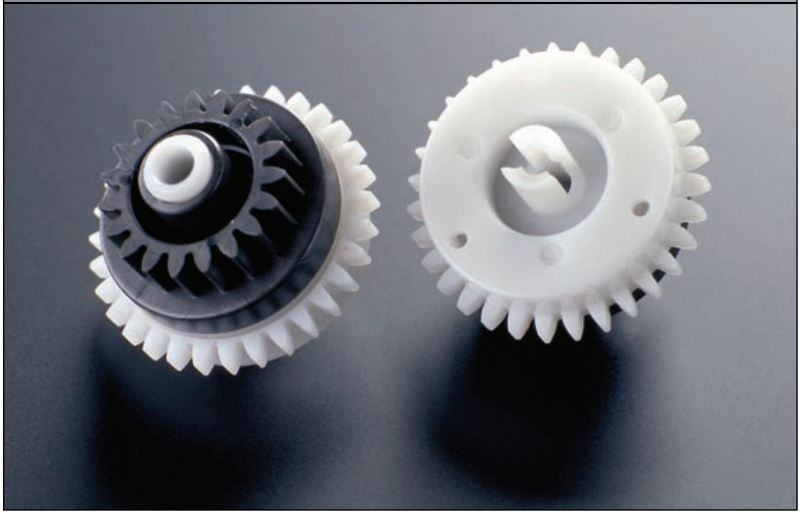
Processing and the Design of Precision Plastic Gears

Zan Smith and Dave Sheridan



Some gear geometries are more practical to produce than others. Since choices made early in the design process affect the ease and cost of fabrication, those who design gears would do well to consider molding and how molders operate, especially when they create precision gears.

Gears intended to maximize power and minimize transmission error can push tooling and processing equipment and the methods and plastics used to their limit. The same is true of designs for quieter drives, longer-lived gears or smaller gearboxes that retain the power of larger ones. The type of gear fabrication also affects molding operations.

Although plastic spur gears are usually produced in a straightforward injection molding process, as precision rises they demand more advanced tool-building skills to meet criteria for concentricity, tooth geometry and other features. Weld line considerations also become more significant with greater precision, especially when fiber-reinforced resins are used. Similar considerations apply to other gears, such as face gears and those having eccentric shaft locations and variable pitch surfaces.

Designs for plastic helical gears call for complex tool movements to aid in ejection. The tool must also account for differential shrinkage, such as in the axial versus radial dimensions. Part ejection is also an issue with internal gears and crowned gears. Tooling for internal gears may need ejector rings, floating cores and other mechanisms so parts can be removed from the core on which they form after a plastic shrinks upon cooling. The variable tooth profile in crowned gears and enveloping worm wheels has driven processors to devise proprietary methods to ensure their removal.

A Brief Look at Plastics in Gears. The polymer chosen affects fabrication. For instance, those that shrink relatively little in molding, such as liquid crystal polymer (LCP), make it easier to design tools for high-precision gears. The nature of the material also affects many molding parameters, such as the temperature and pressure used, mold filling speed, cooling time and mold release.

Plastics give gear designers many cost, design, processing and performance advantages compared to metal. Plastics can form gears that are hard to create at a reasonable price in metal, such as internal and cluster gears. They usually need fewer fabrication and assembly steps and are more forgiving because they deflect to absorb geometric irregularities and impact loads. Many have an inherent lubricity that makes them ideal for dry-running, low-load gears. In addition, they often resist water and many chemicals better than metal.

Acetal, polyester and nylon are the most common gear plastics. They process well and form gear sets with good fatigue and wear resistance, lubricity, rigidity and toughness. These and other engineering polymers tolerate elevated temperatures (Fig. 1). Unfilled acetal copolymer works to about 115°C, unfilled polybutylene terephthalate (PBT) and nylon 6/6 to about 150°C, glass-filled PBT and nylon 6/6 to about 170°C, polyphenylene sulfide (PPS) and liquid crystal polymer to about 220°C. High-temperature nylons and polyphthalamide have somewhat lower thermal limits than PPS, while imides and polyetheretherketone (PEEK) have higher limits.

