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Simple and Inexpensive Hobbing for the General Shop

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Abstract: -Gearmaking is typically the province of specialty enterprises due to the substantial investment in particular machine tools designed for the purpose. General lathes and milling machines do not lend themselves to fine gearmaking, although wire EDM is becoming more widely used and can serve in this capacity according to the limits of its articulated degrees of freedom. In this article, we introduce a new, simplified method of generating precision gears of the spur, worm, or helical types that has been adapted for general purpose milling machine use. The method can use standard taps to make gears of standard 30-degree pressure angles, ACME taps to create standard 14-1/2 degree pressure angles, as well as standard hobs for 20-degree or metric gear standards.

I. INTRODUCTION

Gearmaking through the generation of involute profiles [1] has been known since about the 17th century, and the first hobbing machines appeared in about 1835 [2]. Machines for the production of both spur and helical gears appeared in about 1897. [3] The standardization of gear profiles and methods was introduced by the American Gear Makers Association (AGMA) in 1916, [4] and continues to improve processes and productivity for its members. Form tools specially ground for the purpose have been used for the creation of gears by milling and shaving. Also, specialized cutting practices are needed to make dies for the high-throughput process of plastic injection molded gear products. Most recently, CAD processes have enabled the making of arbitrary gear prototype profiles through additive manufacturing. [5]

Common to the processes that remove material from gear blanks, a hobbing machine uses a sharpened and hardened gear rack profile to generate involute profiles on conjugate blanks (almost always circular). Non-circular forms can be made today by CNC processes. Here we will focus on a non-CNC approach involving no programming and no specially-built hobbing machine.

