Resurrecting a Mini-Lathe
Part II: Making Change Gears from Scratch

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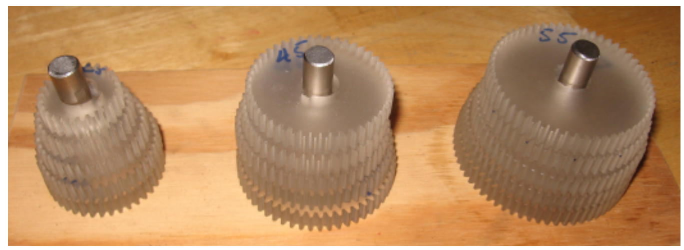
In the first article in this series, we retrofitted a random, scavenged motor and a new controller board to a mini-lathe damaged in a fire (and possibly in a fall). The newly resurrected lathe could then cut metal smoothly and accurately, but it could not thread; the only change gears that survived the fire were the two 20-tooth and two 80-tooth gears used in the fine-feed configuration. As promised, this article shows how I made a complete set of change gears, starting from scratch (***Picture 1***).



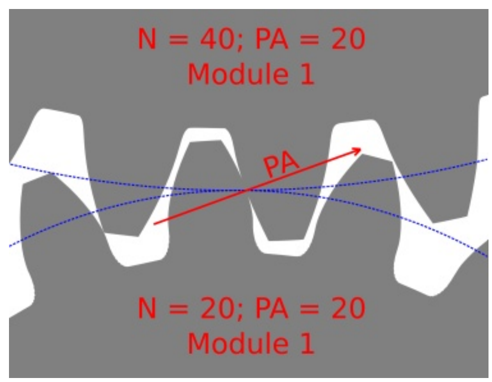
Actually, "starting from scratch" is a bit of an exaggeration—I didn't even have "scratch" to start with, at least when it came to tooling. I did have a mediocre mill-drill and an indexing head, along with the mini-lathe and my trusty old Cincinnati TrayTop lathe. I also had some pieces of thick acrylic sheet, donated by a friend, from which I could make the gear blanks. But I didn't have any gear cutters at all, much less the complete set of module 1 cutters I would need to cut a full range of gears. Neither did I have any broaches, much less a 3 mm broach to cut the key way in the plastic blanks. Perhaps most important of all, having promised my spouse that this lathe would not require any expenditures beyond the initial $50 purchase price, I did not have any budget to purchase tooling! Fortunately, an article by John A. Cooper, "Spur Gears and Pinions" (*Machinist's Workshop*, April 1999), gave me the clues I needed to make my own gear cutter, and I was able to make a reasonable facsimile of the needed broach as well.

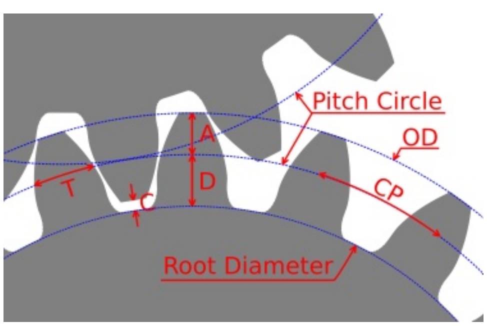
Once again, I should offer a disclaimer. Change gear sets for the mini-lathe are readily available from a number of sources, including a supplier that advertises in this magazine, and they are reasonably priced. Why then go to the trouble to make them from scratch? And believe me, it is trouble. It takes long enough to make the tooling and even more to make the blanks. And then, when it comes to indexing and cutting every tooth of fifteen gears . . . let's just say that there is a new entry under "tedium" in my personal lexicon!

And yet I would do it all again in a heartbeat, even if I had the budget on hand to purchase the gears instead. Why? First of all, making my own set of gears allowed me to include several custom sizes, such as 46, 51, 54, 57, and 63 teeth, which allow me to cut a huge variety of both inch and metric threads with much greater precision. While some of these sizes may be available commercially, others are not, or at least not for a limited budget. More than that, however, making my own set of gears allowed me to develop techniques which will stand me in good stead down the road whenever any odd or hard to find gearing is needed. And most of all, even in spite of the tedium, it was fun—fun to see a working set of gears emerging from tooling that I built from scratch. If any of these reasons appeal to you, read on.