Acetal, a primary gear material for over 40 years, offers dimensional stability, fatigue resistance, and good chemical resistance and lubricity. PBT works well in gear sets having gears made of other plastics and metal and yields smooth surfaces in molding. Nylons offer exceptional toughness and wear, but their dimensions are subject to change when they absorb water and many lubricants. As a result, they are not usually used when precision is needed.

Polyphenylene sulfide is stiff and dimensionally stable in molding and offers good fatigue life and chemical resistance. It is often the material of choice for drives in hot, corrosive industrial and automotive environments. Liquid crystal polymer flows exceptionally well to fill intricate, thin-walled parts with great accuracy and works well in small, lightly loaded gears. It withstands temperatures to 220°C and has low mold shrinkage. PEEK is often used in specialty, higher-temperature applications.

The call for quieter gears and low-wear, dry gears has led to greater use of flexible polymers and those having inherent lubricity. Elastomers, like polyester elastomer, help lower-power, lower-load gears run quieter. Lubricious polymers, like acetal copolymer, often enhanced by low-friction additives like a fluoropolymer or silicone, create gears low in wear and noise.

Fibers and fillers improve a resin's mechanical properties, especially stiffness, and let designers fine tune a material to a specific gear application. This is especially true of long fiber-reinforced plastics that can give large gears greater strength and dimensional stability. They also allow the use of less costly polymers; e.g., polypropylene reinforced by long fibers can provide better strength and stability at a lower cost than short-fiber-reinforced nylon. Flow direction in the mold and weld lines and other flow-related features become more important when fibers are present. Proper tool and processing conditions are critical for maintaining fiber length and mechanical properties. Also, with fiber present, weld lines can severely affect gear quality.

Processing Precision Gears. Molders face common challenges in fabricating precision gears. They need to hold exacting dimensions between the hub and the teeth, keep warpage at bay, maintain gear uniformity from shot to shot and cavity to cavity, and much more. These requirements affect all levels of fabrication, from tooling and molding equipment to work procedures and molding environment. Molding operations should strive for a wide and stable processing window that gives optimal material properties during prototyping and the early stages of production.

Tooling for precision gears calls for

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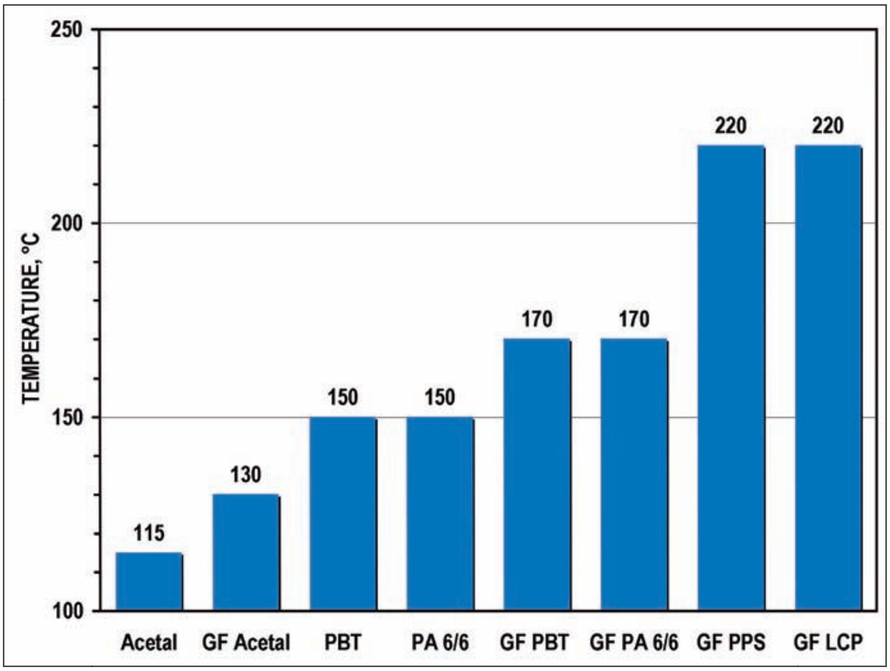

