feature article

FEATURE FOCUS: Power Transmission

gears from scratch

Plastic brings novelty to design and challenges to manufacturing.

by Paul Sharke, Associate Editor

Plastic gear maker Rod Kleiss said that holders of advanced mechanical engineering degrees have sometimes questioned his interest in gears. "Everything is known about gears," they'll often say.

True enough, Kleiss replies, if that means that most gear designers instinctively reach for a hob catalog on their way to designing a new gear. Practically everything needed to make metal gears turns up there, from standard pressure angles to uniform tooth shapes. Gear designers "can buy off-the-shelf hobs and make gears using what's available to them in standard cutters," he said.

Kleiss makes the point that, compared with the staid practice of manufacturing gears in metal, the science of plastic gearing is still in its infancy. Plastic does some things better than metal and many things worse. Making plastic gears requires a willingness to let slip the time-tested principles of cutting gears out of metal.

Kleiss mentions the experience of his principal engineer, a Russian, who worked on aircraft engine gear trains before immigrating to the United States. "He's used to making exotic shapes," Kleiss said. That turned out to be a real attribute when it came time for him to investigate gears of a medium different than metal.

Among the differences: Plastic gears can melt at temperatures where metal hardly sweats. But plastic gears can also run dry—without lubricant. They can be molded in unusual shapes and, in large enough lots, inexpensively.

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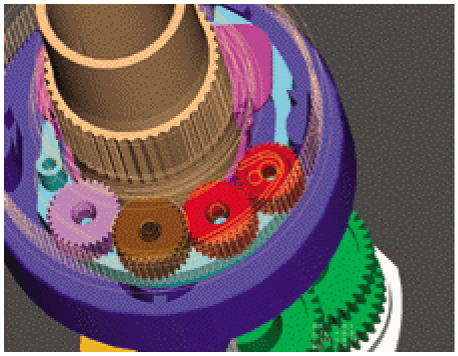


temperatures where metal hardly sweats. But plastic gears can also run dry—without lubricant. They can be molded in unusual shapes and, in large enough lots, inexpensively.

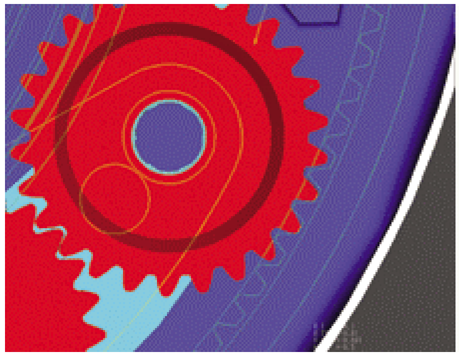
Plastic gears are ideally suited to the power transmission demands of a rotary sprinkler. They operate in wet conditions without oil or grease. Here, they drive a sprinkler head in alternating directions.

Despite many advances in plastic gear technology, users of metal gears haven't begun trading in all their current cogs for plastic versions. "We're in a delicate industry where we have to take things to extremes," Kleiss said, meaning that plastic wouldn't ordinarily be a gear designer's first choice for power transmission. Special circumstances have to apply.

For instance, Kleiss Gears, based in Shoreview, Minn., recently designed an epicylic train that, in a metal version available commercially, uses pins in place of gear teeth because of the expense of shaping internal involutes. The commercial reducer, manufactured by Tokyo-based Sumitomo Heavy Industries Ltd., is capable of reducing speed drastically within a single stage while also transmitting high power.

The Sumitomo train uses a notched wheel rolling within a circle of fixed pins to drive an output shaft. The notched wheel, mounted to an eccentric input shaft, has one less notch than the circle has pins. As the eccentric makes one complete revolution, the notched wheel increments the distance equal to the arc between successive pins. Keys tie the rotation of the notched wheel to an output shaft.

Tight tolerances and precision bearings make the commercial reducer expensive, Kleiss said. Kleiss's plastic version replaces the pins with an internal gear and the notched wheel with an external gear. By using involutes, the plastic version gains the advantage of what



Kleiss called "high tolerance relief," noting that "the center distance doesn't affect conjugate action."

Similar internal and external involute gears could be made in metal, Kleiss said. But making an internal gear takes shaping—a slower, more painstaking process than the simpler hobbing of an external gear. Because they are molded, plastic internal gears don't heed that limitation. Internal or external gears alike can be manufactured the same way.

