


# Manufacturing Single-Enveloping Worm Gear Sets

By Roger Burdick

**F**irst, the basics. Worm gear sets are used to transmit power between non-parallel, non-intersecting shafts, usually having a shaft angle of  $90^\circ$ , and consist of a worm and the mating member, referred to as a worm wheel or worm gear. The worm has teeth wrapped around a cylinder, similar to a screw thread. Worm gear sets are generally used in applications where the speed reduction ratio is between 3:1 and 100:1, and in situations where accurate rotary indexing is required. The ratio of the worm set is determined by dividing the number of teeth in the worm wheel by the number of worm threads.

The direction of rotation of the worm wheel depends upon the direction of rotation of the worm, and whether the worm teeth are cut in a left-hand or right-hand direction. The hand of the helix is the same for both mating members. Worm gear sets are made so that the one or both members wrap partly around the other.

Single-enveloping worm gear sets have a cylindrical worm, with a throated gear partly wrapped around the worm. Double-enveloping worm gear sets have both members throated and wrapped around each other. Crossed axis helical gears are not throated, and are sometimes referred to as non-enveloping worm gear sets.



The worm teeth may have a variety of forms, and are not standardized in the way that parallel axis gearing is, but the worm wheel must have generated teeth to produce conjugate action. One of the characteristics of a single-enveloping worm wheel is that it is throated (see figure one) to increase the contact ratio between the worm and worm wheel teeth. This means that several teeth are in mesh, sharing the load, at all times. The result is increased load capacity with smoother operation.

In operation, single-enveloping worm wheels have a line contact. As a tooth of the worm wheel passes through the mesh, the contact line sweeps across the entire width and height of the zone of action. One of the characteristics of worm gearing is that the teeth have a higher sliding velocity than spur or helical gears. In a low ratio worm gear set, the sliding velocity exceeds the pitch line velocity of the worm. Though the static capacity of worms is high, in part because of the worm set's high contact ratio, their operating capacity is limited due to the heat generated by the sliding tooth contact action. Because of the wear that occurs as a result of the sliding action, common factors between the number of teeth in the worm wheel and the number of threads in the worm should be avoided, if possible.

Because of the relatively high sliding velocities, the general practice is to manufacture the worm from a material that is harder than the material selected for the worm wheel. Materials of dissimilar hardness are less likely to gall. Most commonly, the worm gear set consists of a hardened steel worm meshing with a bronze worm wheel. The selection of the particular type of bronze is based upon careful consideration of the lubrication system used, and other operating

conditions. A bronze worm wheel is more ductile, with a lower coefficient of friction. For worm sets operated at low speed, or in high-temperature applications, cast iron may be used for the worm wheel. The worm goes through many more contact stress cycles than the worm wheel, so it is advantageous to use the harder, more durable material for the worm. A detailed analysis of the application may indicate that other material combinations will perform satisfactorily.

Worm gear sets are sometimes selected for use when the application requires irreversibility. This means that the worm cannot be driven by power applied to the worm wheel. Irreversibility occurs when the lead angle is equal to or less than the static angle of friction. To prevent back-driving, it is generally necessary to use a lead angle of no more than  $5^\circ$ . This characteristic is one of the reasons that worm gear drives are commonly used in hoisting equipment. Irreversibility provides protection in the event of a power failure.

It is important that worm gear housings be accurately manufactured. Both the  $90^\circ$  shaft angle between the worm and worm wheel, and the center distance between the shafts are critical, so that the worm wheel teeth will wrap around the worm properly to maintain the contact pattern. Improper mounting conditions may create point, rather than line, contact. The resulting high unit pressures may cause premature failure of the worm set.

The size of the worm teeth are commonly specified in terms of axial pitch. This is the distance from one thread to the next, measured in the axial plane. When the shaft angle is  $90^\circ$ , the axial pitch of the worm and the circular pitch of the worm wheel are equal. It is not uncommon for fine pitch worm sets to have the size of the teeth specified in

terms of diametral pitch. The pressure angles used depend upon the lead angles and must be large enough to prevent undercutting the worm wheel teeth. To provide backlash, it is customary to thin the teeth of the worm, but not the teeth of the worm gear.

The normal circular pitch and normal pressure angle of the worm and worm wheel must be the same. Due to the variety of tooth forms for worm gearing, the common practice is to establish the form of the worm teeth and then develop tooling to produce worm wheel teeth having a conjugate profile. For this reason, worms or worm wheels having the same pitch, pressure angle, and number of teeth are not necessarily interchangeable.

## Worm Production Methods

The exact form of the worm teeth is a function of the method used to finish the teeth. Worms may be milled in a thread miller or similar machine, using a double conical milling cutter having an included angle equal to two times the pressure angle of the worm. Worm tooth grinding is usually done in a thread grinding machine, using a grinding wheel dressed with a double conical form. The worm teeth may also be produced by using a single-point tool in a lathe. This is the same method used for cutting screw threads. Production quantities of fine pitch worms often have the teeth produced by rolling, using the same type of equipment

used for rolling screw threads. Multiple-thread worms are often produced by hobbing, generating the teeth as a helical gear. Additionally, equipment is available for finishing worm teeth by grinding one tooth flank at a time, using the flat side of a grinding wheel. Machines are also available employing the same principles for milling teeth. This system is most commonly used on large worms.