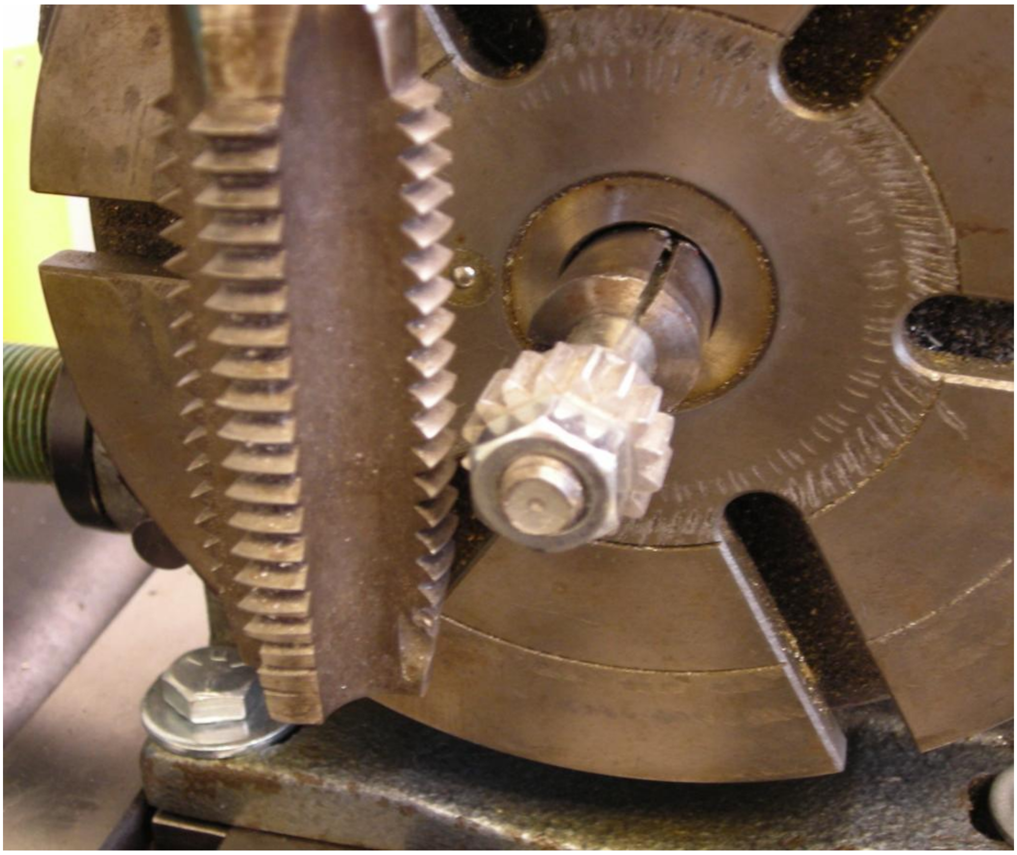

Figure 1: Set-up for Spur Gear Making with a Tap

Gearmaking Requirements and General Shop Capabilities

To generate involute teeth for gearmaking, means must be in place to synchronize the rotation of the hob (Figure 1) with the gear blank such that the number of teeth desired is invariant during the cutting process. (In contrast, form tooling requires that the rotation angle of the gear blank be statically matched for each tooth cut.) Worm gears require that the hob move only laterally with respect to the rotating gear blank until the desired depth is reached. Spur gears require these motions as well as a longitudinal motion to cut a consistent face within the blank. Helical gearmaking requires these motions plus a static positioning of the gear blank axis.

We will show how to accomplish these with a minimum of tooling and a conventional 3-axis milling machine. With this method, synchronization of the hob and the gear blank is accomplished by fitting a timing belt pulley to the spindle of the mill just below the quill and just above the collet holder (Figure 2). Roller chain may also be used in place of the timing belt. The number of teeth on the driving timing belt pulley is fixed independent of the number of teeth to be hobbed, as will be shown shortly. The driven timing pulley is typically smaller in diameter than the driver with a ratio of 1/2 for the driver, such that the speed on the cutter is multiplied to a maximum as determined by the minimum number of teeth recommended in the driven pulley.

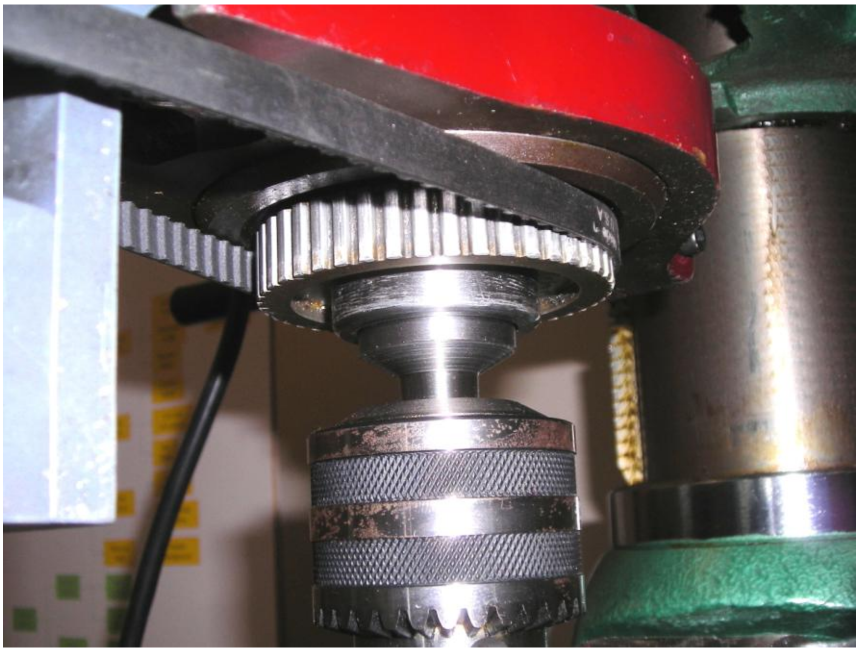

Figure 2. Drive Pulley Fixed to Mill Spindle

The spindle of the three-axis mill is considered to be vertical, and so is the axis to which the driven pulley is mounted (Figure 3). The driven pulley, in turn, drives a wound steel flexible shaft that accomplishes two critical goals: first it turns the direction of the spindle rotation (speeded-up) to right angles, so it becomes horizontal, and pointing in the lateral (fore-aft) direction of the mill table. Second it allows the precise location of the output axis of the flexible shaft to be located within a range of left-right locations. (Figure 4)

The output axis of the flexible shaft is used to drive a third timing belt pulley having the inverse ratio of the input driver. For example, a 2 to one ratio brings the rotational speed of the third pulley to be just twice the rotational speed of the spindle. Finally, a fourth timing pulley is attached to the input shaft of a standard rotary table, mounted with its output axis pointed horizontally and in-line with the mill table left-right axis. The number of teeth on the 4^{th} pulley is just the equal to the number of teeth desired of the gear we wish to cut, say N. Notice that a timing pulley with N standard teeth will be useful for any type of gear (spur, worm, or helical) at any diametral pitch (standard or special). The distance between the 3^{rd} and 4^{th} pulleys are arbitrary, but the two need to lie in the same plane. (Figure 5)

