Tips for Increasing Power Density in Gear Trains

William R. Mack

Introduction

Gear designers today are continually challenged to provide more power in less space and improve gear performance. The following article looks at some of the most common ways to increase the power density or improve the performance of gear trains. The author also takes an in-depth look at the case of a steel worm mating with a plastic helical gear and explores ways to optimize this increasingly common configuration.

Generated Involute Profiles

A generated standard tooth profile for pinions with about 20 teeth or fewer will show undercut near the bases of the teeth (see the 10-tooth standard pinion shown in **Fig. 1**). The bending strength of the pinion teeth is reduced significantly by the thinning of the bases of the teeth caused by this undercut. The most common approach to minimizing or eliminating this problem is discussed below.

Enlarged or Long Addendum Pinion Tooth Modification

In **Figure 2**, we have removed the undercut by creating an enlarged (or long addendum) pinion. This is done by moving the theoretical hob cutting position away from the center of the pinion and then adding full radii to the tips of the hob teeth. The result is a tooth profile that is significantly thicker at the root and has full fillet curves. Tooth bending strength is much improved, both by the increased tooth thickness and by the reduced root stress concentration provided by the full fillet curves. For molded gear teeth, the full fillet curves have the added benefit of improving plastic material flow.

The tooth bending strength factor is called the J-factor (see AGMA 908-B89). It is calculated using equations that consider the gear teeth as loaded cantilevered beams with stresses concentrated at the bases of the teeth.

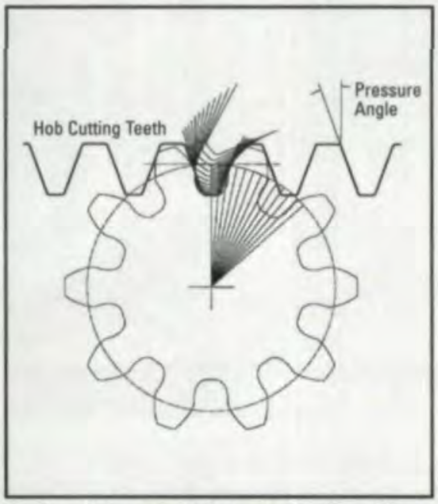

Fig. 1 — Hob-generated standard tooth profiles.

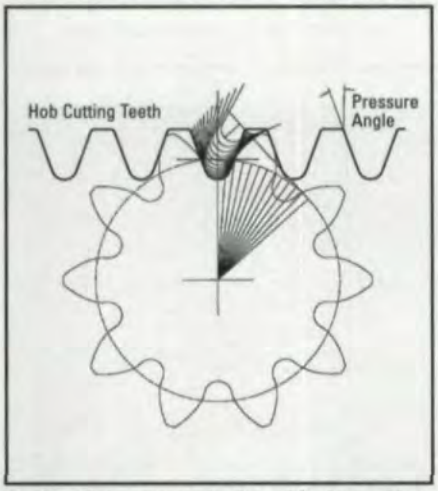

Fig. 2 — Hob-generated enlarged (or long addendum) tooth profiles.

To quantify the benefits of the above 10-tooth pinion modification, the tooth bending strength factor for the standard pinion is 0.0958 (**see Fig. 3**), and for the enlarged pinion it is 0.127 (**see Fig. 4**), when the pinions are mated with the same 36-tooth gear. The modified pinion has a 33% higher bending strength, in this case, equal to that of the mating 36-tooth gear (**see Fig. 4**). Equal bending strengths of the pinion and gear are a desirable design condition, assuming their face widths and material strengths are about equal. Pinion

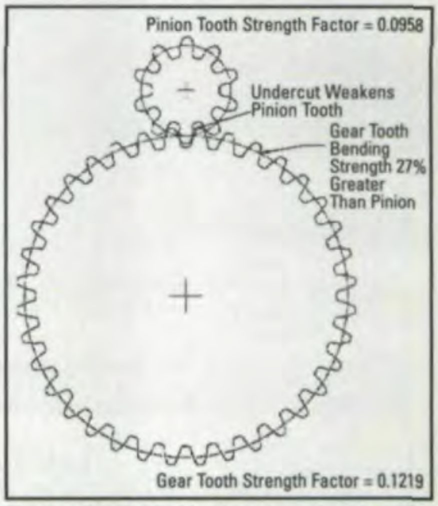

Fig. 3 — Standard addendum 10-tooth pinion with standard addendum 36-tooth gear.

