Gear Cutting 101

By Jim DuBois

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Warning:

We assume no responsibility for accident, injury, or damages. Gear cutting machines are dangerous. Caution mixed with care, followed by practice, is the recommended path. Be prepared to punch the power off switch! Use at your own risk! Chips fly, coolant spatters, cutters cut. Use care, use safety glasses, don't wear loose clothing around rotating parts, and don't work when you are tired. Be careful. I have both scars and trips to ER's to prove these points. I was a slow learner when it came to safety.

Credits:

Let me be very clear, this paper is the work of many people, not just myself. Included are ideas, information, communications, technical data, from but not limited to:

- Dewey Clark
- John Losche
- Malcolm Wild
- Michael Helfrich
- Michael Poisson
- Laurie Penman
- Glenn Seeds
- John Palmborg
- John Shadle
- Jerry Walker
- David Lindow
- T. Harrison-Smith
- Thornton's LTD

I have drawn comments from various emails and other communications dating back over 20 years, so if you see your words included and no credit given, it is purely accidental and an oversight on my part. I will correct it if you will let me know of my error.

Gear Cutting 101

First, BOOKS!! Read and learn!

Malcolm Wild's book on Wheels and Pinion Cutting in Horology is required reading IMO. He describes the process in detail, plus he has many useful tools and setups you can make with minimal effort. His explanations on cutting solutions and equipment are on a par with experts such as George Daniels. If you have the Wild and Daniels books (and understand them), you are almost WOSTEP trained. Bill Smith also offers a couple of videos on the subject that are most helpful.

Necessary stuff and starting thoughts

Gear cutting is not difficult. At a minimum, an indexing device, and a profile cutter for the gear tooth needed to cut, and a lathe, is all that is needed to cut gears. While I have perhaps $10-15-20k in cutters in the shop, most wheels can be cut with a selection of perhaps 10 cutters. Pinions are a bit more difficult as each pinion tooth count requires its own range of cutters.

However, both wheels and pinions can be fly cut, and fly cutters can be made out of 50 cents worth of tool steel and some work....

In any event, I don't see the need to buy equipment specifically intended for making watch and clock gears. Think more like a machinist. In fact, you *could* buy a used vertical mill. This would give you the function of the vertical mill plus enable you to cut gears and pinions.

One only has to look at John Shadle's website http://onlineclockbuilding.com/ to realize that one can produce work of the highest order with relatively simple and inexpensive equipment. So, there may be several different motivations for wanting to cut gears. There are those that simply wish to learn and experience. There are those that seem more interested in collecting every commercially made cutter available, along with the most accurate and costly machines available to drive them. There are those who already do or who wish to make this into a viable business either on its own, or as part of their existing business.

We will try to offer points of interest for all readers….. No matter the motivation. By the way, I like CNC equipment and use it exclusively to cut gears, but it is not necessary at all. Just saves me labor.

Cutters

I use mostly Thornton cutters and a few Bergeron cutters…my Bergeron wheel cutters are not as good quality wise as are the Thornton’s. Copious amounts of coolant/lubrication is absolutely required IMO, a solid rigid mounting is needed. Hence, using a tailstock helps considerably so that both ends are held, a good grade of steel used, and cutter speed is set to not exceed the recommended SFM for the steel being cut. I have broken one escape wheel cutter and chipped some teeth off 2 Thornton escape wheel cutters in the last 30 years. Oh by the way, I did all of these cutting steel racks using the escape wheel cutters. They chip and or break backing out of the rack when the rack is not held firmly against the backing plate.

Even though my cutters have cut many wheels and pinions there is so little work done by most cutters they don’t get dull very quick. I have only ever had to sharpen a very few of them, maybe a half dozen in total.

1. I do not like to use fly cutters, but can and do use them on occasion. 2500 rpm should be more than enough speed. I recently cut a dead beat escape wheel for a small Howard tower clock with a fly cutter I made, and I ran it at 1700 rpm. I made it out of some old tool steel, hardened it, then tempered it to light straw
2. As a beginner you might find it best to start out with a commercially made multitooth cutter so you can get experience at the rest of the process and after you master the gear cutting then start making your own?
3. Smaller involute cutters can be purchased quite cheaply from time to time and you could practice with them. Working clocks can and have been made with involute trains, I don't recommend it, but it can work…good practice. Think DP48 or DP 36 sizes…
4. The cutter, be it a fly cutter or multi-tooth needs to be held in a rigid fashion, the blank has to be held rigidly and backed up also
5. Cutting brass requires lubrication and coolant if you want the cutter to stay sharp, the teeth to be cleanly cut, and the last tooth to look like the first tooth. This is even more critical on a fly cutter……
6. So think rigid setup, sharp cutter be it fly or multi-tooth, use coolant….. it will work

A final point, I have never been able to make as good a cutter as can be readily purchased from Thornton….but what with the dollar to pound issues of late they are approaching $125 each.

When I don't have the mutil-toothed cutter for the wheel or pinion, I make a fly cutter. These are easy to make on the lathe. You turn a profile to fit a good tooth space. Then you file or grind it to its center line and put a little rake on the reverse. Harden and temper. Whole thing takes less than an hour.

The fly cutter holder is simply a lathe arbor chuck with a hole cross drilled through its center and a tapped hole on its axis for a grub screw for holding the fly cutter.

Fly cutting pinions require slow RPM and very slow feed. And don't try to make the teeth in one pass.

Also, for pinions it is useful to make and verify the setups by using a brass blank first. Regarding the Thornton Wheel and Pinion cutters I have about 115 of them including 6/7/8/9/10/12 leaf pinions, some of which go from about .2mm all the way up to 1.0mm, a couple go to 1.5mm. For wheel cutting there is a set of 26 Burgeon cutters. I also have watch and carriage clock sized cutters as well as some DP cutters down to like DP 6 and up to DP 48 or so. I also have a full set of escape wheel cutters, both recoil and dead beat as well as some music box governor worm gear driver cutters.

Materials, brass

The sheet brass I use is ½ hard engravers brass. I buy it from a reputable supplier, the same one for many years. I have cut hundreds if not thousands of wheels out of it. I on occasion also use cast yellow phosphor bronze wheel blanks. These, I had cast to make American banjo parts.

Materials, steel

Here are comments from others regarding "screw machine steel"…..I use it for most pinions…..made about 99% of the pinions I ever cut out of it…I have it from 1/8" up through 1 ½" but not all sizes…the exception would be gathering pallet pinions. They are so highly stressed in some clocks that tool steel is necessary for the additional strength offered by its composition.

Several people have mentioned steel that is an alloy (reputedly) (leadloy or screw machine steel) which includes sulphur and lead, and has good machinability. I most recently saw it referred to in the letters section of Home Shop Machinist.

Can anyone tell me a) does it really have good machinability? And b) can you tell me a mail-order source?

Answer

Leadloy is also known as 'screw machine stock'. Yes, it machines beautifully. I believe just about any steel supplier handles some kind of screw machine stock.

Leadloy is excellent material. It cuts much better than 1018 CRS. It cuts nearly as easily as aluminum or brass. It gives a nice bright finish and yields small chips which are easy to clean up.

Leadloy is known officially as C13L14. In addition to the small amount of lead, it contains sulfur and phosphorus.

It has a machinability rating of 170, where 1018 CRS is about 70 and lousy stuff (think Chinese provided steel) is below 50.

The only steel better than C13L14 is another Leadloy containing tellurium, with a machinability of above 200.

Leadloy only costs about 5% more the 1018 from steel suppliers.

Causes of failures when cutting wheels and pinions

1. not rigid setup,
2. did not use coolant
3. used too fast a feed rate
4. used too high an RPM on the cutter
5. used tool steel that was nearly as hard as the cutter

When I cut wheels and pinions I rarely make direct use of theory. I measure the outside diameter of the wheel/pinion and cut my blank to that diameter + about .020". I use a good tooth space to determine which cutter to use (by fit). This works very nicely with wheels; it is a little harder with pinions. I have mist coolant system for my small CNC vertical mill. When cutting wheels and pinions, I use flood cooling most often.

I cut the pinions supported at both ends if at all possible. When cutting in that fashion I reduce the shaft before and after the pinion head to reduce the work being done by the cutter before I cut the teeth   When I don't support at both ends I only reduce the outboard end before cutting

Coolant discussions

For use with brass coolant use is no more than “moderate usage”. While the coolant does not work nearly as hard when used on brass as it would on steel or even aluminum, it really does fulfill at least 3 major roles. It cools, it provides lubrication that improves surface finish, reduces tool wear, reduces mechanical forces on the cutting engine and tooling, and it provides chip clearance. Now as to engine oil versus a metalworking coolant, I suggest checking with a machine supply and see what they supply and or recommend.

I have used pipe cutting fluid which is very heavy with sulphur. I have used tapping fluids such as “Tap Magic”. I have used light machine oils such as “3 in 1” oil. I have used clean engine oil.   They all work after a fashion, but none of them work as well as a proper coolant. When cutting gears / wheels / pinions I use “flood coolant” which tends to get messy and use / recirculate like a gallon or 2 of the coolant. The flood coolant I use is of the water soluble oil type, it is about 70-90% water. I personally would not like to contaminate a gallon of any of the other fluids with chips etc….

Early on I did try a “dribbler” that would sort of dribble on pipe cutting oil onto the cutter. That is better than no coolant/lube, but it does little for chip clearance and little for cooling by conduction….It does reduce heating by reducing friction, but again, you are missing some of the benefits.

Thornton tables for calculation of addendum for pinions

Table of Addendum allowances			
Number of leaves	*Ogive*	*Ratio Tooth/Space*	*Add to number of teeth or leaves*
6	*Full*	*1/2*	*1.71*
7	*Full*	*1/2*	*1.71*
8	*Full*	*1/2*	*1.71*
10	*1/3*	*2/3*	*1.61*
12	*1/3*	*2/3*	*1.61*
16	*1/3*	*2/3*	*1.61*
Wheel	*—*	*1/1*	*2.76*
For Cutting Pinions for old work with thicker leaves, use cutter 0.05 module smaller than calculated. The addendum allowance is unchanged.			