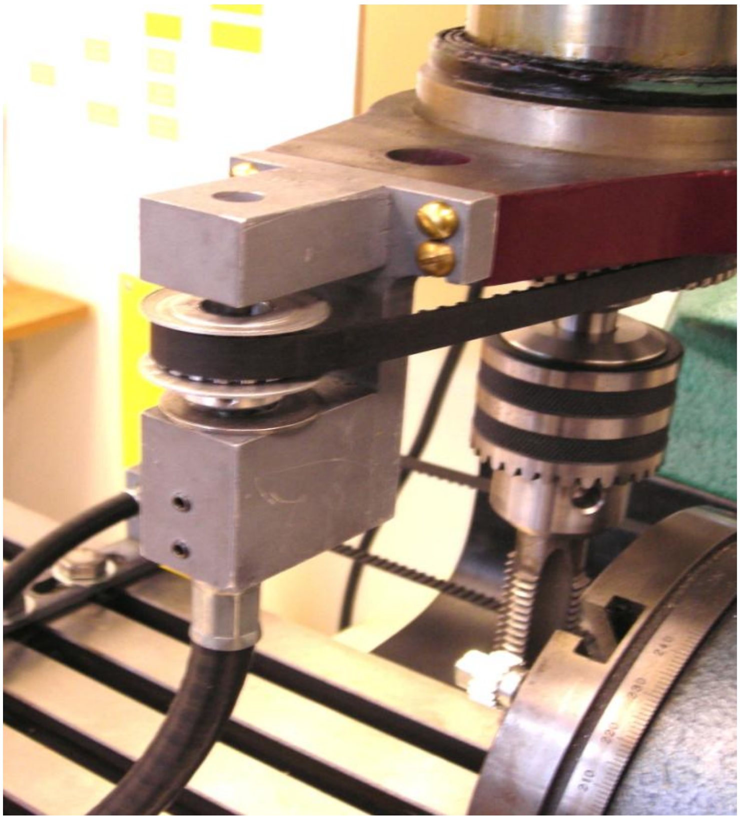

Figure 3. Vertical Fixture for First End of Flexible Shaft

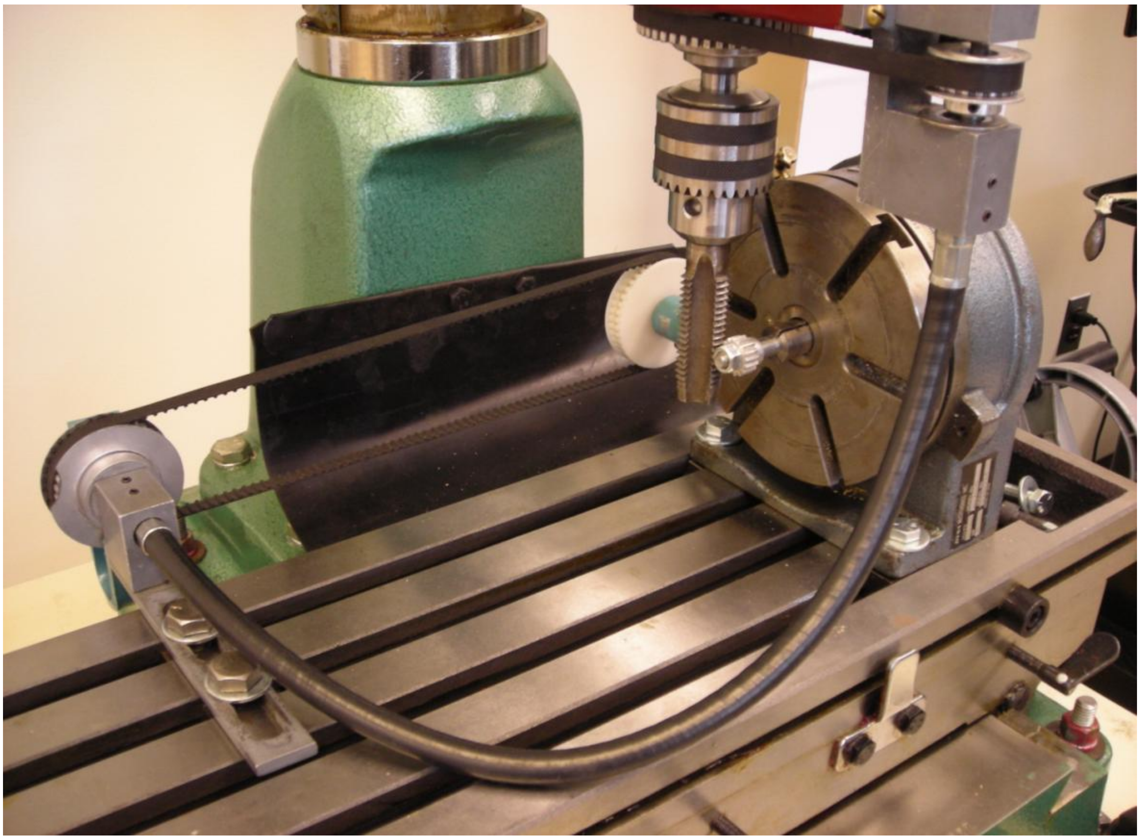

Figure 4. Overall View of the Flexible Shaft for Synchronizing Spindle and Gear Blank

