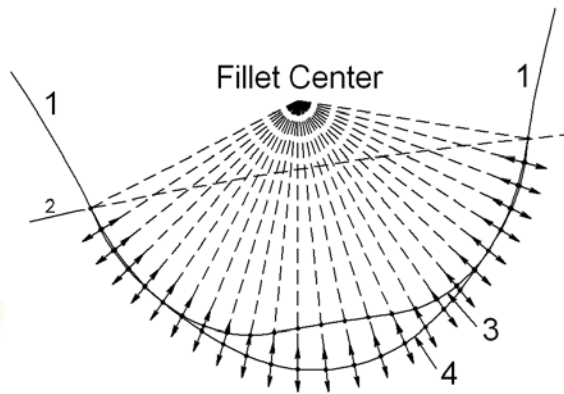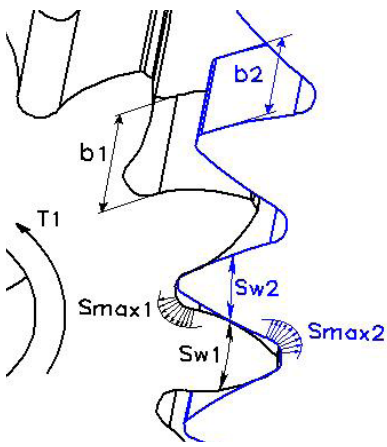
Figure 6: Maximum bending stress equalization

Figure 7: Fillet profile optimization; 1) involute profiles, 2) form diameter, 3) initial fillet profile, 4) optimized fillet profile

Table 1 presents a comparison of maximum bending stress of the standard gear teeth and the same teeth but with the optimized root fillet.

GEAR DATA	
Module, mm	2.5
Pressure Angle,°	25
Numbers of Teeth	20 & 20
Face Widths, mm	12.0 & 12.0
Driving Torque, Nm	20
MAXIMUM BENDING STRESS	
Rack Generated Fillet, MPa	78
Optimized Fillet, MPa	59

RACK GENERATED ROOT FILLET   **OPTIMIZED ROOT FILLET**


Table 1

MATERIALS FOR PLASTIC GEARS

Selection of the proper polymer material for the application is critical to successful gear drives. Factors that need to be considered include mechanical requirements, environmental issues, regulatory concerns, and cost.

Plastic materials are typically divided by the temperature range in which they can be used. The "workhorse" materials, those that can be used at temperature limits from 80ºC up to 140ºC, include some of the nylon family (PA 6, 66), acetals (POM), polyesters (PBT/PET), and polycarbonates (PC). Another group that can be used at slightly elevated temperatures (up to 150-160ºC) include polyphthalamides (PPA), nylon 46, and high-temperature nylon (HTN). The highest temperature materials, those able to operate over 160ºC and as high as 240ºC, include polyetherimide (PEI), polyethersulfone (PES), polyphenylene sulfide (PPS), polyetheretherketone (PEEK), and liquid crystal polymers (LCP). In general, the higher the temperature performance, the higher the cost for the material.

These materials are often modified to make them perform even better in gear applications. Strength modifiers such as glass, carbon, and aramid fibers can be added to provide materials that can take higher loads, which is an important feature when converting from metal to plastic. Other modifiers can be added to reduce friction or decrease wear. Some of these modifiers include silicone, polytetraflouroethylene (PTFE), graphite powders, and molybdenum disulfide (MoS2). Many other modifiers can be added to provide heat and UV stabilization, impact enhancement, thermal conductivity, flame retardance, and anti-oxidation.
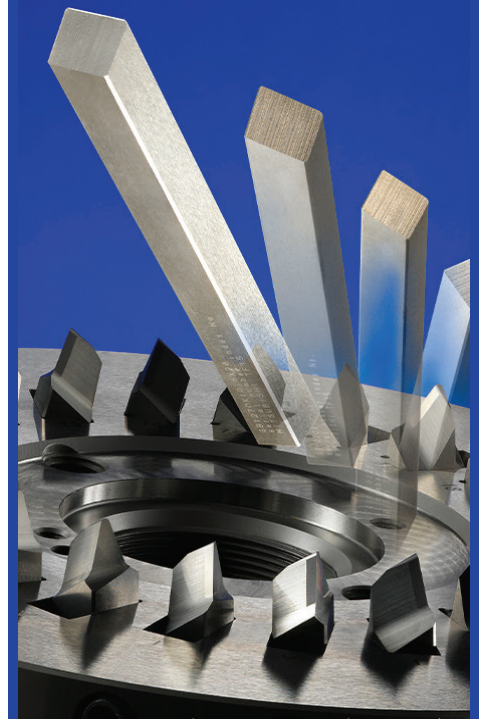
Designing gears with plastic materials requires careful consideration of the unique properties and responses of these materials to the gear drive system dynamics. The designer may want to consult with material suppliers or knowledgeable gear molders on appropriate materials for the application.

