The Whirling Process in a Company that Produces Worm Gear Drives

By Massimiliano Turci and Giampaolo Giacomozzi

Whirling is a fast method of producing worms: a toolholder ring, carrying a series of profiled carbide cutters, is set eccentric to the workpiece axis and rotates at a high speed. This paper describes the machining process and presents a case history with a comprehensive view of the time and cost benefits compared to a previous situation with standard machine tools. Geometric constraints in the worm shaft design due to the whirling process are also discussed.

THE WORM GEOMETRY OF WORM GEARBOXES, especially the thread profile and the shape of the thread flanks, depends on the machining method.

The machined profiles are universally defined by the same criteria in several standards: ISO/TR 10828 [1], AGMA 6022-C93 [2], and DIN 3975 [3]. The most commonly used are:

- Straight-sided axial profile, usually produced on a lathe with a tool having straight sides, placed on the axial plane (Type A or Form ZA).
- Straight-sided normal profile, produced with a straight-sided lathe tool with its cutting face tilted to the lead angle of the thread at its mean diameter (Type N or Form ZN).
- Profile resulting from a rotating straight-sided milling cutter tilted to the lead angle at worm mean diameter. The center plane of the cutter or wheel must intersect the axis of the worm at the centerline of the thread space. Flank profiles are quite convex in axial planes (Type K or Form ZK).
- Involute helicoid, usually machined by grinding one flank at a time using the plane side face of a grinding wheel. Compared to the previous case, the grinding wheel axis is also tilted to the pressure angle (Type I or Form ZI or ZE in old Italian references). See Figure 1a and 1b. It may also be machined with a turning tool that has asymmetric-sided flanks lying on a plane and that are tangent to the base diameter (see Figure 1c) [4]. It is also possible to use a profiled (concave) tool (see Figure 1d) [2, 4, 5].

The ZA, ZK, and ZI types are characterized in that the mesh is always a convex/convex pairing, and the patented ZB profile, where the worm threads are convex and the wheel teeth are concave in the axial plane. However, ZB is typically not used anymore [6]. Also, F-I (ZH or Cavex) and F-II types are known to reduce the Hertzian pressure and to improve the conditions of lubrication [7].

Currently, the cut on a lathe with a milling tool (ZK profile), optionally followed by grinding (ZI profile), see Figure 2, is the most used cutting process in companies with flow production of worm gear drives (see Figure 3). The grinding process is necessary to remove thermal distortions after carburizing and hardening (for case-hardened steel) or after induction hardening (for through-hardened steel). Modern calculation software can plot the profile form and diagram. Therefore, it is easy to check the profiles and to show the differences (see

Printed with permission of the copyright holder, the American Gear Manufacturers Association, 1001 N. Fairfax Street, Suite 500, Alexandria, Virginia 22314. Statements presented in this paper are those of the authors and may not represent the position or opinion of the American Gear Manufacturers Association (AGMA). This paper was presented October 2016 at the AGMA Fall Technical Meeting in Pittsburgh, Pennsylvania. 16FTM02
THE WHIRLING PROCESS

In addition to traditional methods just mentioned, there is also the whirling process. It is already well-known for long ball roller screw machining (up to 10,000 mm in length with a tip diameter of 4-200 mm) and especially in medical industries for the production of bone screws [10]. However, this process is not yet widespread in companies that produce worm gear drives. It is usually defined as a non-traditional method of gear machining [11]. Sometimes, it is called “planetary milling,” even if this terminology could be applied to another thread milling, where the tool rotates around its axis and revolves around the fixed workpiece to machine internal or external threads.

The whirling process is an “internal” milling process: the cutting edges are mounted on the inner side of a ring in radial position. The ring rotates at high speed around the workpiece, rotating slowly (see Figure 6). The inclination between the cutting plane (the ring) and the workpiece axis depends on the lead angle. The longitudinally advancement of the tool head combined with the workpiece rotation generate the required lead. The eccentricity of the whirling ring determines the depth of cut (the root diameter and dimension over pins).