Figure 1—Upper-temperature limits for selected plastics and gears.

great attention to detail and often demands accuracies approaching that of gauge making. Plastic gears are routinely molded to AGMA Q7–Q9 standards and many are made to Q10–Q12 specifications. Designers should use only the precision level needed, since cost rises sharply with precision. A jump of two accuracy levels halves the allowable variation, which demands more sophisticated tooling and molding equipment and procedures, requires more involved inspection procedures, and other steps.

A common tooling issue for precision gears is the ability to cool symmetrically across a gear and uniformly in different cavities. The need to control cooling generally leads tool builders to keep the number of cavities in a tool to four or less for such gears. The mold cavity must be scaled so the gears shrink to the proper size.

Spur gears usually call for straightforward split-cavity molds, while other gears may need special movements so they can be removed from the mold. Helical gears, for instance, often need a tool that lets either the gear or the gear ring forming the teeth to rotate during ejection. With worms, ejection can also be done by unscrewing them from a cavity or by using multiple slides. Tool builders should minimize parting lines on the teeth when slides are used.

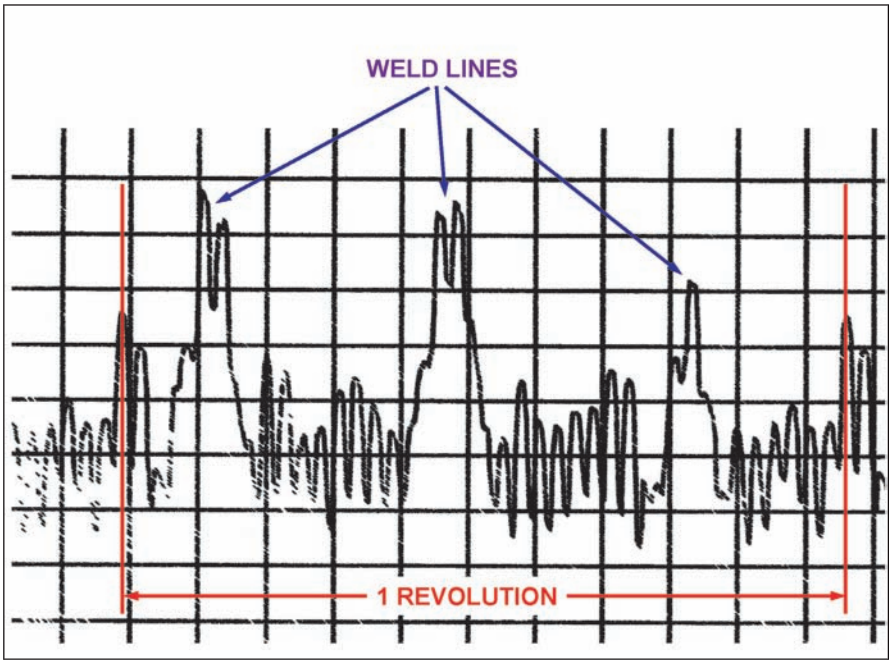

Figure 2—Double-flank roll checker composite measurement showing effect of three symmetrical, radial-weld lines (the three highest peaks) on a glass-reinforced gear.