It is important to note that changes in production methods may result in significantly different tooth profiles, particularly in the case of higher lead angles. For example, a worm milled with a 150mm diameter thread milling cutter will have a different tooth form than a worm of the same axial pitch and pressure angle that has been ground with a 500mm diameter grinding wheel, though the basic cutting principals are the same.

## Worm Wheel Production

Worm wheel teeth are most commonly produced by hobbing. Two methods are commonly used—the radial infeed method or the tangential feed method (see figures two and three). Either method can be used to produce a throated worm wheel.

Before the hob can be designed and manufactured, it is necessary that the hob designer be provided with information about the worm production method, and details of the worm tooth profile, in order that the hob can produce a worm wheel with a tooth profile conjugate to the worm.

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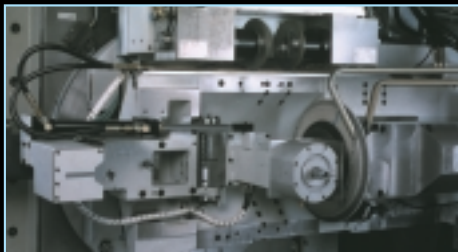
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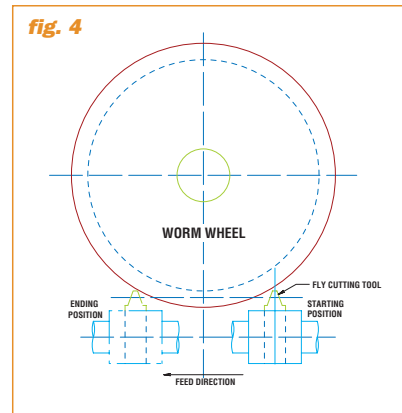
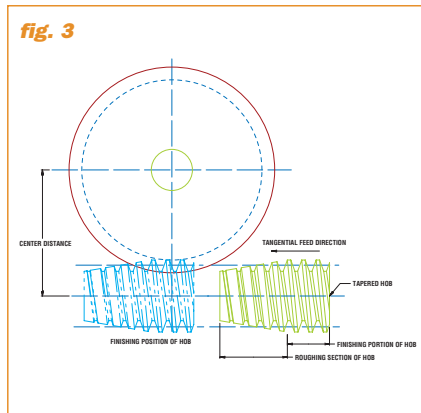
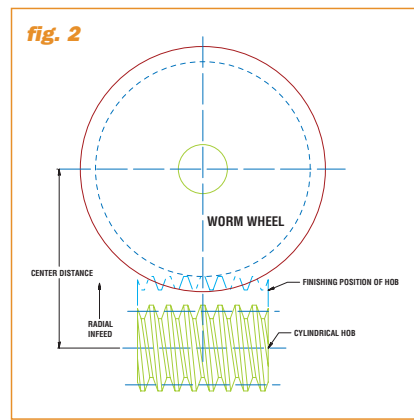
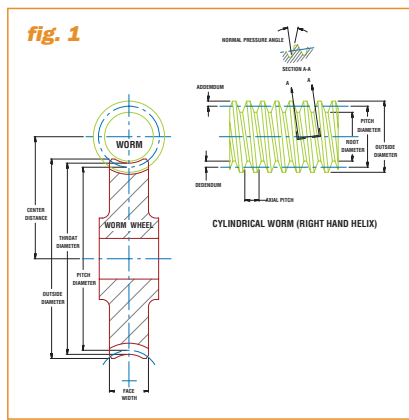
With either method, the hob is not fed axially in relation to the worm wheel, but rather its position is fixed. The axial location of the hob when the teeth are generated establishes the location for the axis of the worm.

In theory, the hob duplicates the worm, in regard to circular pitch, pressure angle, and tooth form, but if the hob was manufactured to these specifications, the hob wouldn't be useable after its first sharpening, as it would be smaller than the worm. The result of cutting a worm wheel with a hob that is smaller than the worm is that, in use, the worm would only contact the worm wheel at the outer edges of the teeth.

Hobs for cutting worm wheels are designed to be larger than the worms by an amount that allows a number of resharpenings before the hob has to be replaced. The use of a hob slightly larger than the worm causes two things to happen: 1) the increased radius of curvature causes the tooth contact to be concentrated in the center of the worm wheel teeth, and; 2) it will be necessary to make a slight correction to the 90° angle between the hob and worm wheel centerlines. The manufacturer of the hob can supply information on methods for calculating the amount of angular correction required at any point throughout the life of the hob.