A Brief Refresher on Gears

Standard involute spur gears are specified with three measurements: the **number of teeth** (N), the **pressure angle** (PA, the angle through which the tooth of one gear transmits pressure to the tooth of a mating gear, which equals the angle of the straight-sided flank of a tooth on the matching gear rack), and the **pitch**, which describes the spacing (and therefore size) of the teeth (**Figure 1**). Pitch is generally specified as a ratio between the number of teeth in a gear and its **pitch diameter** (PD). The latter is not the **outer diameter** (OD) of a gear, but rather it is the diameter of its **pitch circle**, which, as illustrated in ***Figures 1*** and ***2***, defines the theoretical point of intersection between the teeth of properly meshed mating gears. For inch-based gears, pitch is generally expressed in terms of the number of teeth per inch of pitch diameter (N/PD), a measurement called the **diametral pitch** (DP). For metric gears, such as those found in the mini-lathe, the inverse





ratio is used, expressed in terms of millimeters of pitch diameter per tooth (PD/N). This measurement is called the **module** (M).

Once the pitch of the gear is known, either in terms of module or diametral pitch, it is easy to derive all of the other measurements needed to cut gears by using formulas such as those in ***Table 1*** (refer also to ***Figure 2***). Note that, though the terminology nearly always remains the same, the abbreviations used by various reference works can differ quite a bit, and occasionally there are even slight variations in the formulas. With very little in the way of apology, therefore, I have chosen to use the abbreviations that I find easiest to remember, and I have used a simplified formula for the **clearance** (C) of fine pitch gears.

The formulas tell us everything we need to know to cut gears . . . except for how to cut the actual involute shape. The involute is a curved shape which allows the teeth of mating gears to roll together smoothly with a minimum of friction. Obviously, that shape will vary depending on the pitch and pressure angle of the gears. Less obviously, the involute shape also varies

Abbr.	Term	Description	Formulas
DP	Diametral Pitch	the number of gear teeth per inch of pitch diameter	DP = N / PD
M	Module	the number of millimeters of pitch diameter per gear tooth	M = PD / N
PD	Pitch Diameter	diameter of the pitch circle	PD = N / DP PD = N * M
OD	Outer Diameter	diameter of the gear blank	OD = (N + 2) * M OD = (N + 2) / DP
CP	Circular Pitch	the distance along the circumference of the pitch circle between the centers of two adjacent teeth	CP = π / DP CP = M * π
A	Addendum	the height of each gear tooth above the pitch circle	A = 1 / DP A = M
C	Clearance	the gap between the tooth of one gear and the root of another gear when they are properly meshed	C = A * .157 (for DP < 20, M > 1.25) C = A * .25 (for DP ≥ 20, M ≤ 1.25)
D	Dedendum	the depth of each gear tooth below the pitch circle	D = A + C
WD	Whole Depth	the distance from the outer diameter to the root diameter clearance	WD = A + D
T	Tooth Thickness	the distance between the flanks of each gear tooth at the pitch circle	T = .5 * CP

Table 1: Key Formulas for Cutting Spur Gears

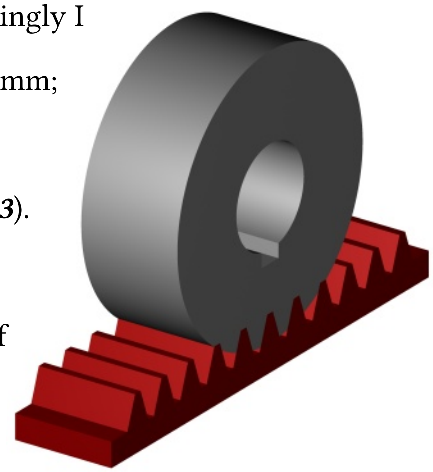
depending on the number of teeth in the gear. (Compare the shape of the teeth for the 20-tooth gear versus the 40-tooth gear in ***Figure 1***.) Theoretically, therefore, each and every size of gear requires its own unique form cutter to cut the precise shape of the teeth. In practice, however, the involute shape is forgiving enough that, for a given pitch and pressure angle, we can get close enough using only eight cutters to cut a full range of gear sizes.