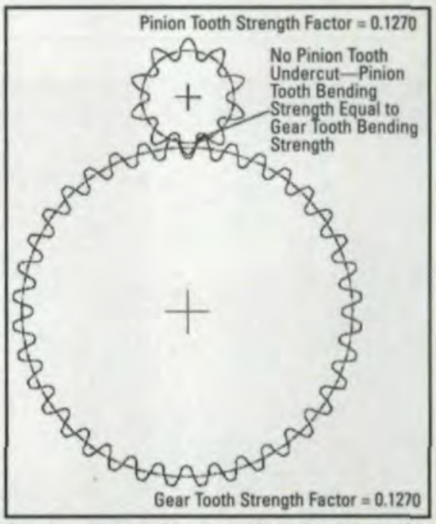

Fig. 4 — Long addendum 10-tooth pinion with standard addendum 36-tooth gear.

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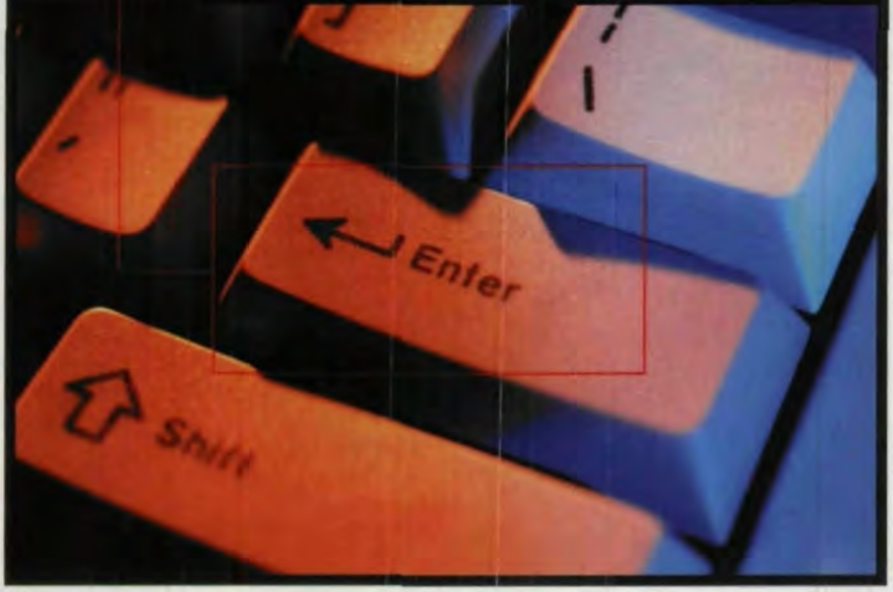


and gear bending strengths are directly proportional to their face widths and material strengths.

Tooth Modifications to Reduce Mesh Interference caused by Tooth Deflection

Figure 5 shows a condition that is more pronounced with low modulus gear materials, such as plastics, but that also applies to metal gears. The deflection of the mating pinion and gear teeth causes a tooth position error as the gear tooth to the right of the centerline rolls into an interference condition with the mating pinion tooth. This would likely result in noise, wear and/or loss of mesh efficiency.

Figure 6 shows a close-up of the interference and how a modification called "tip relief" would be applied to the gear teeth. Tip relief consists of a radius or curve developed to permit the smooth entry of the gear tooth into the pinion tooth space.

Ideally, this kind of interference condition would be modeled by finite element analysis (FEA) or some other beam analysis technique and the tip relief would then be accurately developed from the deflected model. More typically, however, standard tip relief geometry techniques are applied with satisfactory results (see AGMA 1006–A97). A pinion and gear that drive in both directions would require tip relief on both sides of the teeth.