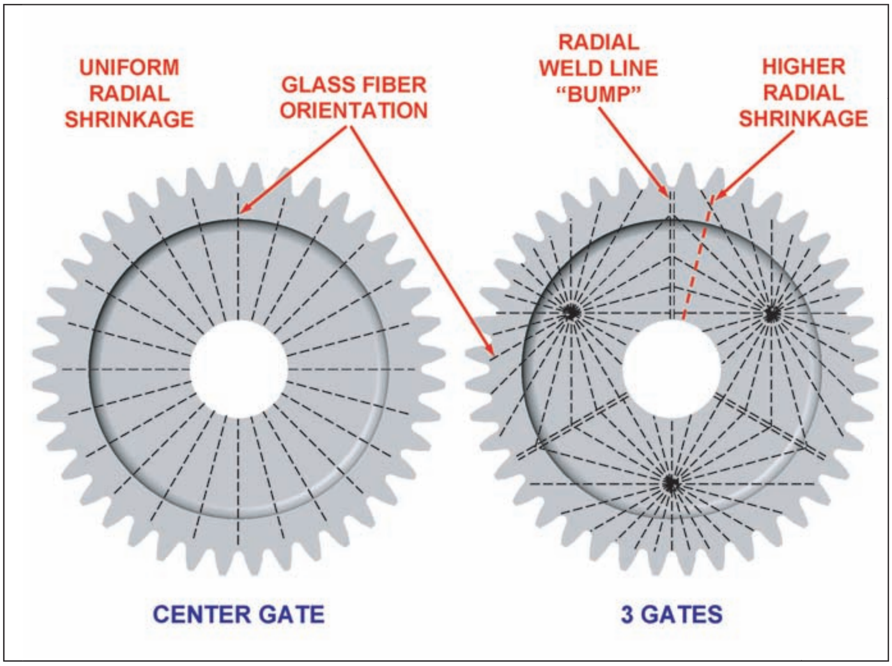

Figure 3—Glass-fiber orientation with center- and three-gate tools.

Controlling the flow in the mold when fibers are present is important for limiting weld lines and minimizing anisotropic shrinkage. Spur gears made with a neat resin can be filled from two or more gates. Fiber-reinforced polymers are best filled by a single gate at the center of the gear to avoid weld lines that form when multiple flow fronts meet (Figs. 2 and 3). Weld lines can affect tolerances as fibers align radially along a knit line and cause "run-out bumps."

In general, the higher the quality level, the less complex a tool should be. The use of multiple pulls, slides and other mechanisms can make it hard to retain precision because each action adds a variable. As a rule of thumb, the process should not give up more than a third of the accuracy requirement to the tool.

There are cases, however, when special mechanisms make a lot of sense. Adding inserts for teeth can reduce recutting costs when adjusting a tool during development. Inserts also reduce retooling costs as a mold wears because only the inserts need to be changed out and not the entire tool. Also, each tooth of a coarse pitch gear may be cored out to avoid the presence of substantial masses of plastic that distort as they cool (Fig. 4). The thinner walls gained in coring also shorten cooling time. While such cores make tools significantly more complex, the economies gained through faster cycle time can more than offset their cost.

Processors should ensure that imperfections caused by tools, such as gate vestiges, ejector marks and parting lines, as well as those that occur in molding, such as flash, flow lines and weld lines, appear in nonfunctional areas of the part so they do not affect gear function or quality.

Molding Operations. Molding is a holistic endeavor that begins with good part and tool design and extends to the molding equipment, polymer and the processing conditions used. Those who mold precision gears need advanced molding equipment equipped with the latest process controls that hold mold temperature, injection pressure, cooling and other variables within a tight window. Some gear processors go a step further and add pressure and temperature sensors in mold cavities to improve consistency and repeatability.

There is also a need to attend to all variables that can affect the process. The ability to make gears as uniform as possible time and again requires a focus on operating procedures and proper training. How workers act is often the deciding factor in producing precision gears. The goal is consistency at every step—from the initial receipt of a resin to packaging and storing the finished gear.

Molders of precision gears also need solid environmental controls. Gear dimensions can be affected as air temperature shifts with the seasons, or even for a few hours if an outside bay is left open. To remedy this, processors may place their equipment in closed cells, especially those elements concerned with cooling a part after it is removed from a mold. Processors often strive to provide airflow over hot gears and use consistent gear placement during cooling. Some shops remove gears from molds via robotics and place them on conveyors the same way every time so cooling is uniform.