The whirling cut could be made on a dedicated machine (see Figure 7) or by adding special equipment to a standard CNC lathe (see Figure 8).

The small amount of bibliographic data on the subject [12, 13] indicates a blank rotation speed of 3 to 30 rpm and a toolholder ring rotation speed usually of 1,000-3,000 rpm up to 10,000 rpm [10]. The machining time is generally three to four times lower than in traditional milling and up to nine times lower for long screws [14].

The toolholder ring and the blank always rotate in the same direction for both a right-

Figure 2: Typical machining process for worms for speed reducers: (a) milling and (b) grinding, showing the double-tilted axis of the grinding wheel

Figure 3: (a) Worm gearboxes and (b) a worm [8]

Figure 4: Comparison between ZI (black) and ZK (red) form profiles \( (m_y = 2.5, z = 2, \alpha = 20^\circ, \gamma = 11.31^\circ) \) plotted by software [9]
and left-hand helix (see Figure 9). So, to shape a worm with an opposite-hand helix, it is necessary to reverse the feed direction and reverse ring inclination from the blank axis.

The whirling process is a discontinuous cutting that produces comma-shaped chips, as in the standard milling process. Considering the same worm geometry and the same angular advancement (same angular speed), the chips produced by whirling or by milling have quite the same volume, but in the whirling process, the chips are longer and thinner. This means that the whirling process requires less cutting force, and so the elastic deformations are lower and with a consequentially better surface quality. On the other hand, with the same chip dimension, the whirling process requires less cutting time than milling, because of the higher cutting speed and feed. To summarize: the whirling process has a better metal-removal rate [15].

Due to the shape of the chips, the heat generated in the cutting process dissipates into the chip itself, without the need of coolants or cutting oils. This is another benefit: dry machining [16]. The chips are blue (see Figure 10) due to the high temperature. The workpiece remains cold even after the machining process. The tool can be coated with titanium
aluminum nitride: Ti to prevent the chips from sticking to the tool, and Al to quickly remove the heat.

Usually, on the same toolholder ring, there are inserts for both roughing and finishing (see Figure 11), mounted in different radial positions, and to cut different thread zones.

In regard to the surface quality previously noted, the whirling cut form (see Figure 12) is not perfectly circular, but polygonal, as in milling (whereas, in turning, it is circular). However, the maximum distance between these polygon points and the circumscribed circle is small, approximately 0.1 \( \mu \text{m} \) for the whirling cut, which is much less than in traditional milling [15]. Therefore, with the same cutting parameters, there will be a better accuracy, or with the same required accuracy, a lower cutting time is possible.

The surface roughness is larger when milling the worm than in the whirling process, because in this last case, the insert enters the piece much more gradually. Milling with a large disc cutter (so the chip volume is the same in both machining processes) is quicker, but the surface is rougher in milling because the cutter attempts to climb the workpiece. In regard to the roughness, the comparison between worm whirling and milling is quite similar to the comparison between peripheral up-milling (conventional milling) and down-milling (climbing milling).

The surface roughness can reach \( \text{Ra 0.5-0.6} \mu \text{m} \) and even up to \( \text{Ra 0.4} \mu \text{m} \) [13]. In the next section, a roughness measurement will be shown.

The accuracy of ball screws machined by the whirling process can reach an accuracy of
3 DIN 6905 [17] or ISO 3408-3 [18, 10], but for industrial worm gearboxes, it is not necessary to achieve such a good quality, DIN 3974 [19].

The whirling process has been successfully used on hardened steels in place of turning or grinding to reduce the cycle time [20].

It can produce exactly a ZI flank form [12] for a worm. Figure 13 shows the comparison between the flank profile, measured by an evolventimeter and generated by a gear calculation software. Both the geometries are for a workpiece before the grinding process. The insert to obtain this ZI flank form is convex.

For a ZK worm, the same insert (with a straight profile) can be used in both the whirling and milling processes for the same piece (see Figure 14).