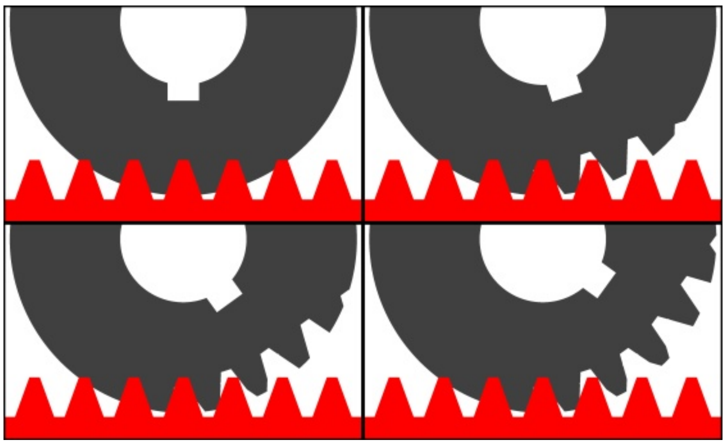
Only eight cutters . . . but that is still a lot of tooling for a frugal home shop machinist to buy, especially one whose spouse has frowned on further expenditures. Fortunately, there is another way to cut gears, one which can generate a full range of sizes for a given pitch and pressure angle using a single cutter. I refer, of course, to gear hobbing, a method based on the fact that the involute teeth of a gear of any size must mesh smoothly with a rack having straight-sided teeth of the matching pitch, height, and angle. The cutter, known as a gear hob, contains the proper straight-sided teeth formed on a spiral; when the hob is set at the angle of the helix, it cuts across the gear blank as if it were a straight rack. Because the teeth are on a spiral, however, the hob can be rotated in time with the blank to effect a continuous meshing of the rack with the gear as it is fed across the blank. Voila! A perfect gear is generated. Too bad I don't have a module 1 gear hob . . . or any means of making such a hob . . . or even a gear hobbing machine to put it on!

Cutting a Gear Using a "Straight Rack Cutter"

This is where the previously mentioned article by John A. Cooper came to my rescue. Generating a gear with perfectly shaped involute teeth requires the smooth, continuous cutting action of the spiral rack on a true gear hob. Cooper theorized, however, that a more-than-good-enough approximation can be achieved by cutting the gear in discrete steps using a cutter with a straight, rather than spiral, rack.

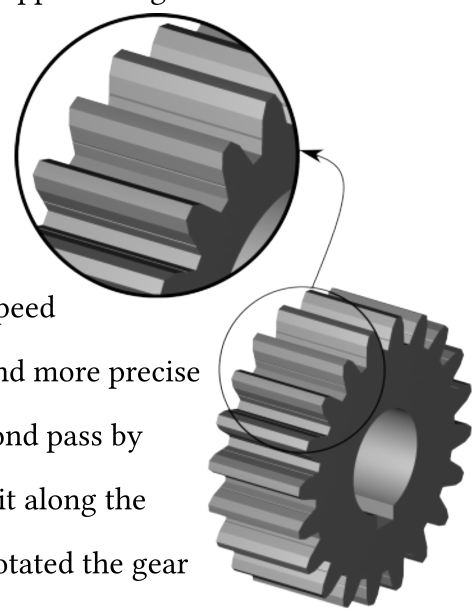
To check his theory and see how many steps it would take to achieve acceptable results, I decided to model the process using a free, open-source solid-modeling program called BRL-CAD (www.brlcad.org). Plugging values into ***Table 1*** for a 20-tooth module 1 gear gave me the following values: OD = 22mm; CP = 3.142mm; WD = 2.25mm. Accordingly I created a "gear blank" as a solid-model cylinder with a diameter of 22mm; I created the "cutter" as a rack with teeth angled at 20° on 3.142mm centers; and I positioned these models to overlap by 2.25mm (***Figure 3***). I then rotated the blank 18° (one tooth) at a time, "subtracting" the rack each time to mimic cutting the gear. ***Figure 4*** shows the result of

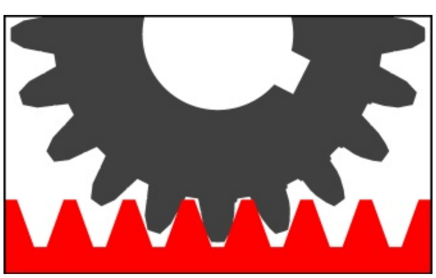




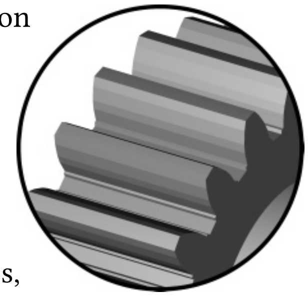
the first few operations; note how the gear teeth begin to change from a straight-sided shape to something approaching an involute curve as each cut refines the shape of the surrounding teeth.