Radial infeed hobbing (figure two) is most commonly used for worm wheels having a relatively low lead angle, and for commercial grade products. There are a large number of worm gear sets manufactured to replace damaged or worn equipment. Many of these are made in plants that don't have equipment for producing worm wheels by any method other than radial infeed hobbing. The number of flutes in the hob influence the accuracy of the tooth profile, which is generated as a number of flats or facets. Radial infeed hobbing is generally considered to be the most economical method of worm wheel production.

Tangential hobbing (figure three) is generally the preferred method for producing worm wheels having high lead angles, and gears requiring particularly accurate tooth profiles. It is necessary to use a hobbing machine equipped with differential gearing, so that the hob is fed longitudinally along its axis as it revolves. The hob is designed with a tapered section and a cylindrical section. The tapered portion of the hob roughs the teeth, and as the hob advances, the cylindrical



section of the hob finishes the teeth. The combination of the rotary and axial motion creates a condition similar to using a hob with many cutting flutes. As a result of this the tooth profile consists of a great many very small flats, more nearly approximating the theoretical tooth profile.

Fly cutting, or fly hobbing, is another method that is used to manufacture worm wheels. This uses a cutting tool that is essentially one finishing tooth from a hob, mounted in a suitable holder on the arbor of a hobbing machine equipped for tangential hobbing. This one tooth is traversed through the work, tangentially. The cutting tool is usually referred to as a "fly cutter" or "fly tool." The tool will rough and finish the worm wheel in a single pass, except in cases where the number of teeth in the gear and the number of threads in the worm have a common factor. In these cases the fly tool will have to be indexed for each thread in the worm until the worm wheel is complete.

Fly cutting (figure four) has several advantages over hobbing. The cutting tool can be produced much more quickly and less expensively than a hob. These are issues of particular importance in cases of very limited part quantities, or situations where the timely production of a worm wheel—as in breakdown situations—is the goal. Other advantages over

hobbing are that a fly tool has no lead errors, flute spacing errors, or tooth-to-tooth form variation errors. Additionally, fly cutting offers excellent control of the cutting center distance. The fly cutter profile can be chosen to provide the optimum fit between the worm and worm wheel. For these reasons, fly cutting is often the method preferred for finishing worm wheels used for precision indexing.

Worm wheel tooth production by fly cutting is much more time consuming than other tooth generation systems. There are several reasons for this, one being that a single tooth is removing all the material from the tooth spaces. Also, to achieve high accuracy and surface finish, the tangential feed rate must be small; this is particularly true in the case of worms having multiple threads and a non-integral ratio. In an effort to reduce production time, worm wheels are sometimes roughed by milling or hobbing before finishing by fly cutting.

## Inspection

The acceptability of a worm set is usually based upon contact pattern and backlash. The inspection of worms and worm wheels has many features in common with the inspection of both helical gears and bevel gears. Worm profile and lead can be checked, and contact patterns can be used to verify mating conditions.

Cylindrical worms are inspected by direct measurement. Lead and tooth spacing may be measured in the same equipment that is used for the inspection of helical gears. The tooth profile is usually not a true involute surface, but rather a form that is straight-sided, or nearly so. Inspection equipment is available that can measure the profile, indicating the deviation from a straight line. Worm tooth thickness can be checked by either a measurement over pins or a gear tooth caliper measurement.


Worm wheels are inspected by meshing them either with the mating worm or a master worm. This may be done using a universal worm gear inspection machine or in a dedicated checking fixture. In preparation for the contact check, marking compound of contrasting colors is applied to the worm and worm wheel. The worm is meshed with the worm wheel, and set at the correct center distance. The worm is rotated, driving the gear. This should be continued until the worm wheel makes at least one revolution. The resulting contact pattern is inspected for width, length, and location. Design requirements will generally specify the size and location of the contact pattern, based on tooth loading, speed, contact ratio, accuracy, and application. Contact at the extreme edges of the teeth is to be avoided, particularly in the absence of contact in the central portion of the teeth. If application information is available to the manufacturer, the accepted practice is to develop a bearing pattern showing less contact on the "entering" side of the mesh. This allows the lubricant to be drawn into the contact area.

Because of the sliding action between the worm and worm wheel, worm sets exhibit more wear when initially put in service than other gear types. For this reason, the requirements will allow a more limited contact pattern on new parts, in anticipation of rapid wearing-in.

Also, because of the concave form of the worm wheel teeth, it is not practical to measure tooth thickness using pins, balls, or gear tooth calipers. Measurements of the backlash of the pair can indirectly measure the thickness of the teeth. Backlash should be checked in several locations; variations in backlash indicate eccentricity or tooth spacing variations.

Software is available to allow the inspection of both worms and worm wheels in coordinate measuring machines. While not a substitute for contact pattern and backlash inspection, this is a very valuable addition to more traditional inspection methods.

## Conclusion

Worm gears have been used for several hundred years, and single-enveloping worm gears are the most common type of worms. A properly designed and manufactured worm gear set offers a compact form of reduction gearing that has low noise and vibration and is tolerant of short-term overloads. Worm gearing can be manufactured economically, and if well maintained and lubricated, will provide a long service life. 

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