That's not to say that making plastic gears is any small matter. The main concern in molding them is that they'll shrink upon cooling, throwing off any chance of obtaining accurate geometry in the final form. Kleiss approaches this problem by machining two cavities in two separate passes. The first one he uses to gauge how much the given design, molded from specified material, will deviate from the dimensions of the mold.

A single cavity can cost $5,000 to $10,000, he said. Wire EDM, Kleiss's method of choice for mold making, ensures a cavity as good as anything made by grinding, he added.

After inspecting an initial cavity and gear, Kleiss's engineers remake the cavity to match actual material shrinkage. Parts shrinkage is more complicated than mere photographic-like reduction, Kleiss said. Although major elements such as the various diameters of the gear shrink at nearly the same rate, other details such as tooth profiles shrink in widely disparate amounts, leading to unpredictability.

In order to reduce the chance of plastic gears jumping teeth in its sprinkler head, Hunter Irrigation molded an asymmetric tooth on the pinion that drives the ring.

For this reason, inspecting the preliminary gear takes on great importance in the quest to make accurate finished parts. The procedure goes beyond measuring the gear's outside diameter and rolling the part against a master gear to check form, he said. Instead, engineers will often scan an entire gear and match it point for point with the original CAD geometry. From that data, the engineers determine an overall shrinkage rate, which they then tailor to account for localized variations.

Cutting the mold for the second gear produces the production tooling from which thousand of parts can be made. But even these parts need testing to maintain a consistent molding cycle, Kleiss said. Techniques from simple roll-testing against a master gear to spectral analysis of finished transmissions ensure that the molding environment stays constant.

The results of this effort can be quite good, Kleiss said. The little plastic epicylic reducer worked fine; indeed, where tooth failure had been the overwhelming cause of transmission dysfunction, that distinction has now fallen to the bearings. "Though it's still a significant failure system, this is a remarkable shift because it has always been the teeth that fail and now we can't get them to fail," he said.

Just as surprising was that Kleiss's firm wasn't the first to make an involute with a one-tooth difference on an internal gear; at the time, though, the company suspected it was. Later, when the principal engineer pulled from the shelf a 1950s gear book written by a Russian engineer, the company learned otherwise.

"Sure enough," Kleiss said, "she'd hobbed 60-degree pressure angle with one-tooth-difference internal gears and wrote about it. Nobody ever picked up on it."

BREAK EVEN

Mold enough of them and plastic gears eventually compete with, then surpass, the economics of metal gears. For some industries—medical device manufacturing, say—the special properties of plastic gears that are unavailable in steel make cost considerations secondary. Most other users, including automobile and computer printer manufacturers, have to weigh the costs of molding plastic against the expense of cutting metal. "We're not trying to switch metal users to plastic," Kleiss said.

Neither is Closter, N.J.-based Intech Corp. The company has developed a method of cutting gears from plastic to take advantage of the material's strengths. At the same time, the company's approach retains some of the favorable characteristics of metal cogs that have made them so popular.
Intech's president, Georg Bartosch, places the break-even point for injection-molded gears somewhere between 3,000 and 5,000 units. For Intech's customers, that's often several thousand units too many, at least.

One of those customers—Procter & Gamble in Cincinnati—installed Intech's hybrid plastic and metal gears on an in-house production machine. Jeff Blumenthal, a P&G technology leader, could describe the machine only as part of a process of making "consumable consumer goods," due to his company's policy regarding proprietary matters. However, he could discuss the gears.

It was Bartosch who suggested that many paper-goods manufacturers liked using plastic gears in lubricant-free environments because doing so reduced the risk of staining the product. But as far as the function of the P&G machine was concerned, either Bartosch didn't know or he, too, wasn't talking.

At any rate, P&G engineers were looking for ways to "push the motor limits" in the new machine as far as possible, Blumenthal said. One way to do this was by reducing gear inertia on a component that accelerates from a stop to 1,300 rpm at frequent intervals. Another way was by running the gears without lubricants to dispense with the viscous drag of oil or grease.

Along with a requirement for repeatability, stiffness, and low chatter, the P&G transmission had an unusual need as well. A portion of the gear needed to mate with other components on the machine. The finished version would have to hold tight tolerances to guarantee its matching up with the other mating components.