The cutting process can be simulated as a motion analysis in a multi-body 3D CAD system to generate the final workpiece shape (see Figure 15).

A real case is shown in this section regarding the worm for an enclosed gear drive size 50 (i.e., with center distance 50 mm) and ratio 1:20 (see Figure 16).
The complete sequence of operation is:
1. Cut of the blank from 20MnCr5 bar stock
2. Turning side 1
3. Turning side 2
4. Milling
5. Slotting
6. Worm threading
7. Case hardening
8. Grinding

Operations 1 to 5 are processed on a single machine, a CNC double-spindle lathe with three turrets and with an automatic bar stock feeder. In the past, each of these operations required a different positioning and more machine tools.

The thread could be shaped on the same lathe with a dedicated tool, but it takes too much time, and there are the limitations of only one start and a module only up to 2 mm.

During the selection process of a new suitable machine tool for this phase, the company considered three alternatives:
- Traditional thread milling with solid carbide cutter (Figure 2a), as described in AGMA 6022-C93, Clause 10.1 [2]
- Traditional milling with insert cutter (see Figure 17)
- Whirling (see Figure 18)

In any case, the cutters are dedicated for each module and are designed to leave the required grinding allowance (usually fixed to 0.01 m₃). The rule to define the value of this stock was put inside the gear design software used in the technical department, so it is automatically written in the CAD drawings.

The following points are the technical and economic characteristics of these three processes. However, the authors prefer to avoid providing machining data such as cutting speeds and feed rates, because they are still classified and dependent on the material, especially on the lead (Pb) presence, which can improve the machinability of steel. Only the cycle and machining times are given, calculated as mean values on most jobs.

<table>
<thead>
<tr>
<th></th>
<th>solid carbide milling tool</th>
<th>solid carbide insert cutter</th>
<th>whirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost [€/piece]</td>
<td>0.54</td>
<td>0.46</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 1: Threading costs for method

Figure 16: Worm main view from its drawing
\((m_n = 1.90 \text{ mm}, \gamma = 5°59', \text{ and } z = 2, 20\text{MnCr5})\)

Figure 17: Milling with solid carbide tool

Figure 18: The whirling process
Traditional Milling with Solid Carbide Tool

The mill has a diameter of between 130 and 160 mm. It costs about 900-1,800 € depending on the size. There are up to 20+20 cutters that can cut approximately 200 parts before needing to be sharpened, and they can be re-tipped 15 times. The total cost of the sharpening is about 2000 €, so the tool cost for the workpiece is 0.54 €/WP. This operation requires oil as a cutting fluid (see Figure 17), so the oil cost should be added to the tool cost, because an oil coating remains attached to the workpiece after machining, even if centrifuged. This process is still used. The mean working time (sum of cutting, loading, and unloading times) for the studied worm is 2 minutes, 20 seconds.

Traditional Milling with Solid Carbide Insert Cutter

The cutter body is bigger than the previous solid carbide tool needed for the same worm, and it costs about the same, but there are also the inserts, up to 18, whose re-sharpening cost is about 50 € for each insert. The total cost of the tool is 0.46 €/WP. In addition, the process needs a high volume of cutting fluid. The main disadvantage of this process, compared to the previous one, is the low quality of the cut, in particular regarding the helix, which needs a higher grinding stock; the cut is ragged. For this reason, this process is not used. It also requires a bigger machine tool due to the larger size of the disc.

Whirling

On the toolholder ring, six inserts are mounted (see Figure 11), costing 50 € each, with two cutting edges that can be re-sharpened 10 times. In this case, the inserts can cut about 200 pieces before being re-sharpened. One head can cut 4,400 pieces. The tool cost is therefore 0.10 €/WP, and there is no cost for oil because the process is dry (see Figure 18); only air and oil mist is needed.

Table 1 summarizes the costs of these processes. The quality of the worms produced by this whirling process is equal or better than that produced by a solid carbide milling tool (see Figure 19, Figure 20b, Figure 21, and Table 2). Therefore, the comparison between the two processes, in terms of time and cost (see previous section), is at an equal surface finish.