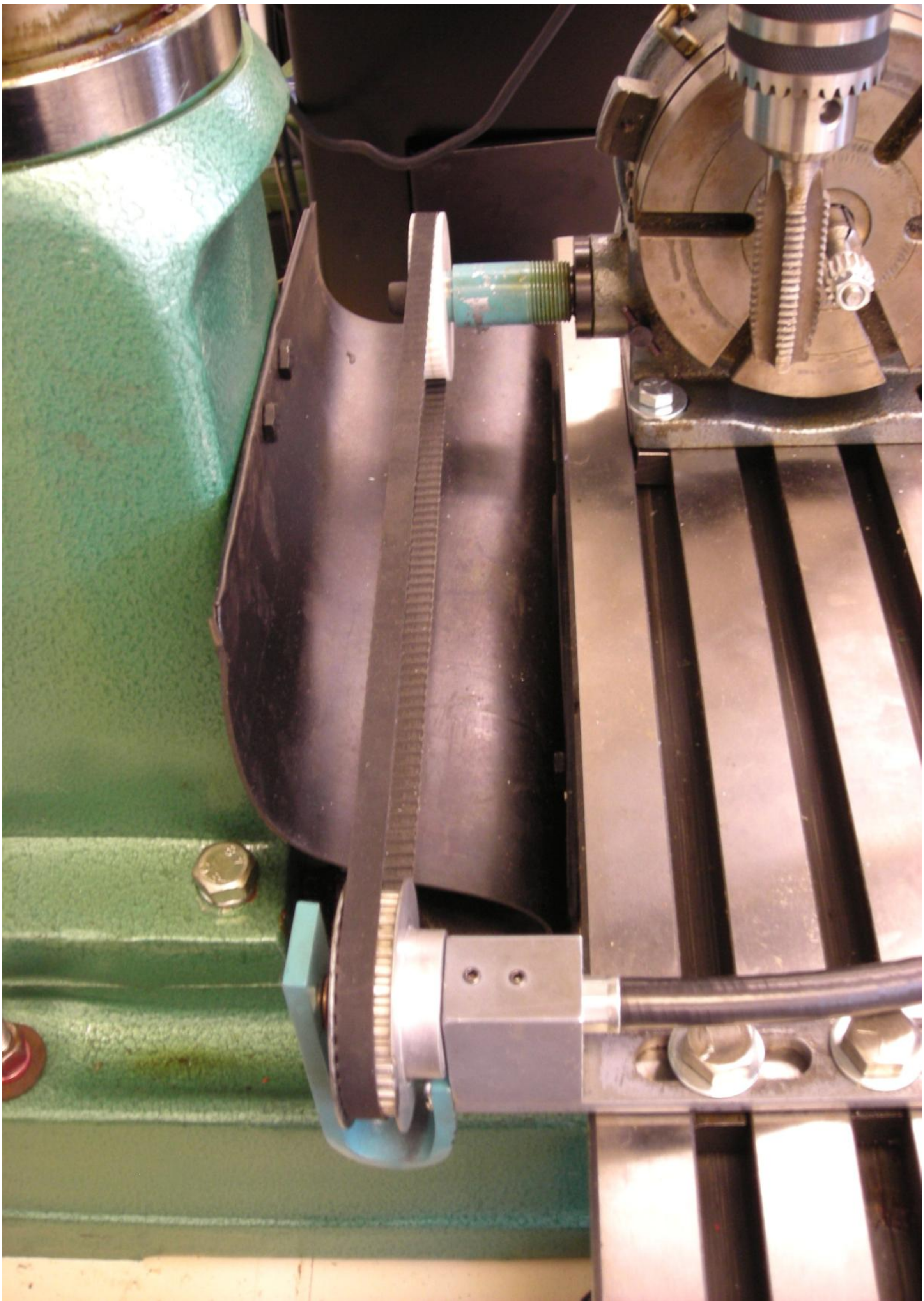

Figure 5. Parallel relationship between 3rd Driver and 4th Driven Pulley

Figure 6 shows a schematic relationship of the tooth numbers for this example.