Often, pinion and gear tooth tips are tip relieved to deal with common tooth-to-tooth error tolerances, even when tooth deflections are relatively low.

Optimization of a Steel Worm Mating with a Plastic Helical Gear

In order to maximize the power density of a steel worm mating with a plastic helical gear, we must first consider the most common failure modes for these gear sets.

Shear stress failure, caused by the worm thread outside diameter shearing through the plastic gear teeth, often occurs at high temperatures, when plastic gear materials generally degrade significantly in strength. This type of failure can be accelerated by high gear tooth contact stresses resulting in wear of the plastic gear teeth over the life of the gear set. Exceeding the Pressure-Velocity (PV) capability of the gear material can also contribute to gear tooth wear-related failures, especially in high speed, high torque worm and gear applications.

High stall friction at the worm and gear interface, which is sometimes caused by high impact loading at stall, can cause a jamming failure. This creates a condition where the available worm torque is not sufficient to overcome the friction and reverse the mechanism.

Worm and gear wear, caused by an abrasive plastic filler like glass fibers, can cause wearing of the steel worm thread and the plastic gear teeth. This can lead to premature failure and high friction caused by metal debris at the mesh interface. In most cases, it is advisable to harden worm thread surfaces that will interface with an abrasive plastic filler.

A standard worm and gear set is defined as one where both the worm and gear have tooth thicknesses equal to one-half the circular pitch (**see Fig. 7**). If the worm and gear materials were equal in strength, standard or near-standard tooth thicknesses would be specified.

When a steel worm mates with a helical gear made from a lower strength material, such as plastic, the shear strength, compressive strength and bending strength of the worm can be significantly greater than that of the gear. Therefore, the thickness of the mating gear teeth should be increased above the standard thickness and the worm thread thickness reduced, correspondingly, to below the standard thickness. This balances the worm and gear strengths and yields a higher power density in the same package size. This concept is illustrated in **Figure 8**.

Other worm and gear modifications are also important for increased power density:

- Minimizing the worm and gear pressure angles will reduce mesh separating forces, increase gear tooth thickness near the tips of the teeth where shear failures can occur, increase mesh efficiency and contact ratio, and provide more teeth to share the loads.
- Maximizing the worm and gear tooth depths can also add significantly to the mesh contact ratio, thus increasing power density.

There are manufacturing limitations, however, controlling the degree to which worm threads can be thinned, worm pres-

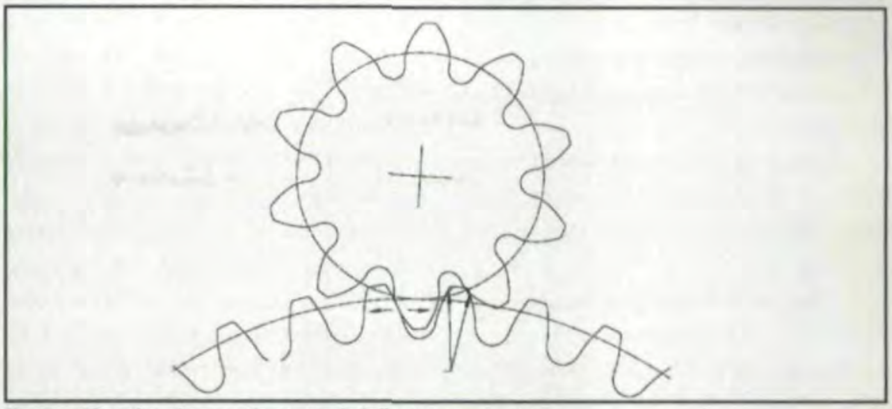


Fig. 5 — Mesh interference due to tooth deflections under load.

