

as the WORM TURNS...

PRECISION, EXCELLENT SURFACE FINISH, AND HIGH FATIGUE STRENGTH ARE JUST A

Cylindrical die worm rolling is a proven high-speed process which can produce precise worms with excellent surface finish and high fatigue strength when correctly applied. In this process, a surface of revolution such as a thread, knurl, spline, worm, or gear is formed in a deformable material by a set of cylindrical rolling dies which are forced into a cylindrical blank while driving it at substantially the same surface velocity. The die axes are either parallel or skewed at a low angle with the worm axis. The rolling torque is provided by an electromechanical system, with each driving the dies in phase rotation with respect to one another.

The radial forming force (radial die load) can be supplied by either of three methods. In-feed is the most common method, where one die is moved with respect to the other on parallel axes by the use of hydraulic or electromechanical means. It is used to produce discrete lengths of worm on shafts.

The other common method uses skewed axis dies whose centerlines are held in rigid position with respect to one another. The worm teeth are created by progressively increasing die teeth penetrating into the bar while it is rotating and moving axially between the dies. This through-feed method is used to produce long worm bars for subsequent machining into a finished part.

toward ROLLING

by Howard A. Greis



FEW OF THE ADVANTAGES TO BE ACHIEVED USING CYLINDRICAL DIE WORM ROLLING.

The third is the scroll-feed method, which is a hybrid between infeed and through-feed rolling. The die axes are parallel and held rigidly with respect to one another, and a series of penetrating ribs the width of the worm to be rolled rise out of the die gradually around its circumference, so that the full penetration of the die is achieved in one die revolution.

Worm rolling evolved from thread rolling in the 1960s. Early uses were window-opening worms and windshield wiper worms. Since then, infeed rolling and scroll-feed rolling have found a much wider use as a secondary process, mostly as a final operation on finished shafts, or as an in-process step on shaft blanks prior to heat treat and finish grinding. Figure 2 shows some typical worms. Included are some which, because of their tooth form or part handling requirements, must be rolled by the scroll-feed method. Worm length is limited by the available rolling die face.

Through-feed worm rolling is used as a primary operation to create continuous worm bar. Figure 3 shows sections of such worm bar which are generally under 20 feet longer, the only limit on length is the ability to support and drive the rotating bar. The bars are machined into short worm shafts, or worms with a bore which are subsequently assembled onto the end of a shaft.

Most of the examples are in the range from 5/16 inch to 1 1/2 inch in diameter, but it is practical to roll worms as small as

1/16 inch and as large as 4 inches. In addition, the number of starts and the form characteristics can be varied as required for the application.

All of the above applications follow the basic rolling process parameters that will be reviewed below. They are generally size scaleable. After determining the general worm and gear size for function, the next question is what tooth form to use? Most of the rolled worms employ standard gear forms in which the pressure angle is either 14 1/2 degrees or 20 degrees, and the addendum is 1 over the diametral pitch, and the dedendum is 1.157 over the diametral pitch. A 16 diametral pitch with a 14 1/2 degree pressure angle with an outside diameter of 3/4 inch is typical for a medium-size rolled worm which would be found in standard right angle gear boxes, where it meshes with a bronze or steel gear. As worms began to be used in automotive windshield wiper, window lift, and similar permanently lubricated gearboxes, the mating gear material has been changed to a molded plastic. In order to balance the load-carrying capacity of the plastic teeth with that of the steel worm, the worm tooth space has been widened and the worm tooth thinned. In some applications, where there is a need to decrease the separation force between the worm and the gear and to increase the contact ratio, the pressure angle had been reduced to 10 degrees.

At the other extreme are worms that are used for adjusting the slack in truck airbrakes. In this application, the goal is to support a high level of repeating of unidirectional shock load without fatigue failure. To achieve this, a deep buttress form is used.

The tooth height consists of the amount of radial penetration of the die into the blank plus the amount of radial growth of the displaced material. In-feed and scroll-feed rolling are essentially constant volume processes in which the displaced material primarily flows radially around the penetrating die tooth. Therefore, for standard tooth forms, the blank diameter is close to the pitch diameter. However, when through-feed rolling worm bar, the blank diameter often is increased to compensate for axial stretch occurring in the initial penetrating area of the dies. The maximum tooth height that can be produced is a function of the part and process variables which create and limit the radial material flow. The part variables, in addition to flank angle, include tooth height to tooth thickness ratio, tooth space to tooth thickness ratio, and root shape and material rollability. In some situations the ratio of rolled OD to tooth depth also limits the total tooth height.