The definition of the geometry of the insert, as previously mentioned, starts from the normal section of the worm, taking into account the required allowance and the protuberance (see Figure 22). The subsequent grinding operation does not work on the tooth root, which is machined only during the whirling cutting. As described in the previous section, the stock allowance is related to the root diameter (as in the cylindrical gear cutting by hobbing tool). Compared to the traditional milling of the two previous points, the whirling process gives a better profile quality, so the stock allowance in grinding is constant along the flank.

Compared to traditional milling, the whirling process has some limitation on the workpiece geometry, especially when there is a big diameter next to the threaded part.

Figure 23 shows the workpiece of Figure 16 mounted between the spindle on the left, where there is the biggest diameter, and the tailstock on the right, after the toolholder ring was positioned around the workpiece. Because the tool wraps the workpiece and is tilted and eccentric to it, care should be taken to avoid interference between the disc and the biggest diameter (see Figure 24). Care should also be taken to be sure that the disc can cross the part that should be threaded.
Fortunately, in the current production, the worm drawings needed no changes; it was sufficient enough to use larger diameter discs in the milder cases.

CONCLUSIONS

In 2013, the company made the decision to invest in a new machine tool to cut worm threads. The evaluation made during this machine selection proved to be well-founded and showed benefits on different levels:

• Lower working time, over 300 percent of productivity (see Table 3).
• Environmental sustainability due to the removal of cutting oil (see Table 5) and to the reduction of the required energy by -23 percent, despite a higher machine power (see Table 4).
• Lower costs (see Table 1), despite that the initial cost of the whirling machine was 20 percent higher than the traditional alternative.
• Better accuracy of the workpiece before grinding, by at least 2 points DIN 3974 (see Table 2).

During the decision-making process, the machine tool manufacturer had envisaged a much lower production cost in respect to the traditional cutting methods, based on the considerable knowledge of the whirling process for the screws. However, this process was not yet widely applied within companies that produce worm gear drives. The competencies of the workshop staff have optimized the process, in particular the cutting parameters and the inserts. Now it has been proven that they have obtained a lower manufacturing cost with respect to initial forecasts (Table 1).

REFERENCES

10. Theusen K. et. al., 2014, Handbuch Spanen, Carl Hanser Verlag GmbH & Co. KG, München, Chap 17.2.4.
Figure 22: Software to calculate the (a) flank form from insert form and (b) layout [16]. The tool flank form is not straight; it is convex to obtain a ZI flank on the worm. The image is on the cutting plane.

Table 3: Time comparison for a worm with center distance 50 mm and ratio 1:28

<table>
<thead>
<tr>
<th></th>
<th>Milling</th>
<th>Whirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting time/piece</td>
<td>3’ 20”</td>
<td>1’ 02”</td>
</tr>
<tr>
<td>Working time h/day</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Qty. of pieces produced/day</td>
<td>400</td>
<td>1280</td>
</tr>
</tbody>
</table>

Table 4: Energy cost comparison

<table>
<thead>
<tr>
<th></th>
<th>Milling</th>
<th>Whirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine power requirements [kW]</td>
<td>2.7</td>
<td>7</td>
</tr>
<tr>
<td>Working time h/day</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Qty. of pieces produced/day</td>
<td>400</td>
<td>1280</td>
</tr>
<tr>
<td>Required energy [kWh/piece]</td>
<td>0.1485</td>
<td>0.120</td>
</tr>
</tbody>
</table>

Table 5: Oil consumption comparison

<table>
<thead>
<tr>
<th></th>
<th>Milling</th>
<th>Whirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil required [liter/month]</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>Oil cost [€/liter]</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Oil cost/month</td>
<td>1600</td>
<td>-</td>
</tr>
<tr>
<td>Oil cost/year</td>
<td>20000</td>
<td>-</td>
</tr>
</tbody>
</table>