Recommended cutting speeds

For cutting carbon steel pinions with high speed steel cutters:

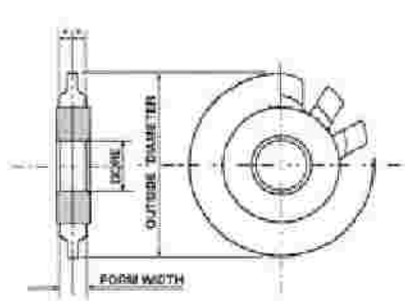
Cutter diameter 14mm 430-500 rpm
Cutter diameter 20mm 300-350 rpm
Cutter diameter 24mm 250-290 rpm
Cutter diameter 26mm 230-270 rpm

A copious stream of cutting oil should be used to keep the cutter cool and remove the chips. Mobilmet 745 or similar.

Pinions should never be cut dry.

For cutting brass a speed of up to 3-4000 rpm can be used, but a much lower speed will preserve the tooth cutting edges.

Recommendations for sharpening cutters and materials for use



Recommended brass and steel

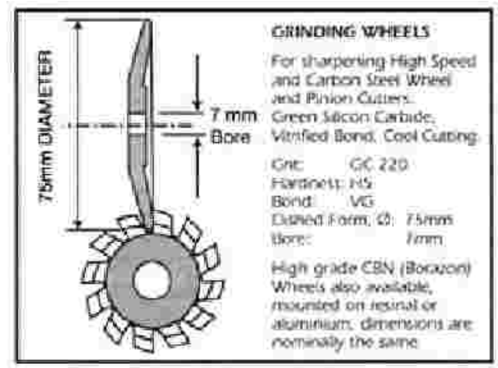
BRASS for wheels should be hard or half-hard leaded engraving brass such as CZ 118, CZ 119, or CZ 120, with a hardness of 120-130 VNP Do not use soft brass which will clog the cutter and spoil the work.
STEEL Clock pinions may be cut from silver steel which HAS BEEN FULLY ANNEALED (it is supplied in normalized condition) but steels

with a lower carbon content such as EN8 or EN9 are to be preferred.

The profiles are made in accordance with BS 978 Part 2, NHS 56702/3 and have square bottoms, also NHS 56704 with round bottoms. These cutters can be sharpened without loss of form. For suitable grinding wheels see right.

The cutters are relieved using profile ground solid carbide tools; the finish on the form of the cutter teeth is therefore of a high quality.

All cutters are made from 8% Cobalt M42 (HSS-E) high speed steel hardened and treble tempered under vacuum, there is therefore no change in the surface chemistry of the tool. This steel is of first quality, and is known for its ability to keep a good cutting edge to give long duration between sharpenings. Hardness circa 68 ROCKWELL C.



Calculations and required formulas

Wheel and Pinion Cutters

Calculation of the Module of existing wheel or pinion

Module **M** = Diameter in mm **D** divided by Number of teeth **N** + addendum.

Also Module = Twice the center distance in mm divided by Sum of teeth in wheel + pinion

Center Distance = **M** divided by 2 multiplied by sum of teeth in wheel and pinion

Converting Module and Diametral Pitch

Module = 25.4 divided by the D P

Diametral Pitch = 25.4 divided by Module

Calculation of blank diameter

Blank Diameter = Module multiplied by N + Addendum allowance from the table below.

Example: For a pinion of 6 leaves and a Module of 0.7 the Blank Diameter = 0.7 X (6 +1.71) = 5.397mm

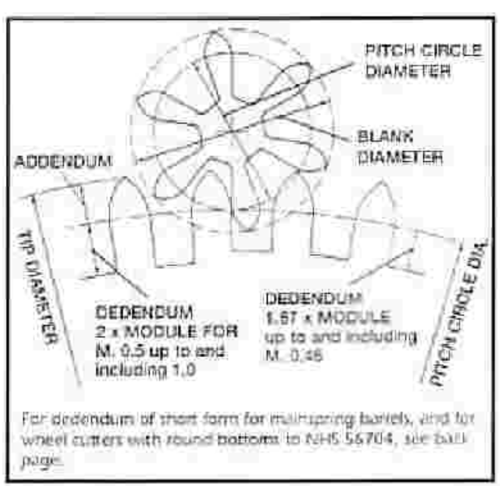
To calculate the module of a wheel or pinion when the center distance is not known.Module = Diameter divided by N + addendum allowance

For pinions of odd numbered leaves use a hole gauge to measure the diameter.

Table of Addendum allowances

Number of leaves	Ogive	Ratio tooth/space	Add to number of teeth or leaves
6	Full	1/2	1.71
7	Full	1/2	1.71
8	Full	1/2	1.71
10	1/3	2/3	1.61
12	1/3	2/3	1.61
16	1/3	2/3	1.61
Wheel	.	1/1	2.76

For cutting pinions on old clocks with thicker leaves use cutter 0,05 module smaller than the calculated one.
The addendum allowance is unchanged.



For cutting carbon steel pinions with high speed steel cutters

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For cutting brass a speed of up to 3-4000 can be used, but a much lower speed will preserve the tooth cutting edges.

PROFILE DIMENSIONS FOR CLOCK & WATCH WHEEL & PINION CUTTERS

WHEELS

All dimensions as ratios of the module, M, millimetres
British Standard 978 : Part 2. As Swiss Standard NHS 56702 except for *

Module M.	Up to and including 0.45, and 1.1 to 1.5	0.5 and up to and including 1.0	Short form 0.2 to 1.0	Round Bottom* 0.2 to 1.0 NHS 56704
Number of teeth	N	N	N	N
Pitch circle diameter	N x M	N x M	N x M	N x M
Outside or tip diameter (diameter of blank)	(N + 2.76) x M	(N + 2.76) x M	(N + 2.76) x M	(N + 2.50) x M
Root Diameter	(N - 3.14) x M	(N - 4) x M*	(N - 2.14) x M	(N - 3.50) x M
Tooth thickness	1.57 x M	1.57 x M	1.57 x M	1.41 x M
Addendum radius	1.93 x M	1.93 x M	1.93 x M	2.00 x M
Angle of cutter flank	2°	2°	2°	4° - 43
Addendum	1.38 x M	1.38 x M	1.38 x M	1.25 x M
Dedendum	1.57 x M	*2 x M	1.07 x M	1.75 x M
Full tooth depth (depth of feed)	2.95 x M	3.38 x M	2.45 x M	3.0 x M

PINIONS

All dimensions as ratios of the module, M, millimetres
British Standard 978 : Part 2. As Swiss Standard NHS 56703 except for *

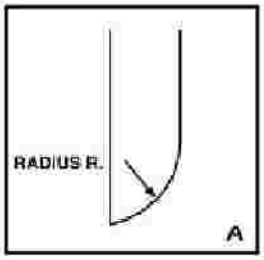
Number of leaves	6	7	8	10	12	16
Pitch circle diameter	6	7	8	10	12	16
Outside or tip diameter (diameter of blank)	7.71	8.71	9.71	11.61	13.61	17.61
Root diameter *	2.84	3.3	4.2	5.9	7.8	11.8
Leaf thickness	1.05	1.05	1.05	1.25*	1.25	1.25
Addendum radius	1.05	1.05	1.05	0.82	0.82	0.82
Form of addendum	FULL OGIVE PROFILE C			1/3 OGIVE PROFILE B		
Angle of cutter flank	20°	17°-9	15°	10°-48	9°	6°-45
Tooth/pitch ratio	1/3	1/3	1/3	2/5	2/5	2/5
Addendum	0.855	0.855	0.855	0.805	0.805	0.805
Dedendum	1.58‡	1.85	1.90	2.05	2.10	2.10
Full tooth depth	2.435	2.705	2.755	2.755	2.905	2.905

‡The old figure of 1.75 is being phased out

P.P. THORNTON (SUCCESSORS) LTD.
HOROLOGICAL CUTTER MAKERS

ESCAPE WHEEL & RATCHET CUTTERS

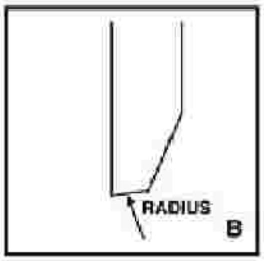
FINE TOOTH



A. RECOIL ESCAPE WHEEL CUTTERS

Ø 26mm. Bore 7.00mm. No. of teeth on cutter - 60.

Size No.	Radius R. mm.	Pitch of escape wheel less Tooth Tip thickness mm.	Cutter thickness mm.
1E	3.28	1.31	1.64
2E	4.10	1.64	2.05
3E	5.12	2.05	2.56
4E	6.40	2.50	3.20
5E	8.00	3.20	4.00
6E	10.00	4.00	4.50
7E	12.25	5.00	5.80



B. DEAD BEAT ESCAPE WHEEL CUTTERS

Ø 30mm. Bore 7.00mm. No. of teeth on cutter - 60. These cutters are designed for a 30 tooth escape wheel, but pitch and number of teeth may be varied up to about 9%.

Size Letter.	Ø Escape Wheel Inches.	Pitch of Escape Wheel less Tooth Tip Thickness Inches.
A	1.75	0.183
B	1.42	0.148
C	1.08	0.113
D	0.75	0.078

Calculation of Escape Wheel Tooth Pitch to select cutter

Example:

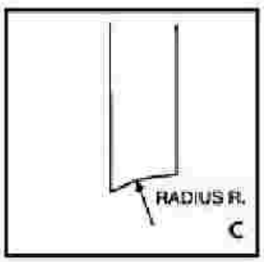
Tip Diameter D = 1.375 inches

No. of Teeth N = 29

Pitch $P = \frac{\pi D}{N} = \frac{3.142 \times 1.375}{29}$

$= 0.148$ inches

Use Cutter size B Dead Beat.



C. RADIUSED TOOTH RATCHET CUTTERS

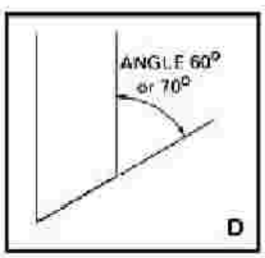
Ø 26mm. Bore 7.00mm. No. of teeth on cutter - 60.