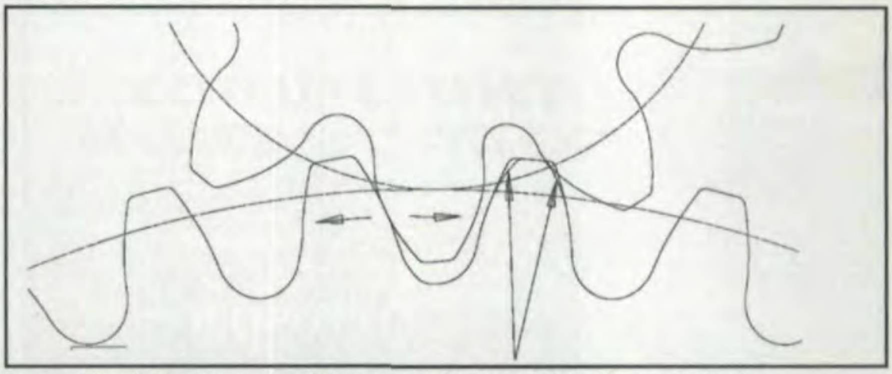


Fig. 6 — Tip relief to overcome mesh interference due to tooth deflections under load.

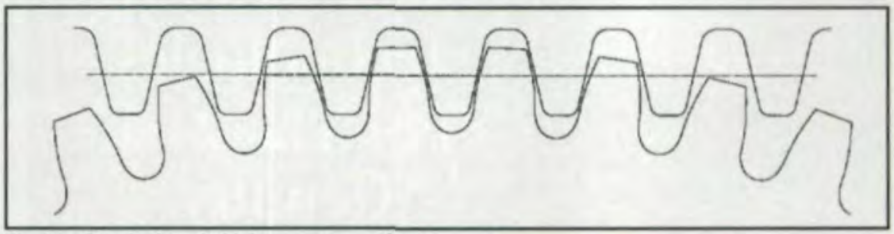


Fig. 7 — Standard tooth thickness worm and gear.

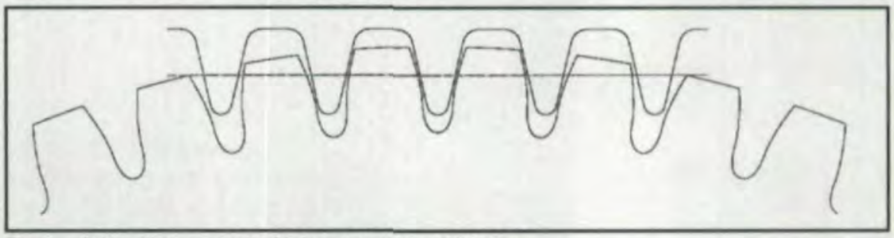
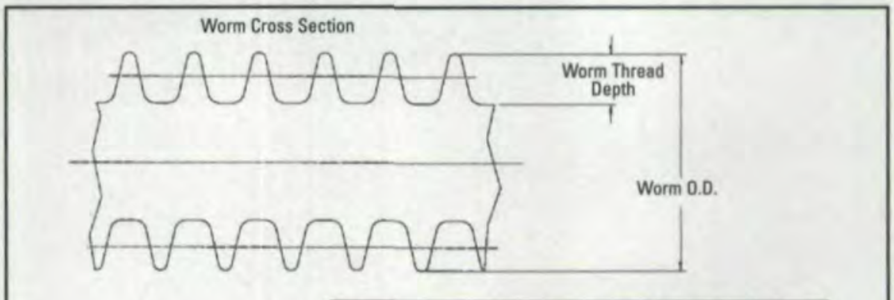


Fig. 8 — Thinned worm tooth, thick gear tooth modification.



	Worm Thread Depth/O.D. Ratio	
Worm Thread Starts	General Guidelines	Observed In Use
Single	0.167	0.200–0.240
Double	0.250	0.250–0.280
Triple	0.200	0.200–0.227

Fig. 9 — Rolled worm thread depth and outside diameter guidelines.

sure angles can be reduced and worm thread depths can be increased. The selected worm manufacturing process will affect these limitations.

The most common worm thread manufacturing processes are machining (hobbing, chasing, or grinding) and rolling (cold forming).

Worm Rolling Optimization Characteristics

In brief, the worm rolling process consists of two cylindrical, rotating rolling dies that move from opposite sides into a plain shaft blank to form the desired threads. This is done using a machine designed specifically for thread rolling.