"Something approaching an involute curve"—after the gear is cut through one full revolution, it looks surprisingly good, at least from a distance; closer inspection, however, reveals that the tooth shape is a long way from a smooth curve, consisting rather of a few relatively large and distinct facets (***Figure 5***). This might be good enough for a low speed and non-critical application, but I wanted something smoother and more precise for the change gears. Accordingly I prepared the model for a second pass by rotating the gear half a tooth (e.g., 9° instead of 18°) and shifting it along the rack by half of the circular pitch (1.571 mm). Then I once again rotated the gear 18° at a time, cutting the gear each time with the rack. ***Figure 6*** shows the fourth

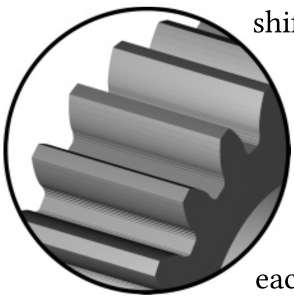




cut of this second pass, illustrating how the rack is further refining the shape of the teeth, and the closeup in ***Figure 7*** shows the much smaller and finer facets that result when the second pass is complete. There is a bit of of a jagged step in the gullet between teeth, but this is in the clearance area, and should not interfere with the operation of the gear.



In a software model, there is no limit to how many passes we can use to cut each tooth, and thus how finely we can form the gear. For example, the closeup in ***Figure 9*** shows the tiny facets that result when the model is cut in five passes,

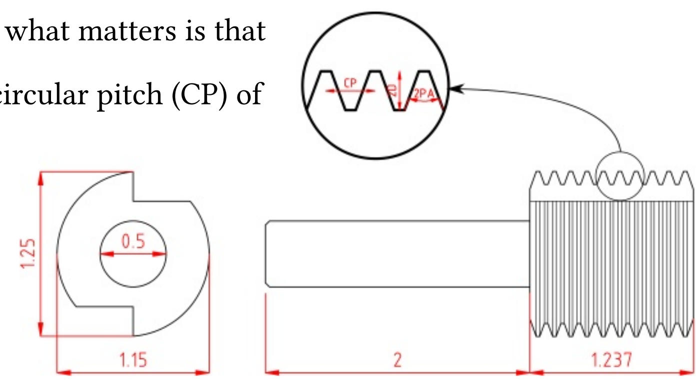


shifting one fifth of the circular pitch and rotating one fifth of a tooth (e.g., 3.6°) between each pass. In practice, however, we are limited by whether we can actually index the gear by the necessary fraction . . . and by the the time and tedium required to crank the mill table back and forth, over and over again, for each pass. After some experimenting, I judged the results after two passes to be good enough, and I made most of the gears for the mini-lathe accordingly. In retrospect, that decision seems to be justified; the gears mesh smoothly and quietly, with no discernible ratcheting or jerkiness.

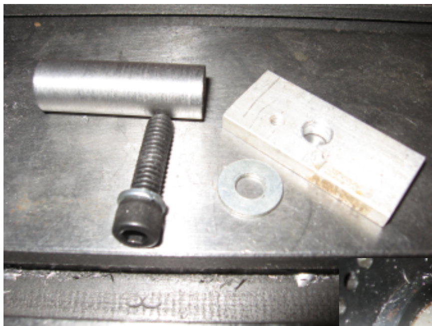
Making the Gear Cutter

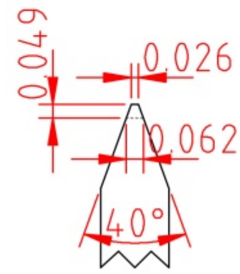
Now that we know how the theory works, we are ready to cut some gears . . . as soon as we make a cutter. ***Picture 2*** and ***Detail 1*** show my version of the cutting tool needed to cut module 1 gears for use on the mini-lathe. The overall length and diameter of the gear cutter

are not particularly critical; what matters is that the teeth are spaced at the circular pitch (CP) of the desired gear, with flanks inclined at the pressure angle (PA) and height equal to twice the

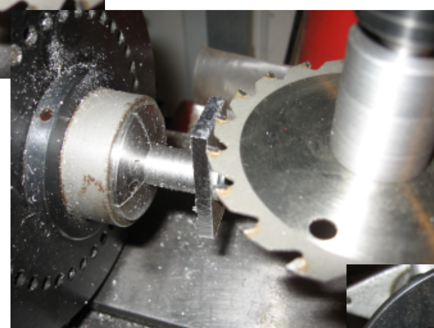


dedendum (D). The gap between the teeth on the cutter, measured at a point half-way down their length, must be equal to the tooth width of the desired gear (T).