Figure 1 — Rolling modes

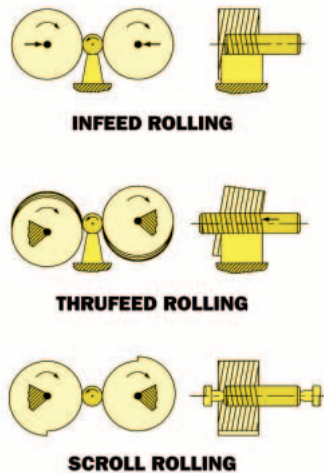


Figure 2 — Typical infeed and scroll feed worms



As flank angle is decreased to a minimum and the tooth is thinned relative to pitch, the reduction of the tooth thickness limits the worms rollability. As shown in Figure 4, measured at half the full depth, a tooth height 2.5 times the tooth thickness is at the upper limit for a single start worm. As starts are added, that maximum ratio goes down. With the thinning of the teeth,

the maximum safe ratio of tooth space to tooth thickness is also about 2.5 at half tooth depth, but in no case is it practical to thin the teeth to the point that it eliminates any crest flat unless it is replaced by a full tangent radius of about 9 percent of the thread depth. All of the foregoing relationships are based on forming good rollable materials.

A rolled tooth form must also have another key characteristic: the shape of the root. Since the root of the worm is formed by the crest of the penetrating die, the shape of that root determines the pattern of metal flow which occurs during the rolling. Roots should be designed with the maximum allowable root corner radius, and if possible that radius should be tangent to the flank and the root flat.

Figures 2 and 3 show worms where the root corner radii were maximized, if possible. However, when it is necessary to achieve deeper metal flow and a high ratio of radial flow to die penetration, a broader die crest is required which in turn increases the worm root flat. This can be seen in Figure 4.

However, the degree to which this can be done is limited by the tooth depth to diameter ratio as discussed below.

For lower gear ratios, it is frequently necessary to increase the number of starts in the worm. Generally, that number is limited by the resulting lead angle. As the lead angle approaches 30 degrees, worm diameter, die geometry, seam formation, and other rolling process factors may limit the number of starts.

However, six start rolled worms are not uncommon, and in Figure 3, a 37-degree pressure angle worm has a helix angle of 45 degrees and 12 starts.

If it is necessary to decrease worm to gear center distance,

the first option is to reduce the worm diameter. This results in a commensurate reduction which can cause unexpected worm failure problems. Figure 5 shows a cross-section of the worm root as opposing dies penetrate into it. The root of the worm is not round while the dies are penetrating. There is a flattened section on the worm under each die in the area where the penetration is taking place. The opposing forming force vectors acting through the center of those areas create a high shear stress on the core of the worm which is repeated twice in each work revolution of the rolling cycle. As the root diameter is decreased and the die tooth space is filled with radially flow-

ing blank material, the forming force increases very rapidly. If the root cross-section is small and unable to handle this rotating shear stress pattern, a hollow develops in the core with radiating cracks which weaken the worm and cause the tooth form to "blow up."

For standard single start worm forms rolled in materials which have at least a 12 percent elongation, a worm tooth depth of 1/5 of the outside diameter will not produce core failure. For two start worms and other even number of starts where the rolling force is more directly in opposition, the limitation may be a tooth depth of 1/6 of the diameter. As the worm tooth space to tooth thickness ratio is increased, it will significantly reduce the allowable tooth depth to outside diameter ratio.

Another limiting factor is the straightness of single start worms to the shaft diameter after in-feed or scroll-feed rolling. Because there is a runout area in the worm at the end of the die, as shown in Figure 6, there is an unbalanced deformation pattern on either side of the shaft centerline. This causes the shaft centerline to deflect away from the worm centerline in the direction opposite the unbalanced deformation of the penetrating root. The deflector can be reduced by either extending the runout area or constraining the blank centerline during rolling or increasing the worm diameter. If these steps do not provide the required concentricity, straightening after rolling may be necessary. This condition is minimal on shafts with more than one start.

The tooth crest shape is also an important factor. Because of grinding wheel breakdown in the manufacture of the worm dies, it is necessary to have a corner radius between the tooth flanks and the die root which forms the crest of the part during rolling. In many cases, the crest radius of the tooth should be enlarged beyond that required for die grinding breakdown in order to accommodate the seam which forms in the crest of the worm being rolled. The seam does not always form at the center of the crest, therefore increasing the crest corner radii will prevent the seam from encroaching on the outer TIF. The crest corner radii also minimizes the effect of positive involute error at the tooth crest.

It should be noted that the crest seam is generally shallow and can be closed, if necessary, for visual quality purposes. In addition, it does not have any effect on the structural integrity of the teeth.

Another reason for the desirability of some corner root radius and incipient root flat on the die is to provide a simple means to measure the runout of the worm with respect to other features on the shaft. Because the incipient crest flat of the form created by the root of the die precisely follows the pitch diameter, it can be used as a surrogate for the PD for process quality control purposes.