Radius R. mm.	Diameter of Ratchet 2R. mm.	Thickness / Pitch mm.
4	8	3
6	12	4
9	18	6
13.5	27	9

For quantity production, form relieved cutters with 12 teeth can be supplied to special order, and extra price, for profiles above in sketches A, B and C.

RATCHET & MUSICAL BOX CUTTERS

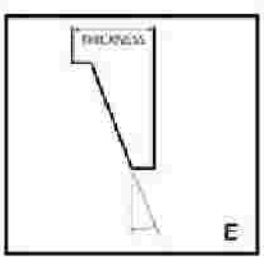
FORM RELIEVED



D. STRAIGHT TOOTH RATCHET CUTTERS

Ø 28mm. Bore 7.00mm. No. of teeth on cutter - 12. Cutter thickness 7.0 (nominal)

Angles 60° and 70°



E. MUSICAL BOX WORM WHEEL CUTTERS

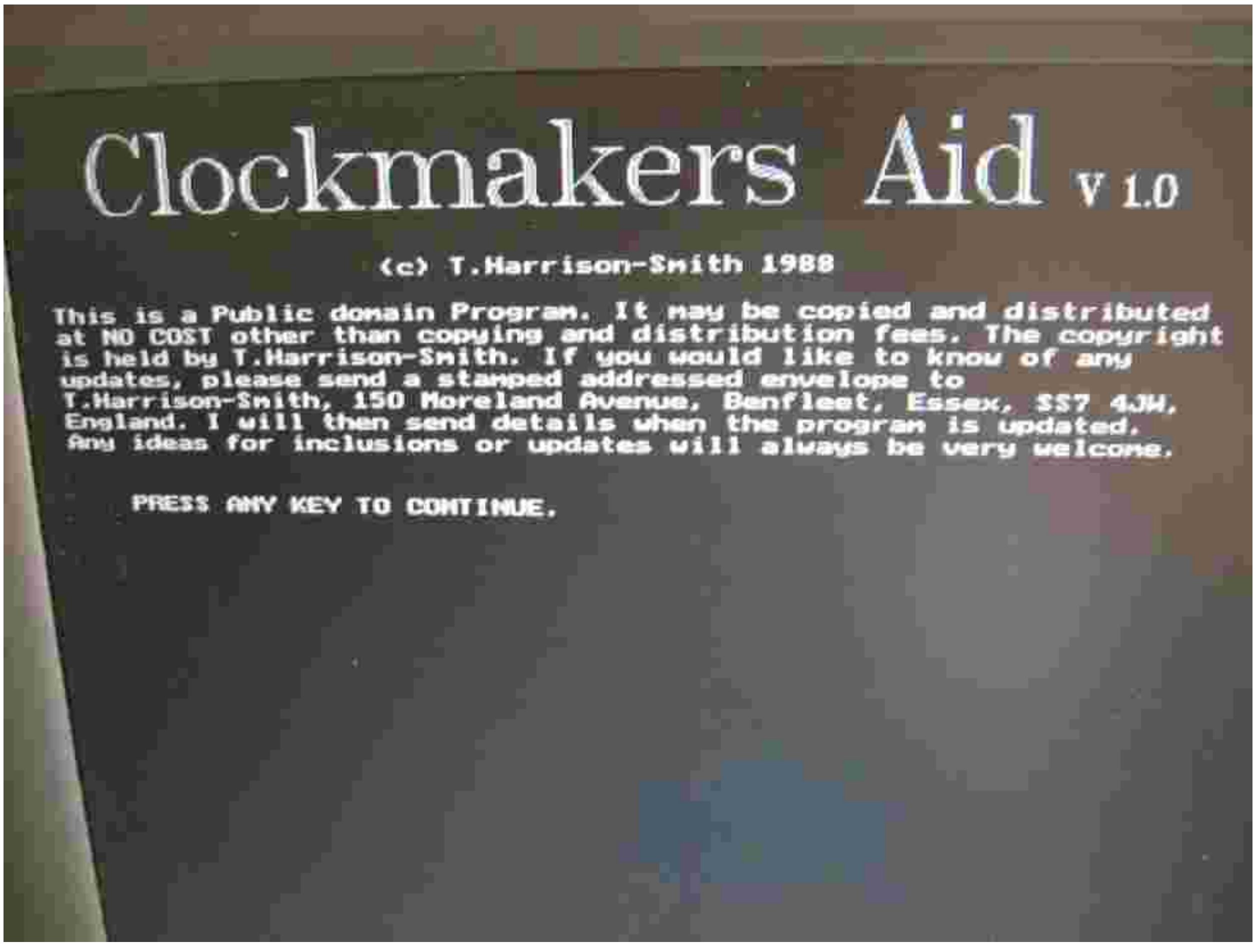
Ø 25mm. Bore 7.00mm. No. of teeth on cutter - 12.

Size No	Standard Pitch mm	Standard Depth mm	Tip Width of Cutter mm	Cutter Thickness (nominal)
00	0.63	0.52	0.20	2.00
0	0.82	0.67	0.26	3.00
1	1.10	0.90	0.35	3.00
2	1.40	1.15	0.45	3.00
3	1.80	1.47	0.57	3.00
4	2.30	1.88	0.73	3.25

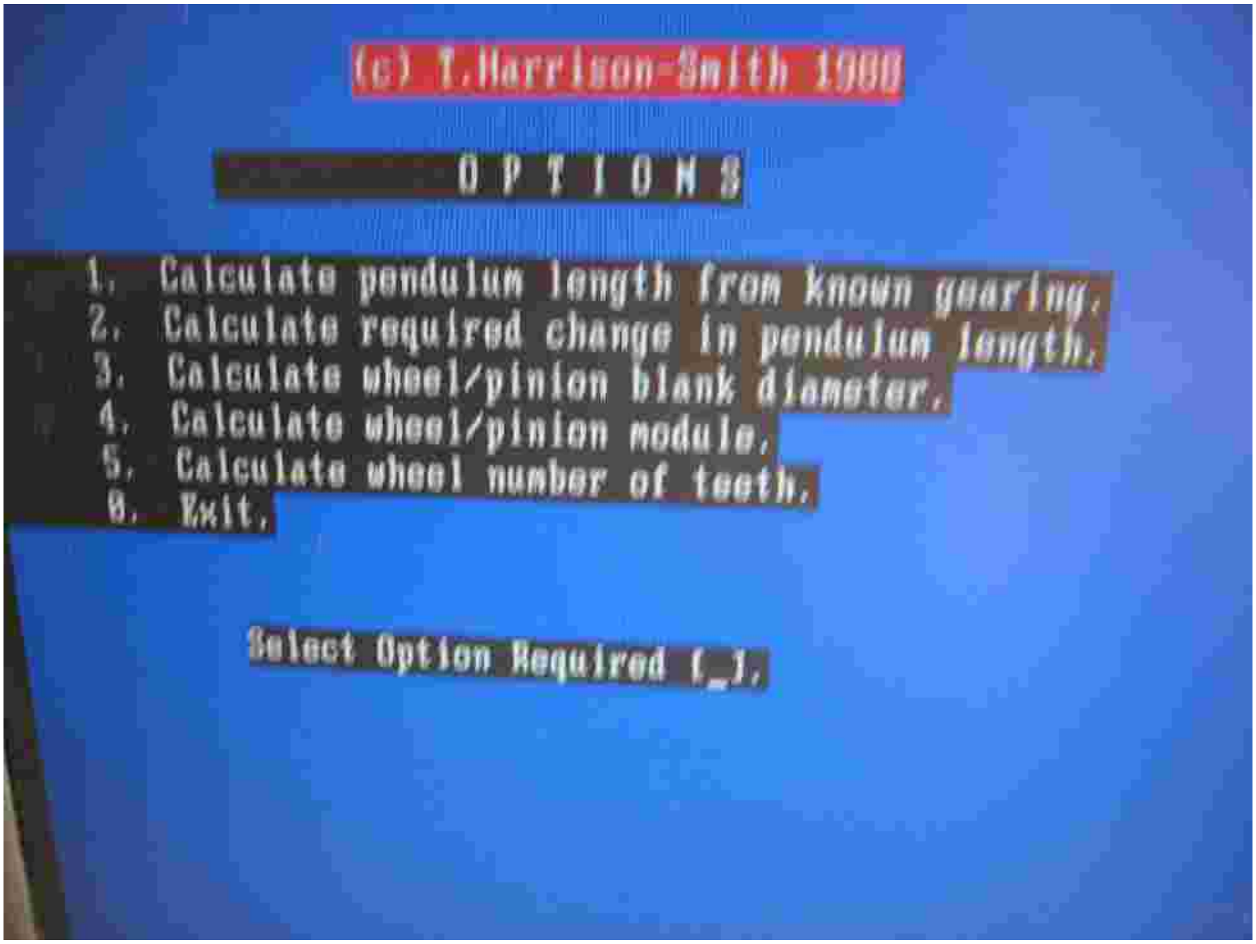
Useful Software Programs to aid in calculations

There are 2 software packages I consider indispensable in my shop. They are both available online, do a Google search for them. They are both quite old, but I am not aware of any more recent packages that fulfill the features of these packages.