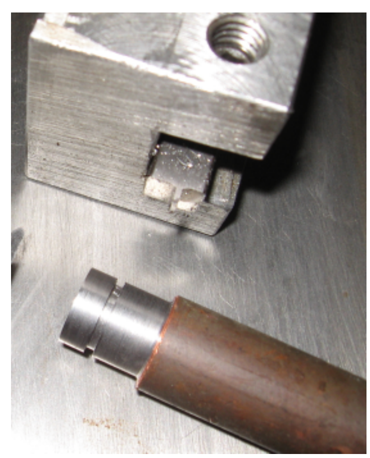




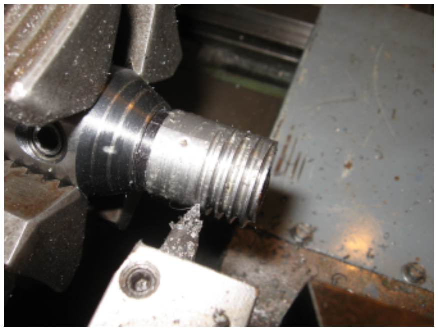
In order to make the cutter, we first must make a form tool to cut the cutter (***Detail 2***). Making this form tool is no harder than grinding a threading bit . . . except for two small problems. Where do we find a gauge to check the 40° included angle, and how can we set the exact width of the flat needed at the tip? To solve the first problem, I made my own gauge out of some scrap aluminum. As shown in ***Pictures 3-7***, I held the scrap of aluminum with an arbor mounted in a 5C collet in a spin indexer. Then, using a slitting saw, I squared up the aluminum scrap, and I cut the notch while indexing 20° to either side. The deeper cut in one side of the notch is intentional; this ensures that there is no burr to prevent the tip of the bit being measured from seating in the gauge (***Picture 8***).



Solving the second problem is even easier. The secret is to realize that the form tool will match the size of the gear teeth that the rack will cut. Thus, as shown in ***Detail 2***, the tool should be .062” (1.57mm) wide (T) at a distance of .049” (1.25mm) from the tip (D). I made a simple gauge with a rectangular notch .049” deep and .062” wide on the lathe using a precisely measured grooving tool (***Picture 9***). After grinding the form tool to a 40° included angle, I carefully flattened the tip until the tool just fit snugly into the gauge. Now I could use this form tool to make the gear cutter.



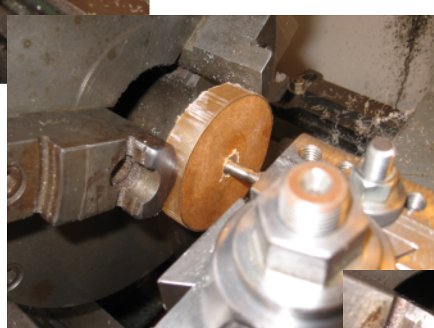
I chucked some A2 tool steel that I had on hand into the lathe and made the blank for the gear cutter. Then, with a dial indicator reading the

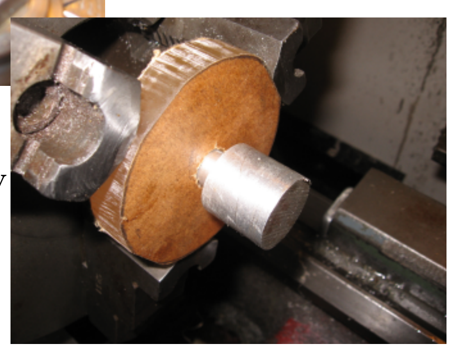


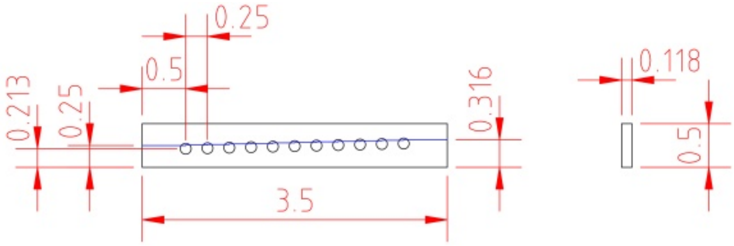
movement of the lathe carriage, I used the form cutter to cut 2.5 mm deep every 3.14mm along the blank (***Picture 10***; note that I am holding the finished shaft of the blank in an end-mill holder to protect it). I then transferred to the mill and cut flats to form the cutting edges (***Picture 11***). You may notice in the pictures and in ***Detail 1*** that I made my cutter slightly oval by offsetting it .050” on either side of center when turning the blank and cutting the teeth on the lathe; this was to build relief into the cutter. Frankly, I’m not sure that was worth the effort, especially for cutting gears from plastic. In any case, once I had hardened and tempered it, I had a cutter ready to cut gears; now I just needed to make the gear blanks.