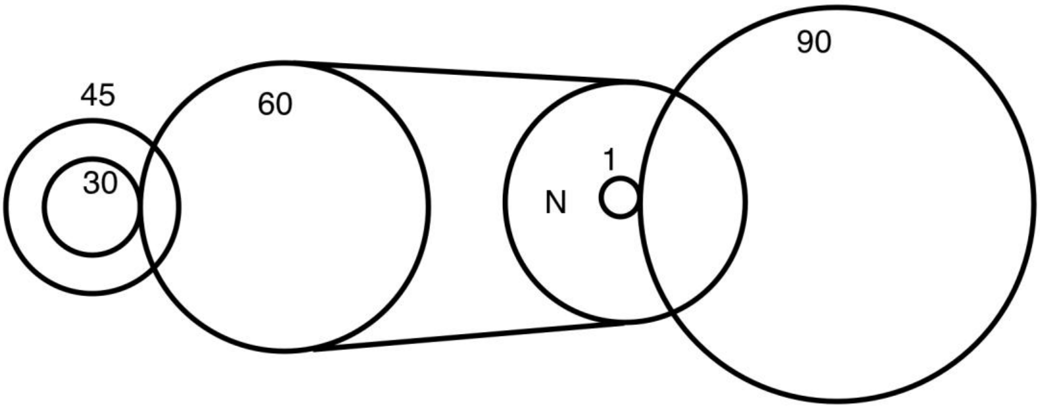

Figure 6. Example tooth numbers for an equivalent gear train

Notice that the number of teeth on the 2^{nd} and 3^{rd} pulleys is arbitrary, but must be in a 1:2 ratio so that the number teeth on the spindle is just matches half of the ratio of the rotary table (worm-driven).Here, the spindle carries a 45 tooth pulley which is just half of the 90:1 ratio of the rotary table. The 1:2 relationship is fixed by a 30 tooth pulley and a 60-tooth pulley. With the fourth pulley at N teeth, the rotary table will turn at precisely 1:N turns for each spindle rotation. Equivalently, a complete table rotation of N gear teeth requires N turns of the spindle.

$$\frac{45}{30} \quad X \quad \frac{60}{N} \quad X \quad \frac{1}{90} \quad = \ 1/N$$

When the table of the mill brings the surface of the gear blank into contact, the spindle-mounted hob will rotate precisely N times for each single rotation of the gear blank, irrespective of the blank's diameter. Also, the angular position of the cutting teeth does not change with respect to the blank irrespective of the X-Y location of the spindle with respect to the blank. We are free to select the depth of cut (fore-aft) on each pass while traversing left-right to form a spur gear. To form a worm gear, the X-axis of the table (the long axis) needs to be set precisely centered on the gear blank width, and only the Y-axis needs to travel to the desired depth. This depth should be computed ahead of time based on the OD of the gear blank and the pitch diameter. [6]

II. PITCH DIAMETERS AND DIAMETRAL PITCHES

A given tap or hob can produce gears of any number of teeth (above a reasonable small number of teeth which would cause undercutting) dependent on the blank diameter and the target pitch diameter. The relationship between threads per inch (tpi) and diametral pitch (Pd) is simply Pd = x tpi. Thepitch diameter, Dp, is simply # of teeth/ Pd. Table I shows several values for tpi and Pd., for inch units and metric units (pitch in mm).