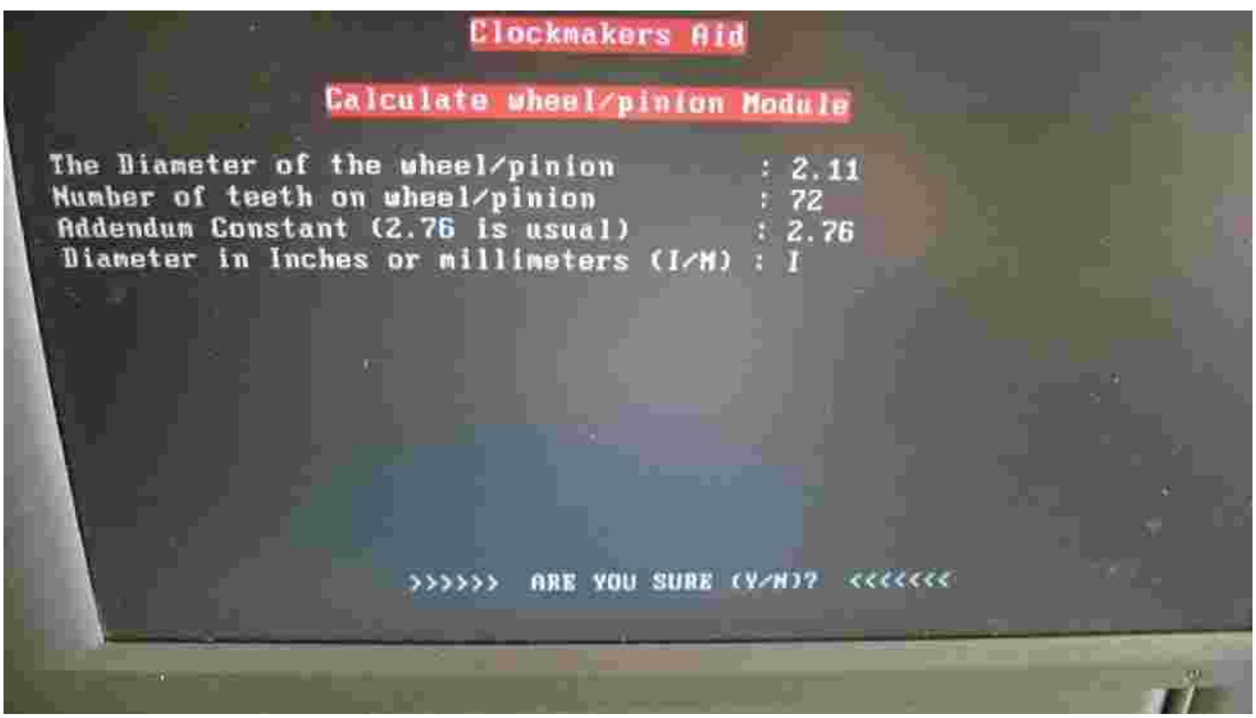
Clockmakers Aid

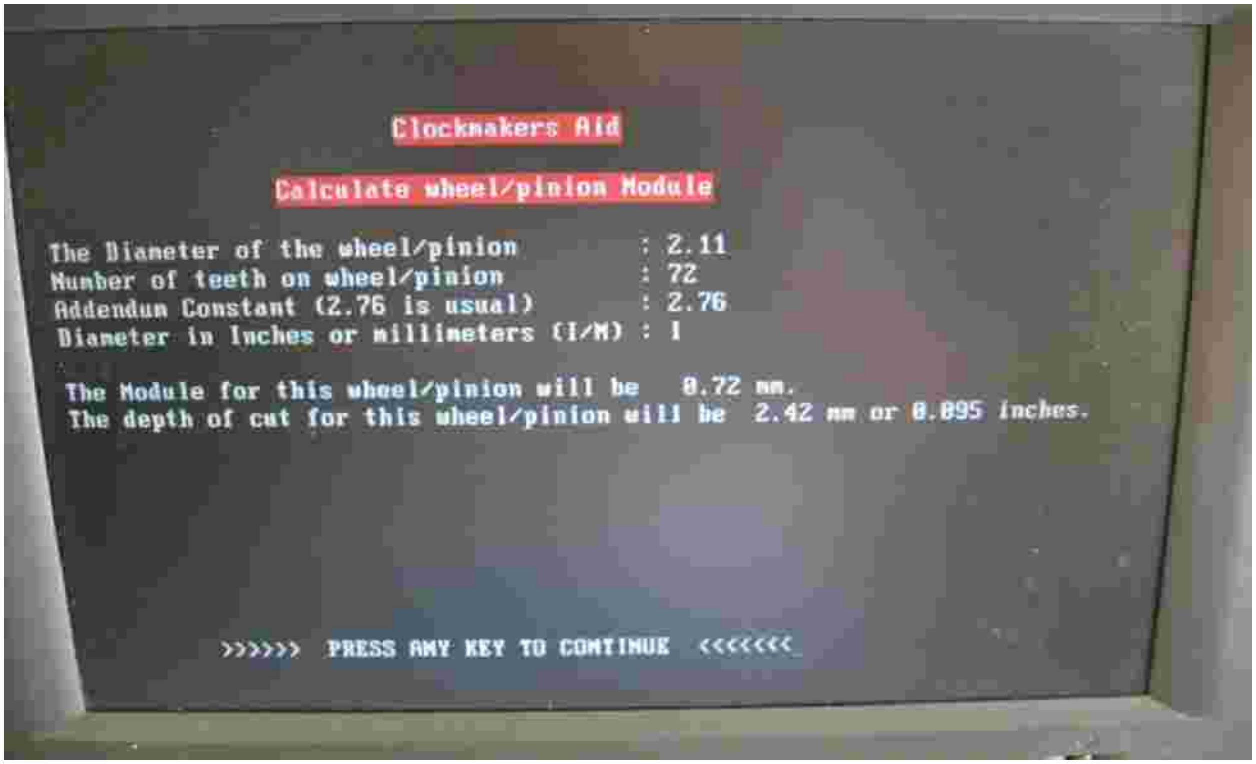


Hit any key and you get:



I use option 4 a lot, you may want to also…..

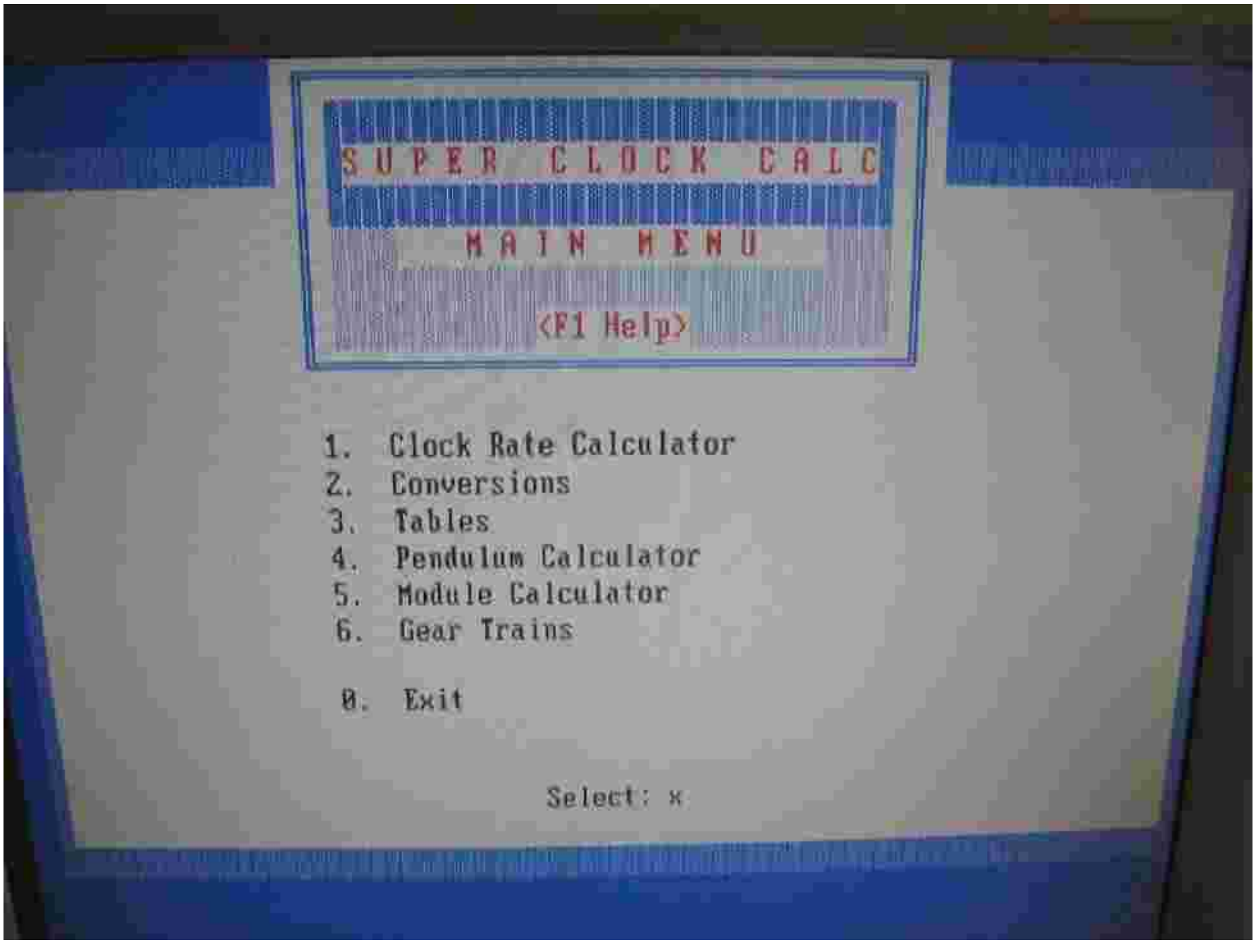




This obviously gives us the all important depth of cut for our wheel or pinion.