Before any manufacturing could proceed, Tody Mihov

Intech's engineering manager, needed to run the opposing constraints of high torque, zero lubrication, fast pitch line velocity, and low inertia through the company's own gear program. To increase the gear's life, Mihov suggested several changes to the mesh, including a wider face, an optimized load sharing ratio and tooth size, a wear-reducing tooth modification, and a special coating on the metal pinion. After these changes, the program showed sufficient tooth root and flank pressure safeties.

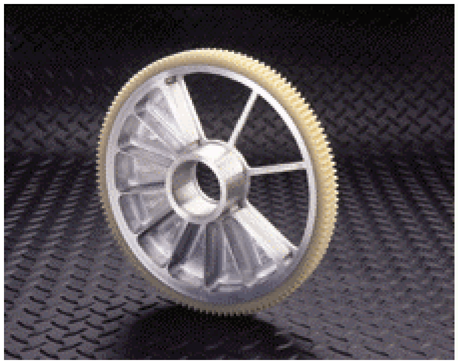
Next came the design of the blank. In fashioning its gears, Intech normally casts plastic around knurled metal hubs. This gear's unusual shape meant increasing the proportion of metal to plastic. Otherwise, the gear would lack sufficient rigidity beneath the plastic gear teeth, where material was cut away to accept the mating components, Bartosch said.

To make the gear, Intech cast nylon 12 around a core of 7075 T 651 aluminum. According to Bartosch, using stabilized aluminum minimized the internal stress that would be released during machining of the core. Such an event could throw off the hybrid gear's final dimensions.

Moisture, too, could cause the plastic gear to swell. But nylon 12, dimensionally stable compared with other nylons, would not require increased backlash in the final gear to compensate for moisture absorption. Actually, humidity wasn't much of a concern in the machine's working environment, Blumenthal said, although thermal expansion was.

Like humidity, heat can also swell plastic gears. Using a metal core cuts down on some thermal expansion, Bartosch said. Metal hubs can cut expansion of nylon 12 in half, he said. Operating with a steel pinion also helps to conduct heat away from the plastic gear teeth. And the metal hub of the plastic gear itself directs heat away from the system.

Heat also affects tooth cutting. So, liberal coolant bathes the cutting surface during hobbing to keep dimensional sway in check. Intech accomplishes the cutting itself with standard American Gear Manufacturers Association hobs and practices.



In developing the gear, both Intech and P&G made extensive finite-element investigations. A negotiation between the companies added one additional millimeter to the thickness of plastic that backs up the teeth. Otherwise, the stress of transmitting power through the tooth could pull the plastic off the core. As a rule of thumb, Bartosch said, they try to maintain at least one tooth depth for the backer to prevent separation of the plastic.

A hybrid gear gave Procter & Gamble lube-free, low-inertia power. Holes in the gear's web mated with other parts on the production machine.

When it came time to cut metal and plastic, Intech's engineers had to proceed cautiously for fear of distorting the final part. So the gear was cut in two stages. First, a machine rough-cut the metal portions, boring the hub and removing those sections of web where the part would eventually need to mate with components on the production machine. Then, the part rested overnight.

The next day, Intech engineers checked for "movement" to be sure that the metal was stable, Bartosch said. Then a machine finish-cut the aluminum to its final dimension.

Intech applied a similar strategy to the plastic teeth. Rather than hogging the gear teeth down with one pass of the hob, the machine made three precision cuts to bring the tooth forms to their rough dimensions. Again, the part sat overnight. Again, engineers checked for movement. Finally, the machine made a finishing hob of the teeth.

Hunter Irrigation of San Marcos, Calif., makes underground sprinklers for watering baseball fields and the like. Its main product, a pop-up irrigation head, uses a water-spun turbine to drive a gear train to oscillate the spray. According to engineering manager Matthew

Beutler, the gear-driven sprinkler head uses a reversing frame to change the direction in which the spray revolves. Any number of replaceable orifices control the throw of the spray.