DIRECT VS. TRADITIONAL GEAR DESIGN

A comparison of traditional gear design and Direct Gear Design is shown in Table 2.

The Direct Gear Design tooth flank and root fillet profile optimization provides a significantly greater contact ratio and bending safety factors.

METAL-TO-PLASTIC CONVERSION

The most typical development of plastic gearing for small engines is the conversion of current metal gears to plastic. However, in most cases, simple material replacement is not adequate. Gears must be redesigned to compensate for some of the "reduced" properties of plastics (lower tensile strength and limited thermal resistance) and emphasize their advantages (shock resistance, low weight, etc.).

Table 3 presents a sample of the metal-to-plastic conversion gear data.
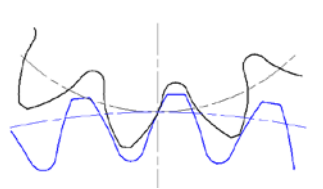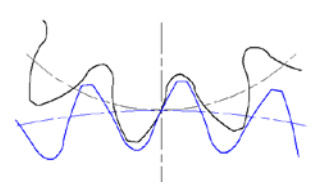
DESIGN METHOD	TRADITIONAL DESIGN		DIRECT GEAR DESIGN®	
Gear	Driving	Driven	Driving	Driven
Number of Teeth	13	47	13	47
Module, mm	2.0		2.0	
Center Distance, mm	60.0		60.0	
Face Width, mm	12.0	10.0	12.0	10.0
Operating Pressure Angle,°	25.0		25.0	
Operating Contact Ratio	1.26		1.46	
Root Fillet	Trochoidal	Trochoidal	Optimized	Optimized
Maximum Driving Torque, Nm	6.5		6.5	
Maximum Bending Stress, MPa	68.2	70.2	55.2 (-19%)	55.9 (-20%)
Gear Material	Zytel 70G33L		Zytel 70G33L	
Yield Tensing Strength, MPa	140 (50%RH)		140 (50%RH)	
Bending Safety Factor	2.05	2.00	2.54	2.50
Gear Mesh Image				

Table 2

MOLDING TOOL CAVITY ADJUSTMENT

The molding tool cavity has a profile similar to the gear, but adjusted for shrinkage and warp that greatly affects the gear size and shape accuracy. Plastic gears often include an intricate body shape that could be incorporated as one piece with other mechanism components, such as shafts and cams. These design specifics in combination with a huge variety of available gear polymers and enhancing additives (for increased strength, thermal resistance, lubricity, etc.) make prediction of gear shrinkage and warp an extremely difficult task. In many cases, gear molders use a trial-and-error method with a varying degree of success. Typically, this educated-guess method works better for gears with a relatively simple body shape (e.g., a flat uniform disk with a small central hole) that are made out of generic unfilled polymers.

A totally different approach to providing molding distortion compensation was proposed by Dr. Yuriy V. Shekhtman [2]. It is called the Genetic Molding Solution®. Similar to how the DNA contains genetic information about the entire live organism, the shape of the molded part reflects the originally designed profile, polymer material properties, tooling design, and molding process parameters. The Genetic Molding Solution method is based on mathematical prediction that defines a transformation function describing relations between the initially molded sample gear profile and its actual initial cavity profile. Once this function is defined, the target gear profile replaces the first molded sample profile as the transformation function variable to calculate the final cavity profile.