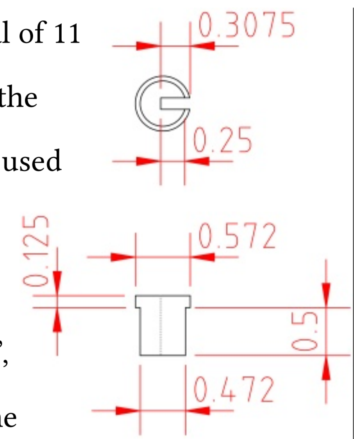
Making the Gear Blanks . . . and the Broach

My strategy for making the gear blanks was to make the bores first, including the keyways, then mount them on an arbor to turn them to final size. Accordingly, I roughed out circles of acrylic and chucked them in the lathe, then drilled and bored them to the 12mm shaft size (.472”), checking them with a previously-turned test plug (***Pictures 12-14***). So far, a very simple process . . . but what about the key way? In the past, when I have needed a single key way here or there, I have generally resorted to filing it by hand. But this time I needed 15 key ways, and I wanted each of them to be as accurately sized as possible. Clearly, I needed a broach—and once again, lack of funds forced me to make my own.



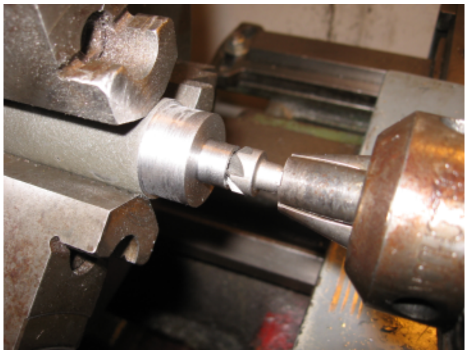
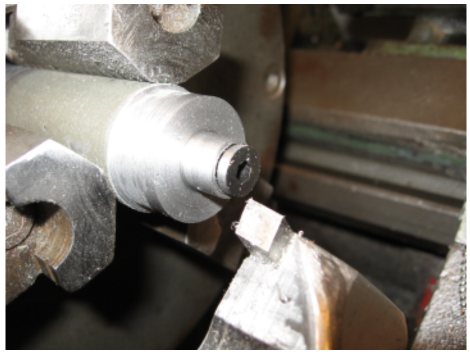
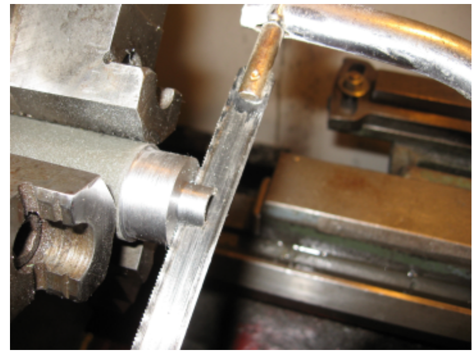




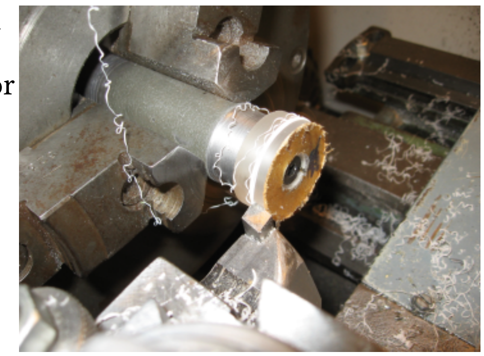


The broach and matching bushing that I made are shown in ***Picture 15*** and illustrated in ***Details 3-4***. I began by sizing some W1 tool steel into a 3.5” x .5” rectangle, 3mm (.118”) thick, which I then held in a vise. After finding the edges, I moved the table to drill the first 1/8” diameter hole .5” from the left and .213” from the bottom, drilling first with a center drill to ensure the drill bit didn’t wander. The table was then moved .25” left and .006” back and another hole was drilled. This movement and drilling was repeated until I had a total of 11 holes, each spaced .25 (x) and .006 (y) from the previous hole. I then turned the blank on edge and clamped it so that at least .25” extended above the vise. I used an endmill to cut the blank down by .184” across the entire 3.5” length, leaving the blank .316” wide (or tall, in this orientation). Then I lowered the spindle by .006” and, starting from the left, cut 3” of the blank down to .310”, ending with the endmill breaking into the last (rightmost) hole. I lowered the spindle by another .006” and, again starting from the left, cut 2.75” of the blank down to .304”, ending with the endmill breaking into the next-to-the-last hole. I repeated the process, lowering the spindle by .006” each time and reducing the length of cut by .25” each time until the broach was finished (the blue line in ***Detail 3*** illustrates these cuts). Finally I heated the broach with a torch until bright red, quenched it in water, and tempered it in the kitchen oven. No doubt the best method of making a broach would include grinding on a surface grinder, and certainly a broach made for use in steel would need much smaller steps than .006” between each tooth, but nonetheless my rough-and-ready approach produced a very workable result (***Picture 16***).