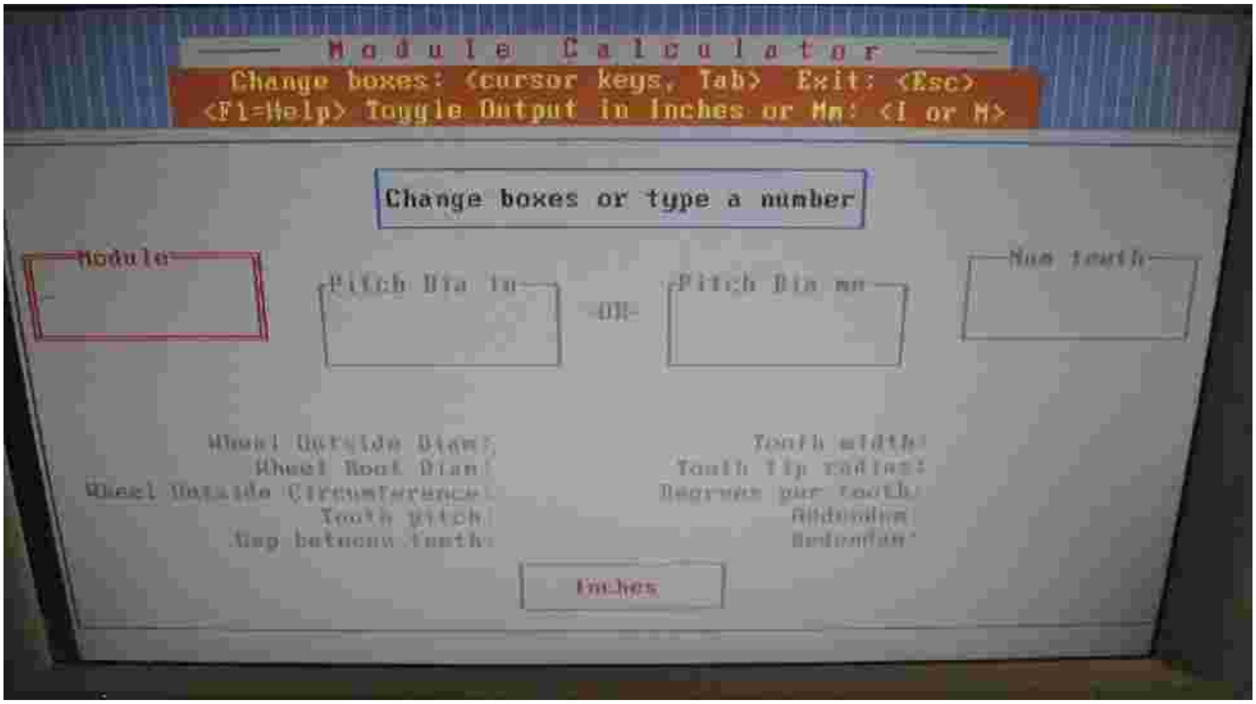
Super Clock Calc

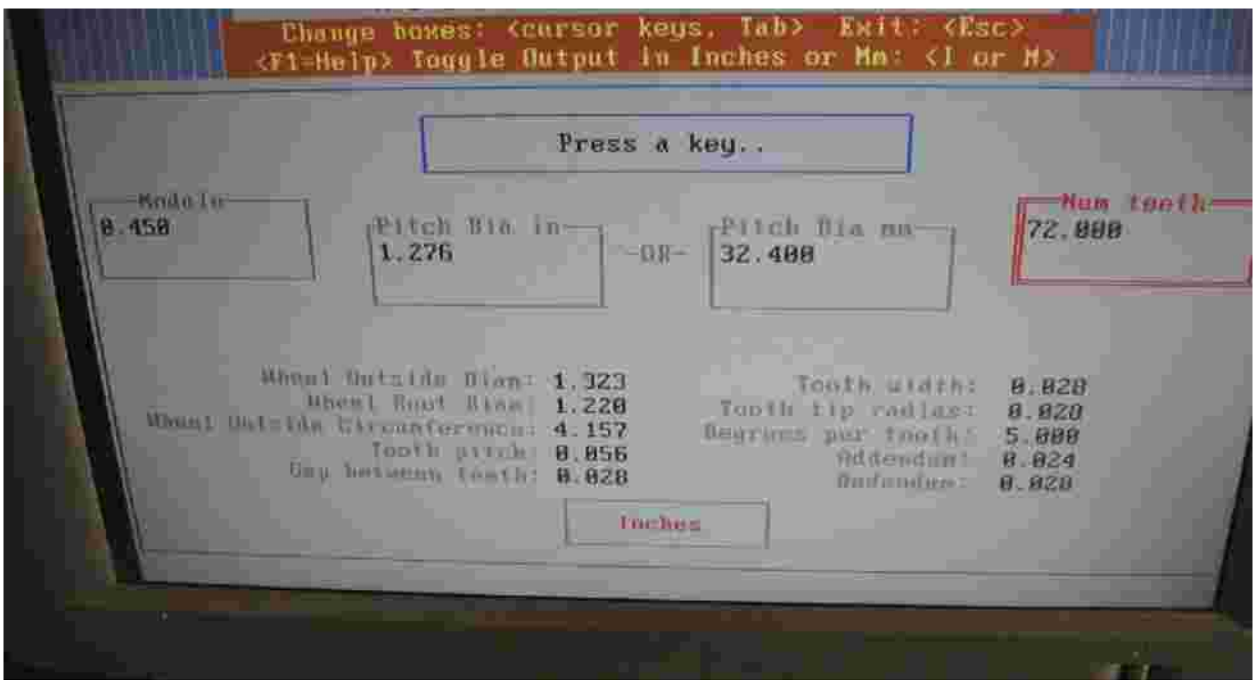
There is a second auxiliary program that may be of use to you. I have never really figured out how to measure a "pitch diameter" for example. And of course MM as well as PD wheel cutting is based upon this all important pitch diameter.



In this case you want option 5

That will bring up the following

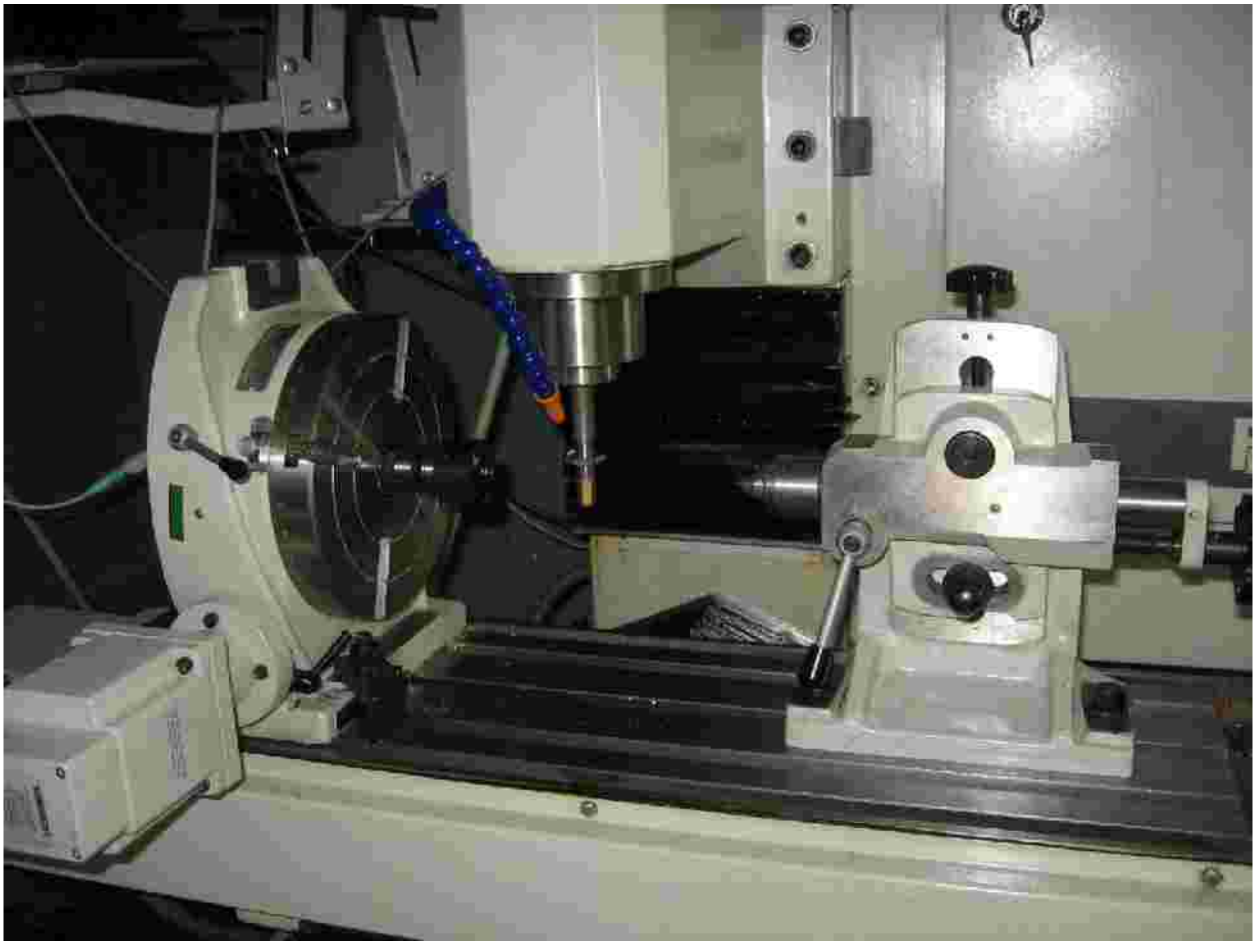




As you can see entering the MM and number of teeth give you all sorts of useful information for cutting gears, but not depth of cut. Too bad neither of these programs has been developed further, but they work for our purposes. Handy!