Finally, if the crest of the rolled worm is used to provide the gripping surface for subsequent turning of the worm shaft bearing surfaces (i.e., to achieve very precise runout of the bearing surfaces to the PD), the crest radii allow some small collecting deformation without any effect on the TIF.

Worms can be rolled on virtually all commonly used metals where the elongation is 12 percent or higher and the hardness is Rc35 and below. Shallow worms can be rolled using even harder materials, but this greatly shortens die life. Since most metal flow occurs in shear, as a general rule, materials which

form well cut poorly, and those which cut well form poorly. Therefore, materials with sulfur, boron, and other additives to improve machinability should be avoided when rolling greater than normal depth or thin tooth worms. Materials which have alloys to create corrosion resistance or high wear, such as nickel,



Figure 3 — Typical Thru Feed Worms

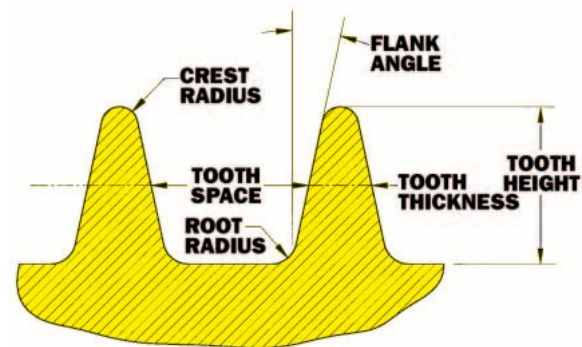


Figure 4 — Tooth form with recommended form ratio limits

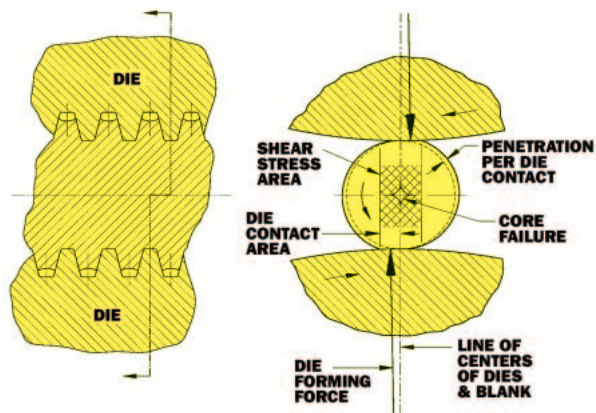


Figure 5 — Core stress diagram
(Diameters to scale, but penetration per die contact exaggerated to illustrate phenomena.)

chrome, vanadium, and molybdenum, tend to work harden while being formed, and therefore have form depth limits.

Common material for high volume rolled worms are the low and medium carbon steels, 1018 and 1040. Commonly used fastener materials 4140 and 4340 also roll well in the annealed or limited draft state. Martensitic stainless steels roll well. However, as the alloying levels increase, the austenitic stainless steels work harden rapidly, and therefore present significant difficulty when attempting to roll deeper worms.

Rollability is also reduced by the prior cold work history of the material. This is particularly true of materials which work harden rapidly. Since the strain rates of the rolling process for deep forms is quite high, any previous work hardening limits how far the rolling process can go before root flake and other surface failures occur.

The material condition also has a major effect on the load required to form the worm. Since the penetration of a hardness

As noted above, the rolling of shallow depth worms generally requires only about 25 work revolutions. For the typical 3/4 inch worm rolled by a 4 1/2 inch die, the dies make 4 1/4 revolutions to form and round up the worm. Die approach and opening typically require three die revolutions. At a die speed of 110 RPM, the actual rolling cycle would be about four seconds. As the tooth depth and worm diameter increase, the rolling cycle increases commensurately.

Because the rolling cycle for in-feed worms is so short, the manual handling of the shafts can take up more time than the actual rolling. To minimize handling time, rolling machines of the type shown in Fig. 7 can be equipped with automated shaft feeding units such as those shown in Fig. 8.

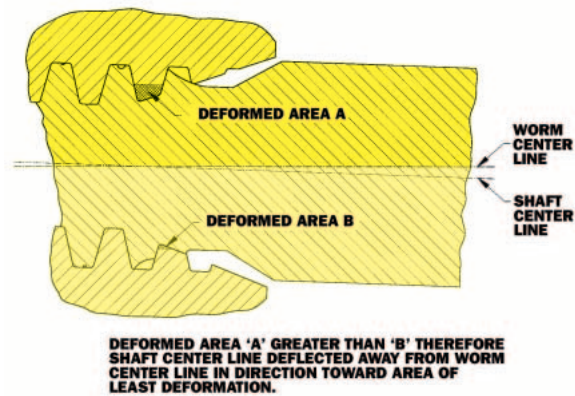
The rolling machine in Fig. 7 is CNC actuated and has a double acting arm system in which both dies move toward the horizontally fixed rolling centerline. The rolling dies penetrate into the work uniformly from each side of the rolling centerline. This facilitates the handling of the blanks by eliminating the need to horizontally side shift the rolling centerline in the loading, during the rolling and the subsequent unloading of the rolled shaft.