I made a simple expanding arbor by turning a short stub on some scrap steel to 12mm (.472”), drilling and tapping for a trimmed down flat-head socket screw, and cutting the stub through the middle with a

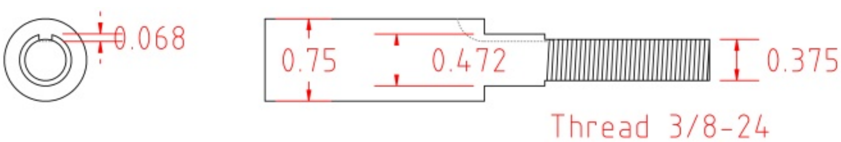
  

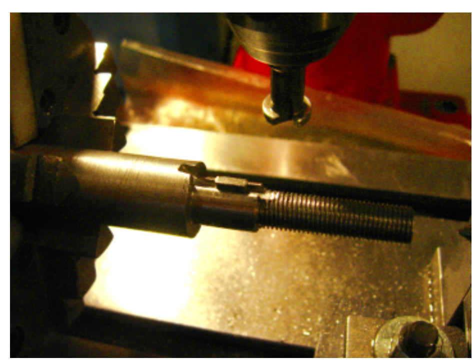
hacksaw (***Pictures 17-19***). I mounted each acrylic blank in turn on the arbor and turned it to the proper outer diameter (OD, calculated using ***Table 1***) and to the required thickness of 8mm (.315", ***Picture 20***). Fifteen rounds later, I had a stack of blanks and was ready to start cutting gears (***Picture 21***).

Cutting the Gears

Actually, I was *almost* ready to start cutting gears. I still needed an arbor to hold the gear blanks in the indexing head on my mill (***Detail 5*** and ***Pictures 22-24***). The only really critical dimension for this arbor is the 12mm (.472") diameter and its 3mm keyway. Note that the length of the 12mm section is just a bit less than the width of two gears; this allows cutting two identical-sized gears (e.g., the two 40-tooth gears needed for a

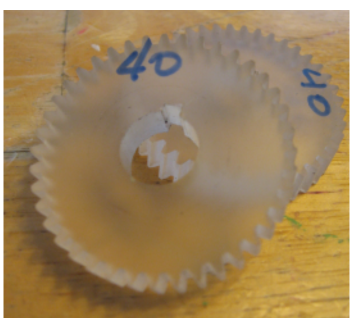


complete set) at the same time. When cutting a single gear, the spacer from the banjo of the mini-lathe is used to take up the extra space so that the 3/8-24 nut can tighten the gear blank securely in place.

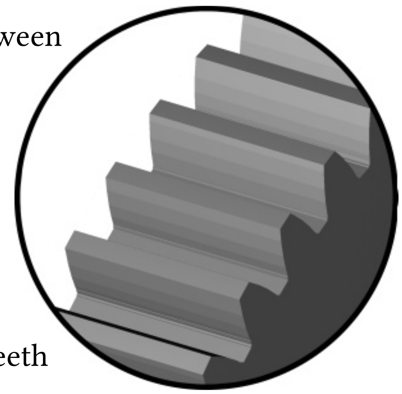
With the arbor made and mounted in the indexing head, the gear blank is mounted on the arbor and the cutter is installed in the spindle. Then the spindle and table are positioned such that one of the middle teeth of the cutter is centered on and just touching the centerline of the gear blank. This does not require extreme accuracy; the "hobbing" effect of the process will take care of shaping the gear teeth properly, and the gears can tolerate a few thousands of error on the depth of cut. Once everything is set and the dials (or DRO, should you be so blessed) are zeroed, cutting can commence (***Picture 25***).