Practical application of this method takes eight steps:

1. Target gear profile definition (data file #1): The X,Y-coordinate points are extracted from the gear CAD model to present a desired nominal gear profile at average material condition. The number of these coordinate points is typically several hundred per one gear tooth.
2. Initial cavity profile definition: Initial cavity profile is the scaled-up target gear CAD profile using the polymer linear mold shrinkage coefficient from the material manufacturer's specification.
3. Fabrication and inspection of initial mold cavity (data file #2): CMM inspection produces the X,Y-coordinate points (several hundred per one tooth space) accurately describing the initial cavity.
4. Molding Process Optimization: Gears are molded using the initial cavity without concern about the gear shape. Here, the goal is to achieve a stable and repeatable

	METAL GEAR PAIR		PLASTIC GEAR PAIR	
DESIGN METHOD	**TRADITIONAL DESIGN**		**DIRECT GEAR DESIGN®**	
Gear	Driving	Driven	Driving	Driven
Number of Teeth	34	54	17	27
Module, mm	0.5		1.0	
Center Distance, mm	22.0		22.0	
Face Width, mm	6.0	6.0	6.0	6.0
Operating Pressure Angle,°	20.0		27.0	
Operating Contact Ratio	1.56		1.27	
Root Fillet	Trochoidal	Trochoidal	Optimized	Optimized
Mesh Efficiency, %	98.8		98.2	
Maximum Temperature, °C	110		110	
Maximum Driving Torque, Nm	1.0		1.0	
Maximum Bending Stress, MPa	128	130	45	45
Gear Material	Steel 4140 Normalized		Amodel AS-1133 HS	
Yield Tensing Strength, MPa	635		193	
Min. Bending Safety Factor	5.0	4.9	4.3	4.3
Image of Driving Gear				

Table 3

molding process with the part dimensional variation significantly lower than the required accuracy tolerances. Any material flaws like voids are not acceptable. Once this goal is reached, the molding process must be locked-in and certified; no changes to the process are allowed. Using the optimized process, several dozen gears are molded.

5. Representative gear specimen selection: All molded gears are roll-tested, and the inspection data is analyzed. Then, the most representative preliminary gear specimen is selected. This specimen should have average statistical tooth-to-tooth and total composite errors (TTE and TCE).
6. Gear specimen inspection (data file #3): CMM inspection produces the X,Y-coordinate points (several hundred per one gear tooth), accurately describing the initial cavity molded gear. Inspection data of the initial cavity and the gear specimen must have the same radial orientation to assure that each gear tooth is properly aligned with its representative gear tooth cavity.
7. Final cavity profile definition and fabrication: The Genetic Molding Solution software uses the gear specimen and initial cavity data (files #2 and #3) to generate a transformation function, f. The target gear data (file #1) is then used as the variable of this transformation function to define the final cavity profile — the output data set. The same radial orientation of all three data files is critical. Any angular rotation or mirroring of the data points totally compromises the mold cavity adjustment results. The final cavity is then manufactured and given a CMM inspection for verification of the gear cavity adjustment.
8. Final gear profile: Gears are molded using the adjusted mold cavity. The CMM data of the molded gears should be identical to the specified gear profile within the molding process accuracy variation.
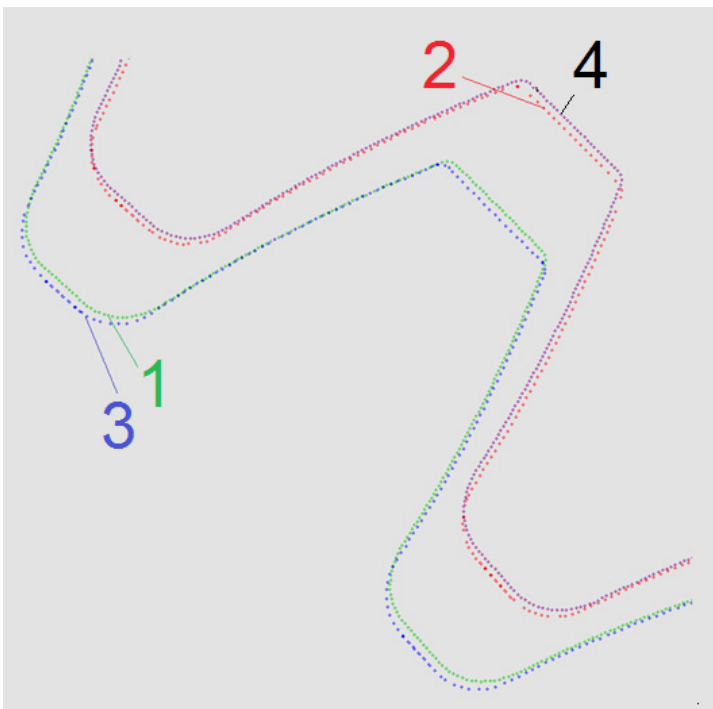
Figure 8: Genetic Molding Solution software application results; 1) target gear profile, 2) first tool cavity profile, 3) first gear sample profile, 4) final tool cavity profile

Figure 8 illustrates the results of the Genetic Molding Solution software application.