Rolled worm threads are commonly specified for high volume applications. While the tooling costs for rolled worms can be much higher than for machined worms, they are generally offset by a production cycle time that is three to six times faster than machining. The rolled worm cycle time is even more advantageous when comparing rolled multi-start worms with machined multi-start worms that sometimes require multiple passes.

Another advantage of rolling threads is a generally higher quality thread flank surface texture than that which is typical of single-pass machined worm threads. Better surface texture can maximize mesh efficiency, reduce wear on the mating gear teeth and yield a quieter gearset. The quietness improvement, however, assumes that the rolled worm thread has the same quality, in terms of runout and other critical thread dimensions, as a machined worm. This assumption is not generally a good one, as discussed below.

Work-hardened thread flank surfaces, resulting from the compression of the metal during the rolling process, can produce a harder and more durable surface.

The Effects of the Worm Rolling Process on Gear Set Optimization

Rolled worms have more manufacturing limitations affecting the optimization process than machined worms. These limitations affect the following key thread elements:

- Tooth depth
- Tooth thickness
- Pressure angle

When you optimize any one of these thread elements, you limit the optimization of the other two. Therefore, a balance must be achieved by seeking the best combination of the three elements to produce an optimized worm and gear set.

Tooth Depth Optimization. This is a very effective tool in gear set optimization. Rolled worm thread Depth/O.D. guideline data is shown in **Figure 9**. This guideline data shows that the overall quality of a worm thread, especially in terms of runout, is more easily achieved for an even number of thread starts than it is for an odd number. The reason is that the rolling die teeth are directly opposite one another when rolling an even start worm, and are offset from one another when rolling an odd start worm. Offset die teeth tend to cause more bending (runout) of the worm during the rolling process. However, rolled worm runout can be improved by the addition of a straightening operation after rolling.

Tooth thickness optimization. Thinning is also a very effective optimization tool

because thickened mating gear teeth reduce their shear and bending stresses. Tooth thinning optimization in rolled worms is limited by the requirement that some minimum tip radii must be specified so the material will flow properly to the tips to allow for a knit line void where the two sides of the thread meet during rolling. The size of the tip radius limits how thin the thread can be. Generally, a tip radius of about 0.010" is the minimum.

Pressure Angle Optimization. Reduction for rolled worms requires the rolled material to flow up a steeper slope to fill the rolling die profiles, making it more difficult to achieve acceptable profile quality and thread flank surface texture. Pressure angles as low as 10–11° have been rolled, but this can limit tooth thickness and tooth depth optimization.

Power Density Optimization Characteristics of the Worm Machining Process

Some of the most common worm thread machining processes are hobbing, grinding and chasing. When optimizing the design of a worm thread, the same basic optimization characteristics apply to all three processes. Again, we'll consider the optimization of the following key thread elements:

- Tooth depth
- Tooth thickness
- Pressure angle

Tooth depth. This is limited only by how small the worm minor diameter can be before causing excessive deflection and/or bending stresses under load. Also, care should be exercised to avoid undercut of the mating gear profiles caused by a deeper-than-standard worm thread.

Tooth Thickness Optimization. Thinning is limited by reaching the point where the thread tips come to a sharp edge. However, a sharp-edged thread has the potential disadvantages of production handling damage, injury to workers handling it, and scraping and wearing of the loaded mating gear teeth. In addition, a worm thread can be thinned to the point where it becomes so weakened that it could fracture under load.

Pressure Angle Optimization. Reduction has limitations relative to thread surface texture. A machined pressure angle in the 10–12° range will make it more difficult to control surface texture than a pressure angle in the 14.5–20° range. Machine settings can be adjusted to deal with surface texture control, but cycle time and tooling costs may increase.

A major advantage of machined worms, relative to rolled worms, is their ability to hold thread runout closer than rolled worms, which results in fewer noise and wear issues.

In conclusion, if a machined worm thread can compete with a rolled worm thread in meeting cost and quality goals, the gear designer has a greater advantage in designing a higher power density gear set. ⚙

This article is based on materials that were first presented at the SAE Plastic Gears for Power Applications TOPTEC held August 26–27, 1998 in Dayton, OH.

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