Consistency extends to many other areas. Molding operations for precision gears should use dedicated equipment, a stable power supply and drying equipment that gives the polymer feed the same temperature and moisture level in all runs. If regrind is used, it should be clean, free of fines, dried properly to eliminate trapped moisture and added to the virgin material in consistent proportions.

Quality control inspections should occur at the same time after fabrication.

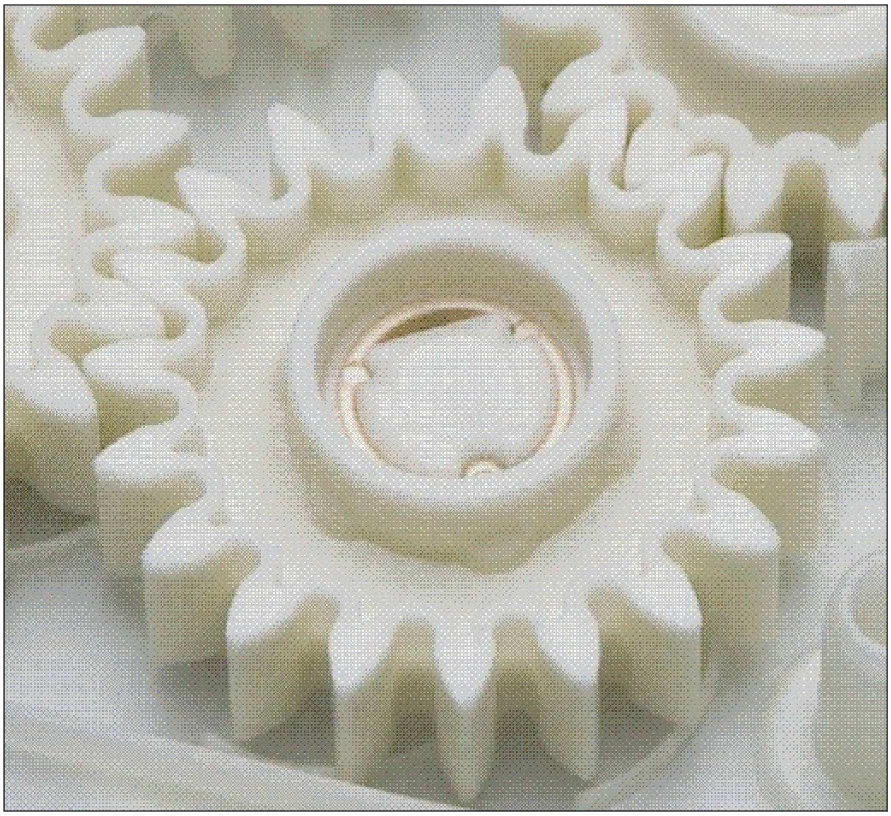

Figure 4—Coring out coarse pitch gears reduces processing time, weight and cost, and improves gear dimensional integrity.

Part weight is used to gauge the consistency and repeatability of the molding process. Production gear checking usually involves double-flank roll checkers, which give a composite measure of tooth thickness, runout and other features. Elemental inspection is often used when building and fine tuning precision tools and in prototyping to identify the cause of an error. Additional gear production quality control instruments include calipers and other standard hand tools.

Conclusion

The market for precision plastic gears is expanding in many directions, given the demand for gears that are quieter, more powerful and more accurate. While it is tempting to adopt elaborate solutions to meet gear design challenges, the ramifications for tool complexity and molding practices should be factored into the design process. In other words, those involved in the front end should keep the back end in mind by understanding the molding process and its inherent options and limitations.

This is best done in collaboration with a resin supplier, a tool builder and a molder early in the design process to help evaluate the processing aspects of different gear solutions. Such input can eliminate many production missteps and the extra cost and time lost in reworking a design that does not process well.

Designers who are knowledgeable about molding close-tolerance gears can also play a role in selecting a processor that offers the needed high-performance molding machines, procedures and environment to ensure gear consistency and repeatability.

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