Table I. English and Metric Tap Sizes and their Equivalent Pd

tpi -- 4 4.5	5	6	7	8	9	10	11	12	13	14
Pd --12.56	14.14	15.71	18.85	21.99	25.13	28.27	31.42	34.56	37.70	40.84
mm--6	5.5	5	4.5	4	3.5	3	2.5	2	1.75	1.50
tpi – 4.23	4.62	5.08	5.64	6.35	7.26	8.47	10.16	12.7	14.51	16.93
Pd–13.29	14.51	15.96	17.72	19.95	22.81	26.61	31.92	39.90	45.58	53.19

In addition, one notes that the outside diameter of a gear blank will be equal to the Dp of a gear with 2 additional teeth. The depth of cut including clearance is found from the root diameter which is the (number of teeth – 2.5)/Pd [7]

III. MAKING HELICAL GEARS

For 45-degree helical gears, a small fixture needs to be made. This fixture (Figure 7) secures the rotary table to the mill table so that the axis of the gear blank is tipped upwards 45-degrees. Since the hob and blank are synchronized, one may advance the X-axis of the mill (right-left) to cut the face width, while advancing the Y-axis (fore-aft) a few thousandths toward the blank with each pass. (Figure 8) Results of this process are seen in Figure 9. These gears are of the same "handedness" and will mesh at right angles to each other. To make gears of the opposite hand, so that they mesh on parallel shafts, one would relocate the rotary table so that the hob cuts on the "outside" portion of the blank, rather than the "inside" as seen in Figure 10.

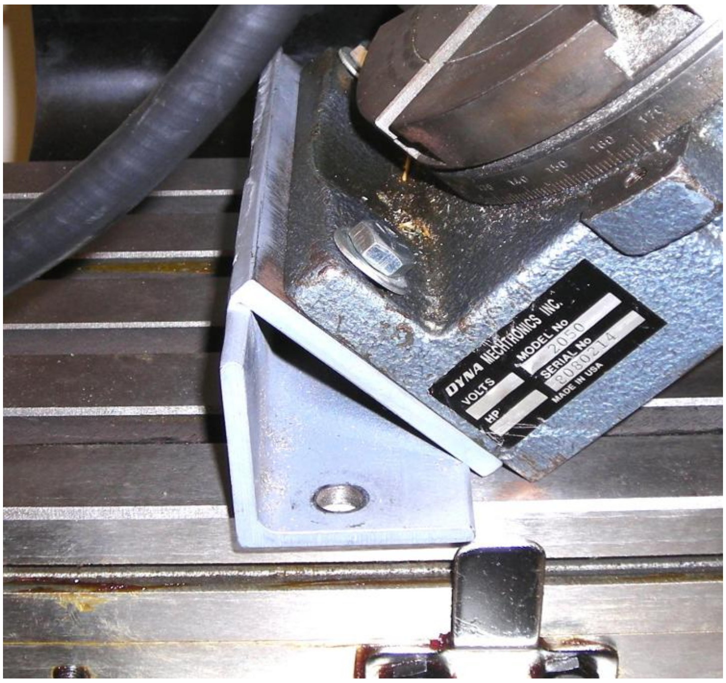

Figure 7. Bracket for Tilting Rotary table 45-degrees.