Hardware installation on a mill

The wheel cutting machine will need to be set up with the rotary axis on the left side of the table and the stepper motor drive for the "X" axis motion positioned on the right end of the table. See the following example on my machine



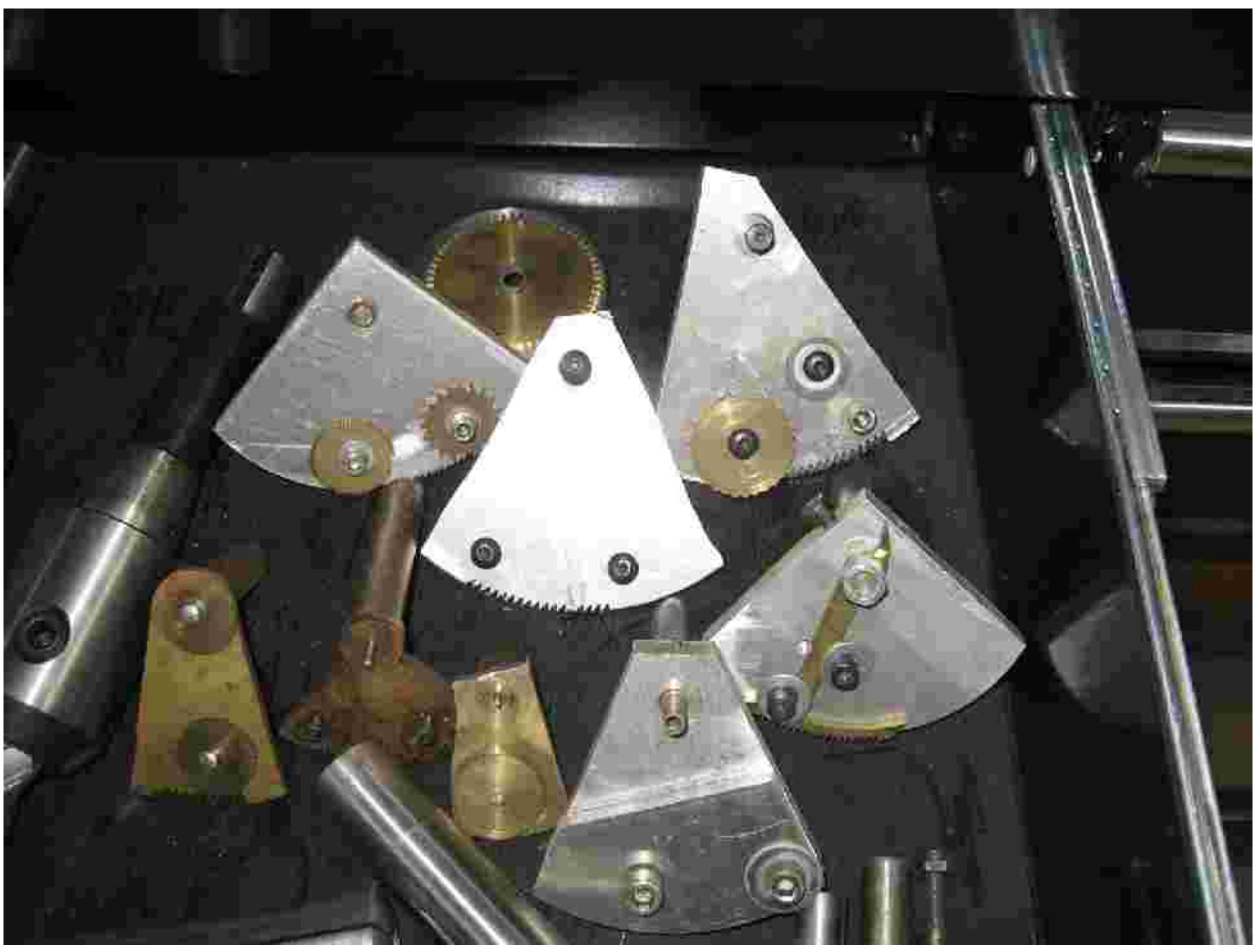
Use of a tailstock

You will note a tailstock is shown in the photo. I very highly recommend its use for all cutting. Absolute rigidity is a must, and a tailstock provides a big step to just that need.

Arbor construction

I am including photos of a number of arbors, just for your consideration. You will notice that arbors get chewed up. I consider them to be disposable or consumable in nature and use a rather disorganized approach to their build, maintenance, and storage.

As mentioned above absolute rigidity is required. An arbor supported at both ends, with backing plates or a mass behind the point of cutting is a requirement. Otherwise, you will have chatter, and chatter results in junk, not wheels and pinions. I turn the arbors between centers and for the greater part need to treat them as consumable items for gear cutting. I have standardized on clock size wheels on a ½” shank arbor and a ¼” x 28 thread holding device…..bigger parts require a scale up and smaller a scale down…go figure?



As you can see from this selection racks require a special holding arbor. I have cut a fair number of them.   It is easier than one might think, easier to explain than write it out….

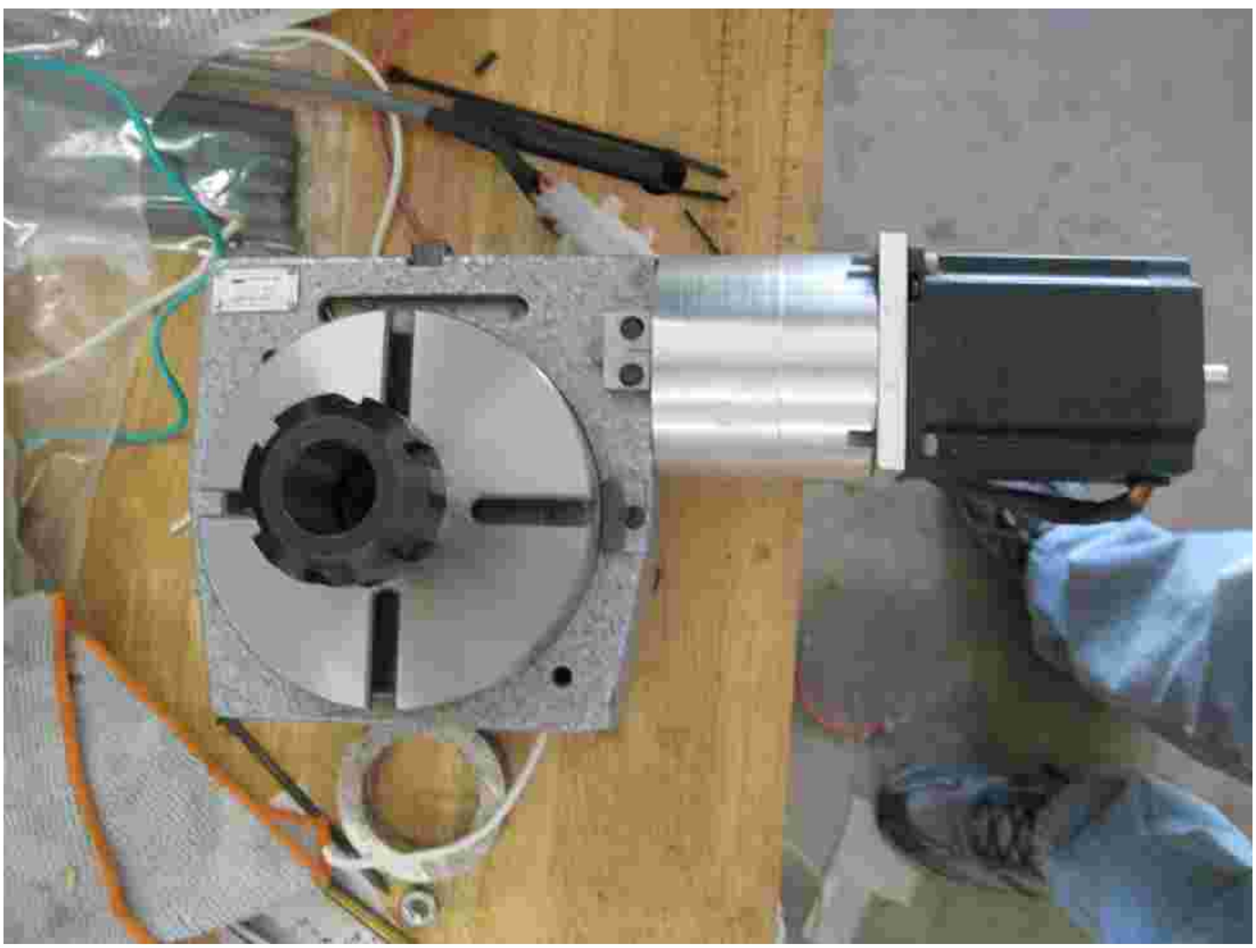
Round, flat, rigid, and concentric are all concepts to cover in the making of arbors.

Passing note of consideration:

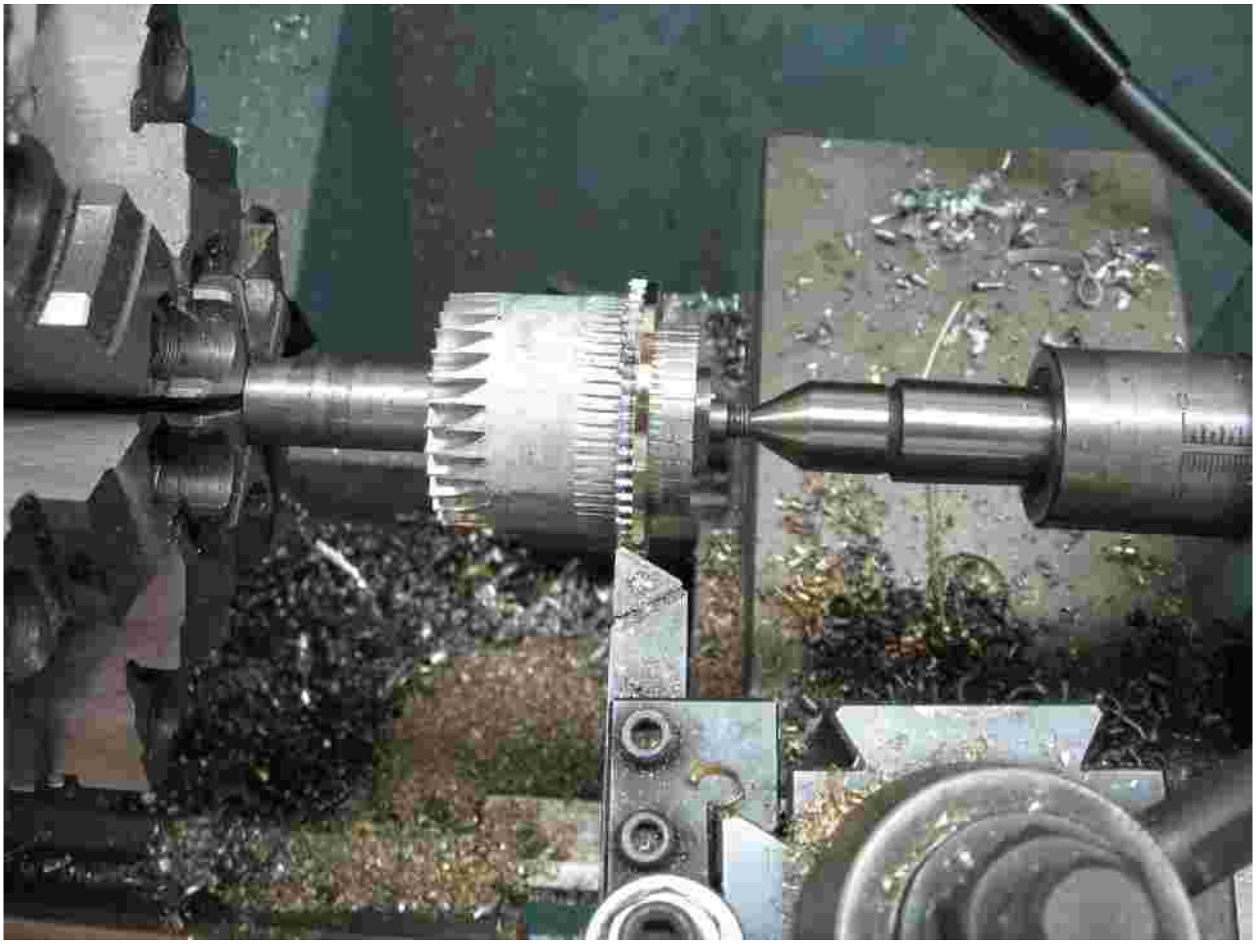
Whatever you do, do not try to hold a cutter or a blank with a 3 jaw Jacobs drill chuck. Both the cutter arbor and the blank arbor need to be accurate, round and concentric to be certain, and not likely to lose its grip. I don’t even use a Jacobs chuck for drilling if I can help it… a proper sized collet is recommended if accuracy is needed….. And when is it not needed?