For successful application of the Genetic Molding Solution method, the initial and final gear molding must be done with the same batch polymer on the same molding press using the same mold and locked-in process parameters.

An example of this methodology is for the cam shaft gear application shown in Figure 9. This gear is not particularly molding-friendly: it has a metal over-molded shaft, two cams, six spokes, and three material delivery gates located in the middle of these spokes. Mold development for this gear using traditional methods requires considerable time and guesswork, as well as several mold cavity iterations. The Genetic Molding Solution method develops the desired cavity in a short time by direct calculation with only one cavity adjustment.

The chart in Figure 9 shows a comparison of roll test graphs on the initial most representative gear specimen with the final gear sample. The initial gear roll test measurements (TTE and TCE) greatly exceed the required accuracy level, but the final gear roll test results fit well inside the TTE and TCE tolerance limits.

The Genetic Molding Solution method significantly accelerates the mold cavity development for plastic molded gears. It eliminates a guess component of the final cavity prediction and provides the profile definition by the use of direct calculation. It is applicable not only to plastic molded gears but also to other plastic components. It also can be considered for other gear-forming processes that use mold or die cavities such as power metallurgy, die casting, and net forging.

CONCLUSION

The application of Direct Gear Design maximizes performance of plastic gearing by compensating for some of the polymer property limitations. Its guidelines for polymer gears include:

- Increased safety factors to guarantee sufficient tooth strength considering the wide range of material property variations caused by the molding process, operating temperature, humidity, etc.
- Increased tooth size (larger module or coarser diametral pitch) to reduce bending stress
- Lower number of teeth to fit into required center distance with given gear ratio
- Higher operating pressure angle and contact ratio to reduce bending and contact stress, and an increase tooth flank wear resistance
- Bending stress balance that equalizes safety factors of mating gears
- Specific sliding balance for higher efficiency and tooth flank wear resistance
- Root fillet profile optimization for bending stress reduction

The benefits of Direct Gear Design application include higher load capacity, reduced size and weight, extended lifetime, reduced noise and vibration, higher efficiency, higher reliability, and reduced cost.

The Genetic Molding Solution provides a methodology for a scientific, accelerated, and accurate gear cavity definition based on data derived from material, process, and initial mold cavity geometry. ▐

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2. Kapelevich, A.L., Shekhtman, Y.V., and McNamara, T.M., Turning an Art into Science. Motion System Design. August 2005: pp. 26-31.
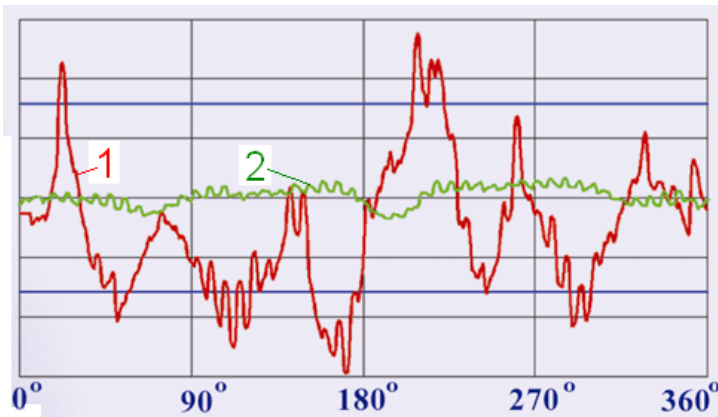
Figure 9: Genetic Molding Solution application; a) cam shaft gear, b) roll test chart overlay, 1) initial specimen chart (red), 2) final gear chart (green)

ABOUT THE AUTHORS: Dr. Alexander L. Kapelevich is the founder and president of the consulting firm AKGears, LLC, a developer of modern Direct Gear Design® methodology and software. He has over 30 years of experience in custom gear transmission development, and he is the author of "Direct Gear Design" and many technical articles. Kapelevich can be reached by email at ak@akgears.com.

Thomas M. McNamara is the research & development director for Thermotech Company. Thermotech is a precision custom molding company with expertise in plastic gear design, development, and manufacturing. Thermotech employs Direct Gear Design as the design methodology for plastic gear trains. McNamara has over 30 years of precision molding experience. He can be reached by email at thomas.mcnamara@thermotech.com.