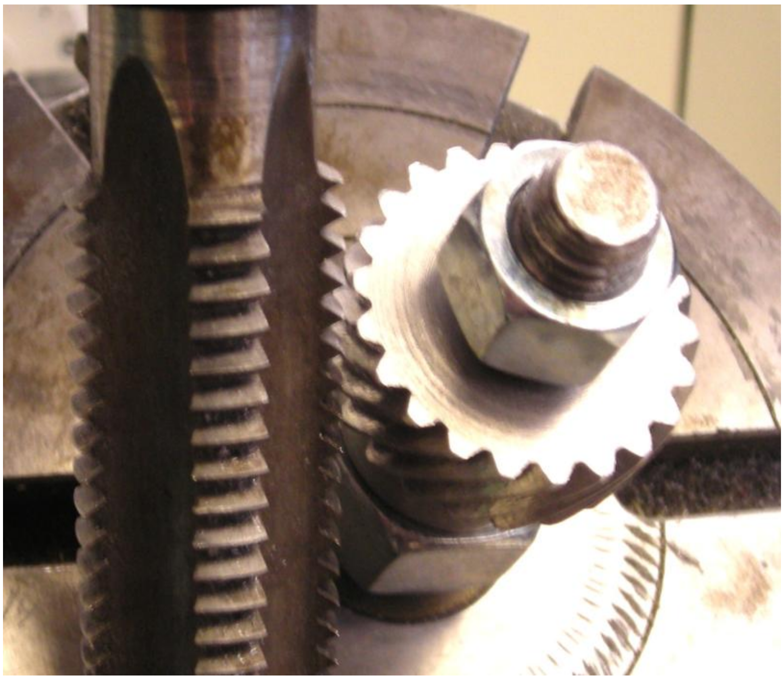

Figure 8. Cutting a Helical Gear

Figure 9. A Helical Gear Set Made with a Standard Tap

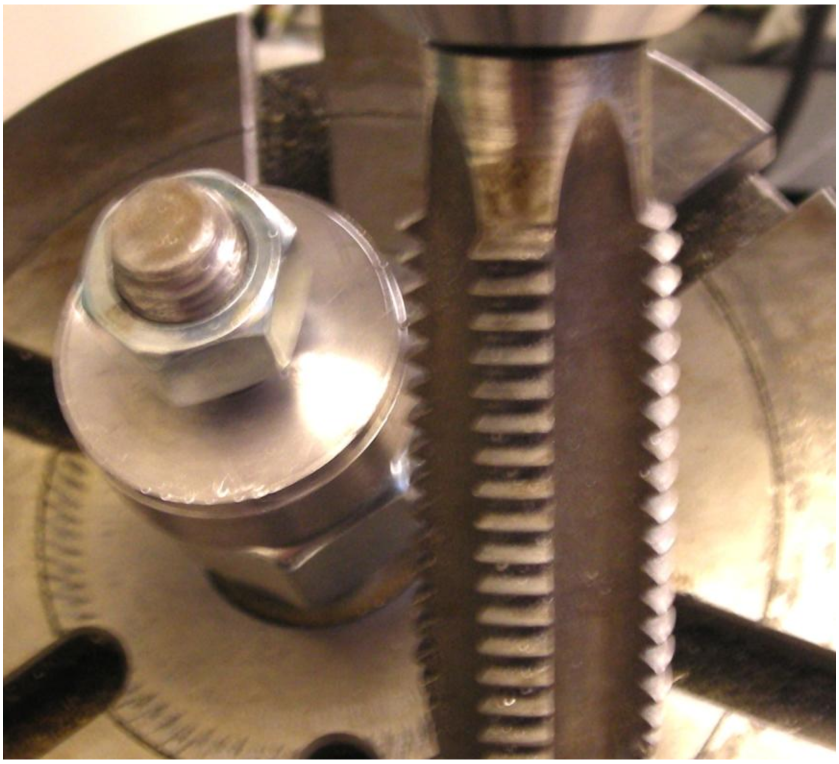

Figure 10. Cutting a Helical Gear of Opposite Hand.

IV. ACCURACY OF MANUFACTURE

The quality level that one can achieve with this new method depends on two factors. First is the care with which each pass is taken on the gear blank for spur and helical gears. Similarly for worm gears, the change in depth of cut versus number of blank rotations will determine the surface finish. An added constraint on left-right feed for spurs and helicals determines the finish, in part. We recommend that the feed direction not be reversed, that is, if a movement of the blank is leftwards versus the hob, then each pass should also be leftward. This practice will avoid any backlash in the rotary table or the quill of the milling machine.

Secondly, the variation in belt manufacture and the errors in meshing can cause a displacement of the ideal rack in forming the involute teeth. Specifically, if a mesh error of ±0.1 mm is imposed randomly on the 4^{th} pulley, that error would be divided by the ratio of the rotary table. For example, a 90:1 rotary table ration would reduce the 0.1 mm error by a factor of 90, resulting in a lateral cutting position error of 0.0011 mm. If this were applied consistently (and it generally would not) the worst case surface position would be ±1.1 microns. Taking the worst case to imply a ±3s deviation from perfect, as more realistic limit on surface quality would be ±0.3 microns, well into the range expected of precision gears. Translating this value to a representative AGMA quality value depends on many factors besides the roughness and will not be addressed here.

More likely, an error due to elastic wind-up of the flexible shaft could occur under the varying load conditions of the depth of cut, or the material removal rate (MRR). Such elastic displacementhas been measured to be about 2 mm on the surface of a 30 tooth pulley for a 6 mm nominal flexible shaft diameter. In the worst case (a reversing load) this error is also divided by the rotary table ratio. For example, a 90:1 rotary table ratio would reduce the 2 mm error by a factor of 90, resulting in a lateral cutting position error of 0.022 mm. If this were applied consistently (and it generally would not) the worst case surface position would be ±22 microns, which is not sufficient for quality gear products. In practice the wind-up error would be relatively constant if the torsional load on the flexible shaft were held constant. This torsional load is made up of two components: the drag on the pulley shafts and the drag of the rotary table, plus the contribution of the MRR of the cutting process.By strobe light measurement we have observed that the variation in shaft windup during cutting is 0.2 mm at the surface of a 30 tooth pulley, or about a tenth of the worst case error.Thus, the surface roughness may be reduced by an order of magnitude, and would fall into the category of the belt manufacture and meshing errors. Thus, we emphasize that high quality gears are possible with this new simplified arrangement, but will depend on holding cutting parameters and system backlash limits to within carefully set boundaries.