For the through-feed rolling of worms, the axial feed rate is a function of the die diameters and machine power capacity. For the slack one inch adjuster worms shown in Fig. 3 and rolled on the machine shown in Fig. 7, the through-feed rate was 45 inches per minute on a rolling machine with a radial die load capacity of 54,000 lbs and a die drive of 20 HP.

Prior to rolling the blank must be turned, formed, or ground to a diameter necessary to produce the level of tooth fullness required when the die has penetrated it sufficiently to produce the desired pitch diameter. Generally, the theoretical values for blank diameter are close to correct, but even when rolling by the in-feed method, stretch and spring-back occur, and their level varies with the material, the worm configuration, and rolling machine setup. Therefore, blank diameter and worm pitch must generally be validated by test rolling. Blank diameter and tolerance can then be established. In some cases, die pitch must also be adjusted.

Worms are generally rolled with some small visible seam, unless visual appearance requirements prevent it. When rolling with an open seam the machine diameter setting will be the predominant factor in the PD tolerance that can be maintained. However, because of the high radial die loads required, especially on deep worms, basic machine spring

Figure 6 — Single start worm bending action



test penetrator is similar to the initial penetration of a rolling die into a blank, the measured hardness of a material is a good indicator of its rollability and the required radial die load when rolling a worm. Although most of the organized rolling load tests have been made on thread-rolling applications, they provide a good comparative figure. Rolling a 1-inch diameter 20TPI four start, 30 degree, flank angle thread form with 4 1/2" diameter dies using 25 work revolutions on the CNC worm roller shown in Fig. 7 required the radial die loads shown below.

For worms longer than 1 inch, multiply the above radial die load estimates by the actual length in inches. The thread form is the approximate rolling equivalent of a 16 diametral pitch worm. A 12 diametral pitch worm will use approximately 60 percent more die load than shown on the chart. An 8 diametral pitch worm would require approximately 110 percent more, if the worm was rollable. The foregoing are approximate extrapolations from a variety of general applications where the process variables were not tightly controlled. Therefore, they are for informational purposes only.

Material	Hardness	Approximate Radial Die load for 1 inch of worm length form
1018 steel	169 Bhn	10,000 lbs
416 SS	183 Bhn	12,000 lbs.
1095 steel	207 Bhn	13,000 lbs.
1045 steel	232 Bhn	14,000 lbs.
4140 steel	241 Bhn	16,000 lbs
303 SS	260 Bhn	18,000 lbs.

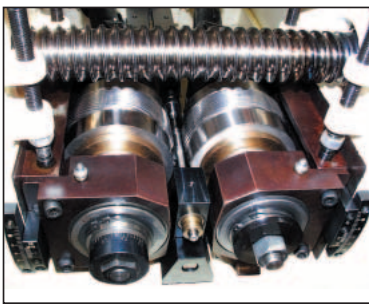


Figure 7 — CNC cylindrical die machine infeed rolling small worm



Figure 8 — Cylindrical die worm rolling machine with automatic shaft feeder

will attenuate the effect on die setting and actual PD change. Therefore, the tighter the blank diameter tolerance and roundness, and the more consistent the blank hardness, the more precise the resulting pitch diameter repeatability. When the blank conditions, dies and setup are established and controlled, it is practical to hold over wire tolerances on standard 20 degree pressure angle worms in the 3/8 inch to 1 inch diameter range to a tol-

erance of +/- .001". For 12.5 degrees pressure angle worms with maximum thinned teeth, an over wire tolerance of +/- .002" can be held.

For worms which must be rolled full with virtually no visible seam, a different condition prevails. The rolled worm tends to follow the blank and machine size setting has limited size change effect. Once the die form is full, closing in the size setting cannot force the die to penetrate the blank any further. The spring of

the rolling machine accommodates the size adjustment and causes "over-rolling" the worm. This causes surface failure on the root and flanks of the worm being rolled. However, when size adjustment is correct, and the worm is rolled full by any method, with a good setup and consistent hardness blanks, the OD and pitch diameter will maintain the same tolerance as the original blank. Therefore, a blank with a .001" tolerance will produce a .001" tolerance PD.

In addition to the size precision, worm rolling creates flank surface finishes generally better than 8 microinches. With such levels of high-speed and high-quality performance, certainly worm rolling is worthy of consideration for many high-volume worm shafts. ☐

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