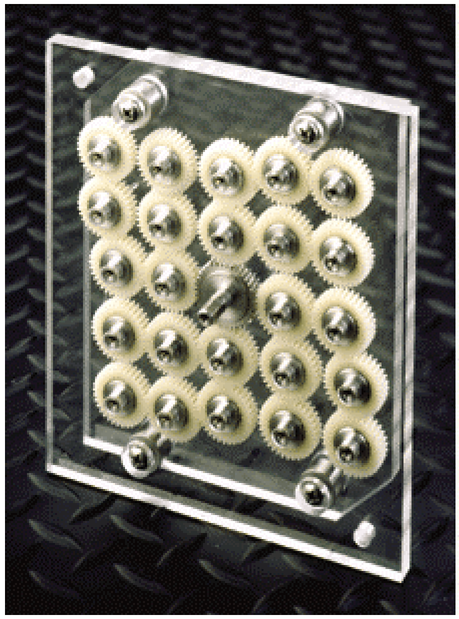
The reversing frame holds several gears in mesh. One gear brings torque up from the turbine and reduction below. A single and a pair of intermediate gears on either side of the input gear transmit its torque to two final gears. Spinning in opposite directions, the final gears alternate engagement with a large internal gear to drive the head in counter directions.

Beutler said the original design, which dates back to the 1960s, used standard gear teeth. In one direction, the final drive gear had a tendency to climb out of the ring gear under high loads and skip a tooth.

The company reevaluated the design in the 1980s. It found that by steepening the pressure angle on mating faces, Hunter could reduce the force acting to push the gear away. On the back side of the tooth, Hunter reduced the pressure angle, resulting in what Beutler called a "two-faced gear." The resulting tooth maintained sufficient thickness at the root so that it lost no strength, while reliability of the sprinkler improved.

As for materials, Hunter manufactures its gears from acetal resin, which swells less than nylon in wet conditions. Normally, the parts shrink initially after they're removed from the molds, then swell. But after 72 hours in humid conditions, the gears don't expand much more upon immersion, Beutler said.

Sprinklers are the kind of application in which plastic gears excel. Kleiss said his firm had done some work for another maker of geared rotary sprinklers, Rain Bird Corp. of Glendora, Calif. For one particular design Kleiss used an asymmetric buttressed tooth form to increase tooth strength. The new shape improved on the original part, he said. However, the original part was not so highly stressed that the company wanted to risk adding possible assembly mistakes by using it. So, Rain Bird stayed with the symmetric gears, Kleiss said.



BUILDING DATA

LNP Engineering Plastics Inc. of Exton, Pa., makes pellets for manufacturers of plastic parts. Ed Williams, an LNP application development engineer and chairman of the AGMA Plastic Gearing Committee, said that despite limited engineering data for plastic gears, designers can find other ways to determine how well certain materials will suit an application. Compiled wear data exists for plastic based on thrust washer wear tests, for instance.

The trouble with thrust washer data is that they are generated from tests that are purely tribological. "It's only testing wear," Williams said. "You've got two flat discs wearing against each other—all sliding—and no dynamic loading going on."

In this mockup for a latex dipping machine, 24 interchangeable hybrid gears replace 28 molded gears that required selective assembly.

Spur gears slide, but they also roll. "Every tooth is subjected to bending and then released," Williams explained. Both wear and fatigue affect a gear.

A thrust washer test is looking only at dry sliding or adhesive wear, he said. "There's a whole other set of circumstances thrown into plastic gears," he added.

That's why, several years ago, LNP began testing its materials as gears. But gear testing looks mainly at wear, not issues of shrink or thermal expansion or moisture absorption. Those properties LNP makes a part of its general characterization of materials.

"From that point of view, our aim toward the designers is mostly educational," Williams said. "They can't just run the same close center distances that they might run with metal. They need to understand that plastic can change shape with changes in temperature and humidity."

Shrinkage means that every cavity cut to make a plastic gear is "basically a custom cavity," Williams added. It doesn't cost any more to mold special designs. Not for manufacturing, anyway, even though design costs could rise due to the need to prove concepts.

It's becoming more practical in gear design to create odd teeth forms or unusual gear ratios because every molded gear is a custom design anyway. Even before the age of plastic gears, "people were throwing around the idea of unusual gear shapes," Williams said. The machinist with the rack of existing hobs made pursuing those ideas in metal unrealistic because of the costs.

"Some designers are really opening the box and stepping outside the commonplace, not just saying, 'I'm going to use a five-pitch gear because I can buy that hob,' " he said. Now, they don't have to do that. Still, custom gear shapes are not being done every day, he stressed. "It's still pretty rare. But, people are definitely looking at it."