V. PRESSURE AND HELIX ANGLES

In practice, we used taps to take the place of hobs to minimize expense when a 30-degree pressure angle is sufficient. Figure 11 shows a spur gear set made with a standard tap for a hob. They mate smoothly. If we need to match, say, a 14.5 degree pressure angle, we would need twice that value, or a tap with a 29-degree included angle. Fortunately, acme taps are made precisely this way. Matching a 20-degree pressure angle gear would require a standard hob with a 40-degree included angle, but the setup would be the same.

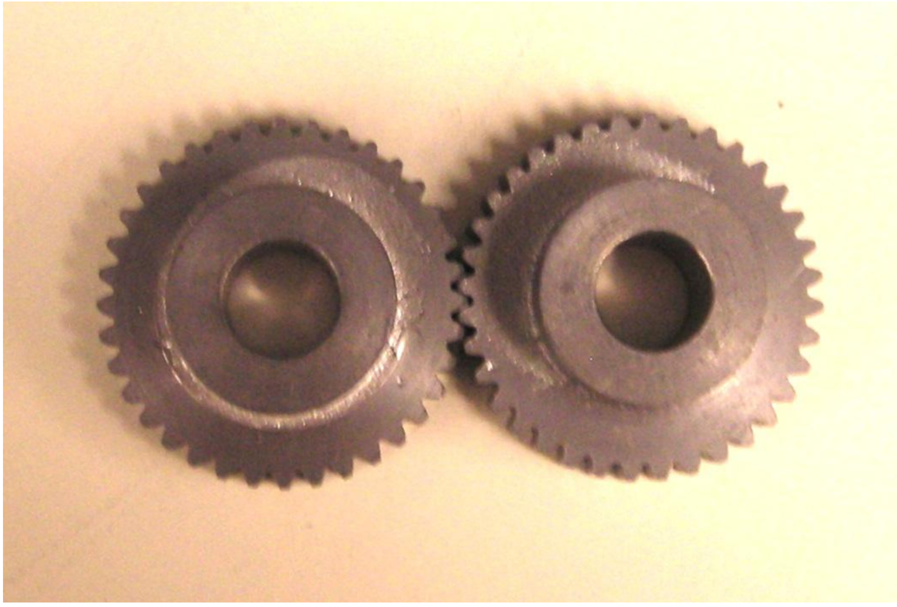

Figure 11. A Spur Gear Set Made From a Standard Tap

The helix angle of a tap or a hob is not zero, but depends on the diameter and the pitch. To compensate for this, the spindle axis of the mill needs to be tilted a few degrees, or else the tooth form will be exaggerated, i.e., more material will be taken from the space between the gear teeth and the teeth themselves will be thinner than normal, leading to excessive backlash. For example, a nominal 1-inch major diameter x 8 threads per inch tap has a helix angle of 2.48 degrees. These values for other taps can be found in [8].

VI. CONCLUSION

Standard milling machine accessories (rotary table, collets and/or drill chuck) supplemented with a fixture to mount a flexible shaft turning the spindle axis by 90-degrees and displacing it over a short range can yield a shop-based gearmaking set-up. Standard taps can produce gears of 30-degree or 14.5-degree pressure angles. Investing in a set of hobs extend the diametral pitches given in Table I, above. Since hobs are designed to operate with both ends in bearings, the cantilevered arrangement shown in Figure 1 dictates that the MRR should be about a factor of 4 less than that recommended for the hob to reduce the bending stresses in cutting. Also, the hob may need to be shortened from one end to clear the rotary table in helical gearmaking. Besides the far smaller investment needed to cut gears as shown in this article, the set-up time will be greatly reduced. The only special part needed is the timing pulley with the desired number of teeth which can easily be profiled with a CNC mill. A library of such pulleys can be built-up gradually as the number of teeth for each job changes.

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