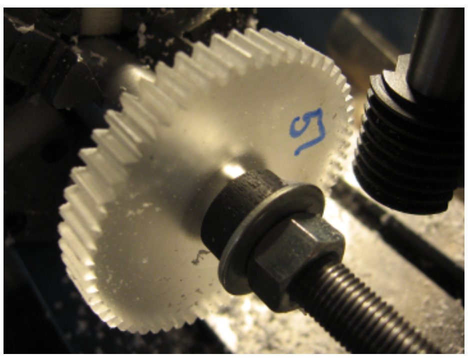
I usually took two or three passes to reach the full depth of cut (WD) when starting each gear, but after that, the gear blank can be indexed to the next position and cut at full depth in one pass. If you look back at ***Figure 4*** you can see why; the rack cuts parts of several teeth each time, so only a little more has to be cut off the next tooth when it is indexed. After the gear has been indexed all the way around, I indexed the gear by half a tooth and moved the spindle down (or up—it doesn't matter which) by .062" (1.57mm, CP/2), then took a second pass all the way around to further refine the shape of the teeth. At that point, the gears are finished (***Picture 26***).



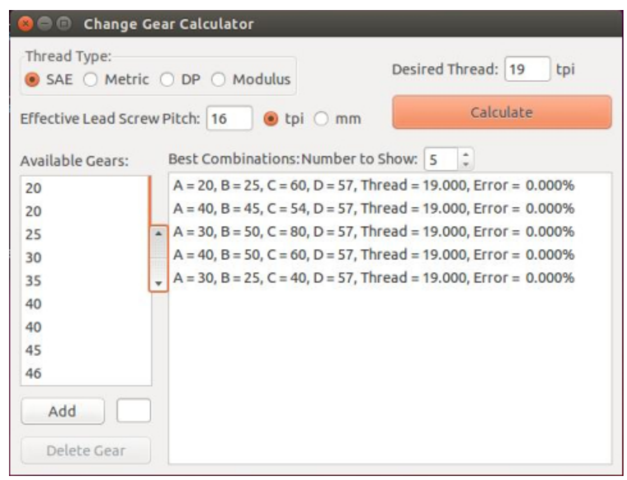
Unfortunately, though this process worked well for most of the gears I wanted to cut, it did not work for all. Consider a 57-tooth gear, useful for cutting a 19 tpi thread (yes, this can be needed—see below). The problem is that my dividing head does not have any way to index 57 divisions. I do have the ability to index 19 divisions, but that would mean indexing by three teeth at a time, and just cutting every third tooth would leave a very uneven gear (***Picture 27***).

Fortunately, there is a tricky way to solve the problem. When my dividing head is set up to index 19 divisions, each index requires traversing 40 holes in the 19 index circle, due to the fact that the worm gear in my dividing head has 40 teeth. If I could evenly divide 40 by 6, there would be no problem; I could cut six passes spread over three teeth per index, giving me the equivalent of cutting two passes over each tooth, with each pass advanced by half a tooth. Since I can't evenly divide 40 by 6, what if instead I divide it by 5? In effect, that would give only 5/3 passes per tooth rather than 2. (To say it another way, this would shift the gear ⅗ rather than ½ a tooth between each revolution, and the spindle would correspondingly need to move down or up ⅗ rather than ½ CP each time). The final result would be slightly coarser, . . . but perhaps it would still be good enough.





Once again, the modeling software lets us see exactly how five passes over three teeth per index will look. As ***Figure 9*** shows, the results are not bad, not bad at all, so this is what I did to generate the 57 tooth gear (***Picture 28***). I did the same for the 51 and 63 tooth gears as well, using the 17 and 21 division indexes respectively. Note that it would have been possible to divide 40 by 8 or by 10, providing even smoother results by doing 8 or 10 passes over three teeth per index—but in practice, these "5/3" gears have proven smooth and quiet.



Using the Gears

The proof, as they say, is in the pudding—or rather, in this case, in the cutting. I now had a complete stack of gears, including 20 tooth (2 of these), 25, 30, 35, 40 (2 of these), 45, 46, 50, 51, 54, 55, 57, 60, 63, 65, and 80 (2 of these). I also wrote a small computer program that can calculate the best combination(s) of gears to achieve any desired thread pitch, including not only inch and metric, but even module and DP as well (***Picture 29***). I was ready for anything!

Sure enough, shortly after I completed the gears, a friend asked me to help repair a damaged screw from an antique plow plane. The screw measured .25” in diameter, but a 20 tpi nut definitely did not fit; after much careful measurement, I finally determined that it was a 19 tpi thread, something I’ve never heard of before or since. I would not have been able to cut this thread on my Cincinnati TrayTop lathe . . . but armed with my new set of change gears, it was a piece of cake to set up the requisite gears on the banjo (***Picture 30***), and in short order I had made a brand new 1/4-19 screw, and my friend’s plane was back in working order.

Notes: All photos are by the author. The ChangeGear program is available for download on the Home Shop Machinist forum, as is a script for generating gear models with the BRL-CAD software.