Collet Holding Adapter

A good method of holding tooling in the rotary dividing device is by using a collet holding adapter in the rotary table with a good range of collets, 1/8” to 5/8”. See the following:



Gear cutting details



Here I am turning up the wheel blank on an arbor in an accurate 6 jaw and dead center. I leave the blank about .020” oversized and cut the teeth to the correct depth, then rebore the center holding the wheel by the tooth tips. This approach makes for an accurate sized wheel with no blunted tip teeth and a bore that is concentric with the teeth.

Setting the cutter on center using a laser center finder

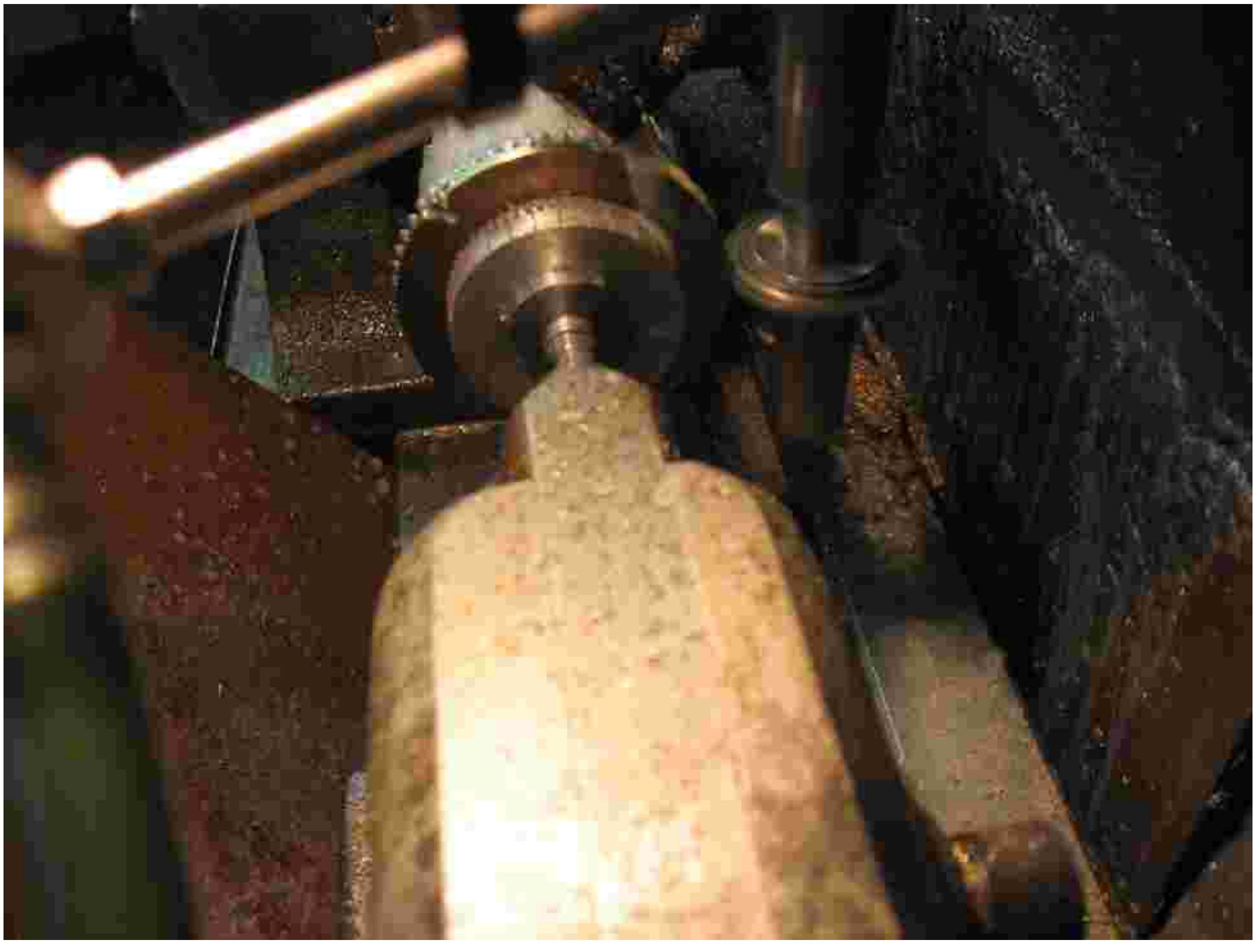
Low tech cutter centering method

I also have found a needle held in a collet to be a low tech method of determining center for the cutter

Bring the cutter in until it just barely touches the wheel blank

Zero the Y axis readout

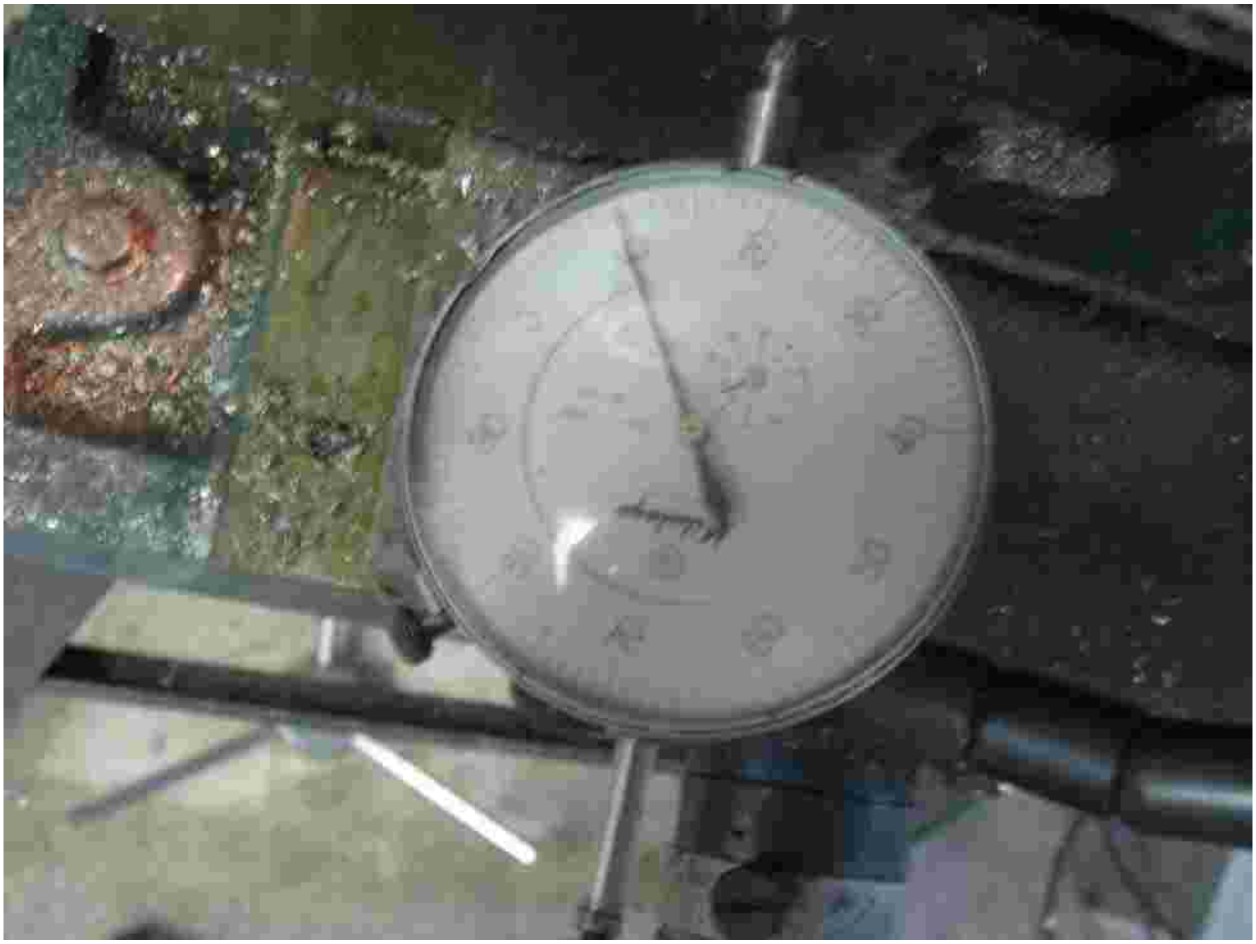
Power up the cutter and coolant and bring the cutter into the correct depth



The correct cutting depth can be determined by the formulas supplied by Thornton or by the recommended software packages.

In this case the cutter speed will be 1650 RPM, which is as fast is this mill will run. I have used upwards of 5000 rpm cutting brass wheels on other mills with coolant. Gets messy, but works well. IMO when fly cutting higher spindle speeds are useful.

Depth in this case is .110”



Move the work past the centerline of the wheel then return it to its start position. Move the table back to a clear start point, just clear of the wheel blank so it will rotate without nipping tooth tips. Evaluate the depth of the cut and verify you have made a pass completely across the centerline of the tooth surface and returned to it starting point. It is useful to mark the table or fix a stop on the manual table for both points.

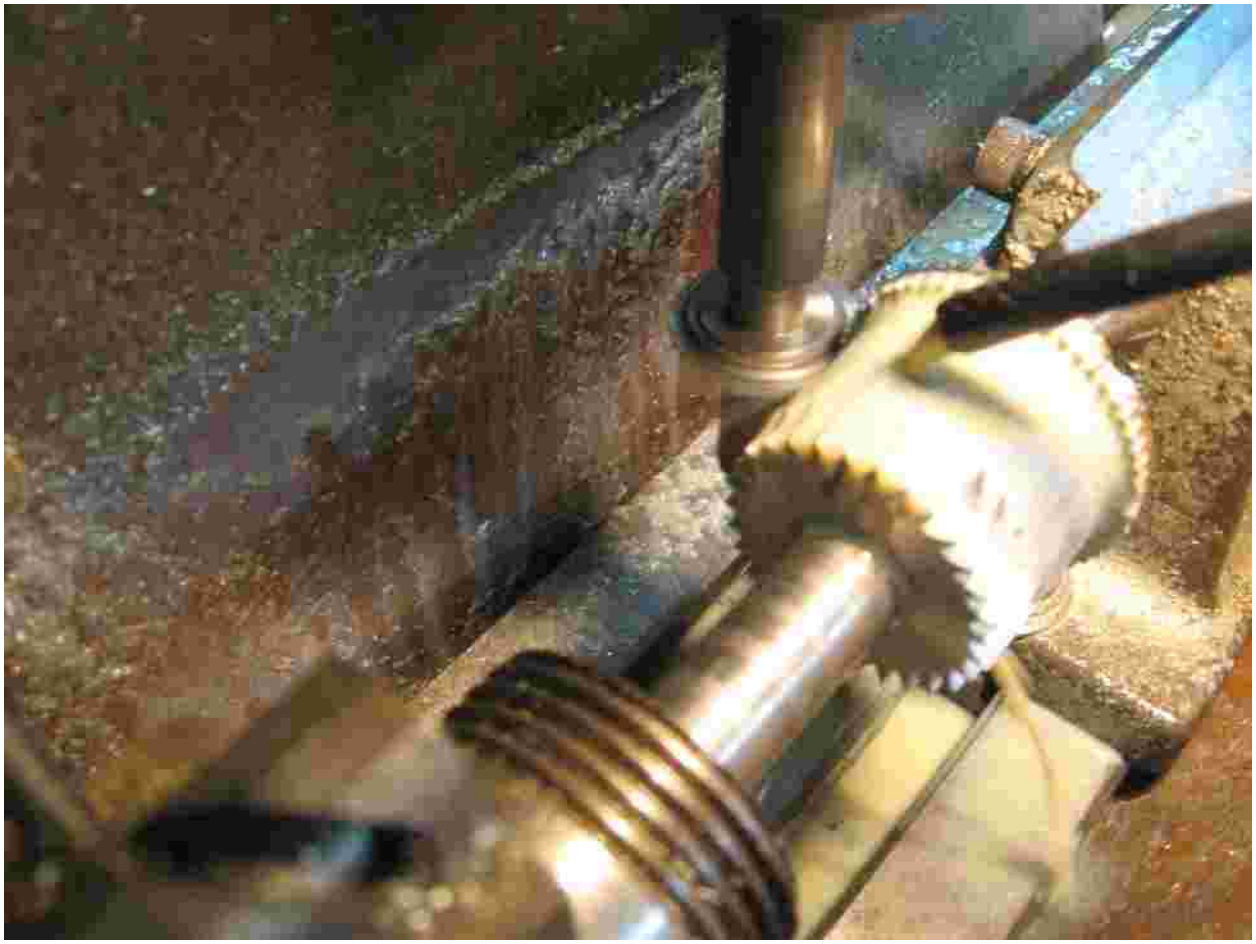
Coolant return on my wheel cutter

Coolant pump “Little Giant”

Pinion cutting

In cutting pinions coolant / lubrication is absolutely required. Cutting speed in this case is 255 rpm. You may be limited by spindle speeds but when cutting steel, too slow is better than too fast on speed of cut (feed) and speed of rotation of the cutter.

Progress, nearly done, notice how the sheet metal behind the cutter rests in the table groove and directs the coolant and chips…..have one on the front side also. Cutter is running at 1750 RPM and does throw coolant about….



All Done! After shutting off the spindle the first thing I do is look at first tooth and last tooth to make certain I have not cut a 71 ½ tooth gear. Assuming all is well with the first tooth last tooth, I then measure the diameter of the wheel or pinion.

Too large? Need to move the table in by ½ the diamenter reduction required and make another pass. It is important to not remove the wheel or pinion from the headstock until complete.

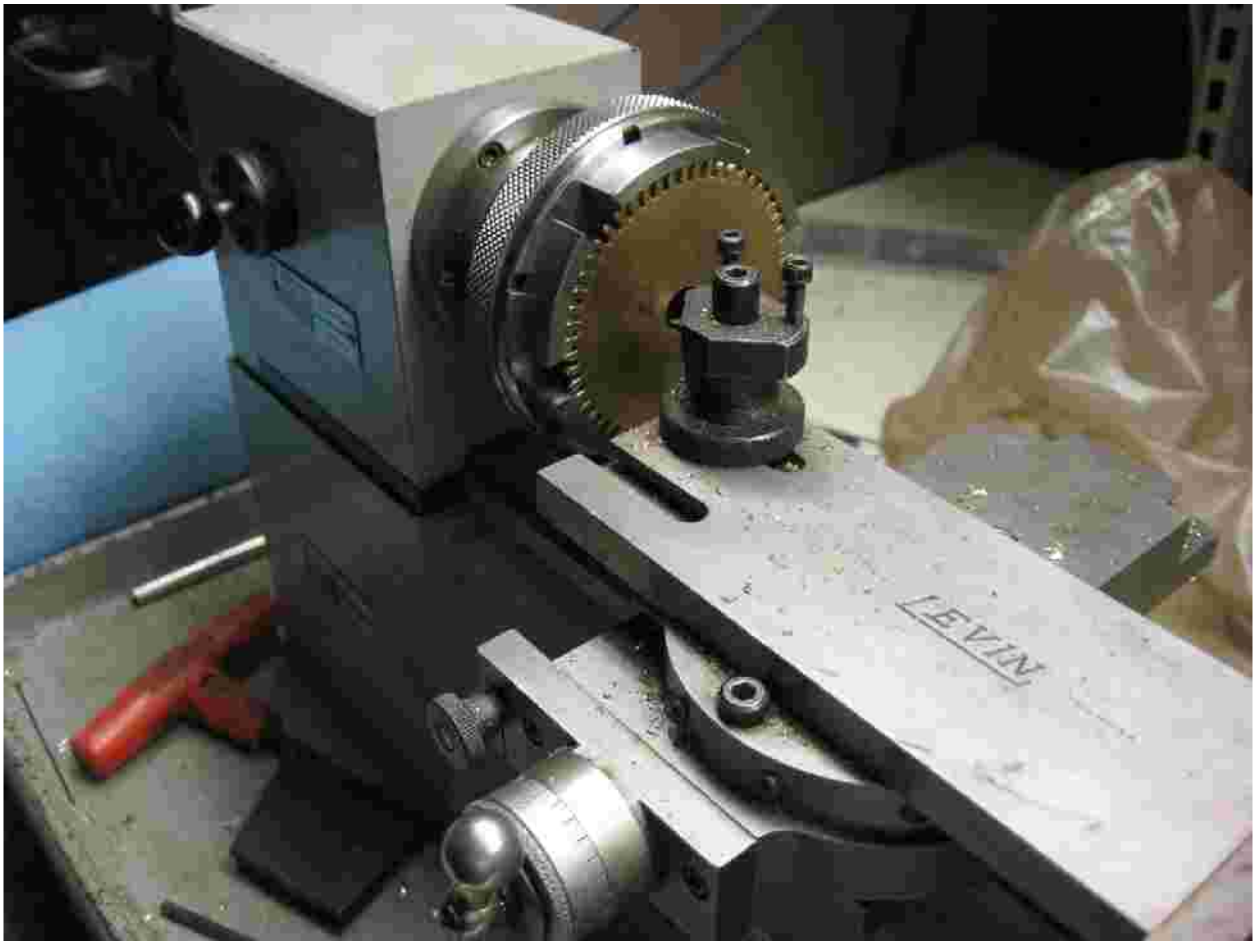
Note: An odd number of pinion teeth requires the use of a hole guage to measure diameter. A suitable guage can be made by drilling a hole of the correct diameter in a piece of scrap…….

Too small? Feed the scrap drawer and start over!

> **Please note, and this is important, if you remove a cut wheel or pinion from its arbor or from the gear cutting machine and then decide to reduce its diameter by cutting it again, IT IS VERY LIKELY YOU WILL BE MAKING SCRAP AS YOU WILL HAVE SOME HALF TEETH WHEN DONE.** Don't ask me why this is, it defies conventional wisdom, but it is. You need to get it "right" before you remove it from the machine. I have done this many times and I estimate that more than 50% of the re-cuts have been scrap, no matter how careful I have been. If you leave it in the machine and don't mess with the rotary axis positioning you can make many passes around a wheel without issues. Just FYI.

Burrs removed, center bored out, ready to be brushed and an arbor staked in. 56 tooth calender drive wheel for American tallcase

Boring setup


LEVIN

Tailstock Boring Bar