Horological Wheel Cutting -

(Jerry Kieffer's) Modern Means & Methods

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SAFETY NOTE:
DURING ALL MACHINING OPERATIONS, PLEASE USE YOUR SAFETY GLASSES.
For those of us who wear glasses, an alternative you might try is prescription safety glasses from your nearby eye vision store. Ask for the ANSI approved models. Be warned they won't pass any fashion tests☺. But, they work really good, particularly when you attach one of Behr's non-distortion single or double eye loupes[50].

Introduction

One of the holy grails in horology is the mastery of wheel cutting. As part of studying the many wheel cutting means and methods, prescribed by the masters and amateurs alike, I happened upon a means and method taught by Jerry Kieffer (Jerry, JK). Jerry, a self made master micro-machinist who hails from the state of Wisconsin, teaches the method at NAWCC. I took the two day course and afterwards practiced until I was able to obtain repeatable, good outcomes. It is hard for me to believe that now I am able to make custom single point cutters a/k/a fly cutters, grind form tools to cut escape wheels, cut train wheels and even ratchet wheels. I am finally beginning to feel like a real clockmaker. J.M. Hucklebee said it best…"it is not until you make a clock or two does one really feel like a clockmaker". These writings originally started out as clockmaker notes and they grew from there. So, I hope you will enjoy my journey as much as I did. First though, I need to point out three important aspects of Jerry's means and methods 1) modern machine tools are used, not the traditional clockmaker tools and methods 2) access to a micro mill and lathe such as Sherline's product lines with their precision accuracy is essential and 3) Sherline's CNC rotary table with its programmable controller is used in place of traditional indexing tools.

The primary focus of this article is a step by step set of instructions for modern day wheel cutting. Included within that are general observations, those nuances and bits of information that make all the difference between success and failure, excerpts from Jerry's class, subsequent discussions with Jerry and plenty of pictures all overlaid by my observations and lessons learned from mastering the particular technique or concept.   As Jerry says, he teaches a concept. He expects folks to adapt it to their own preferences and develop their own particular "modern means and method". There are several types of clock wheels that need to be cut. Included are train wheels, escape wheels (both recoil and deadbeat), ratchet wheels and mainspring barrels and each of them require a unique form cutting tool. Discussions on each of these types will be incorporated into this text and pictorial journey via Sections I, II, III & IV respectively. A bit of a discussion is also included on non-horological gearing. Clockmakers should be able to distinguish the differences between horological and non-horological gearing as they will encounter each in readings and in "boot" sales and the facts and observations provided herein will make for a greater understanding. Lastly, there are some side trip discussions that seemed appropriate to include.

All that said, the credit for the content of this article goes to Jerry Kieffer. It is his concept and his means and methods. While I've adapted my preferences, and perhaps coined some phrases, it is because of Jerry that I am able to present this article. My contribution was simply to have taken the time to attend Jerry's class, practice (a lot) and write this text and pictorial journey. Beyond that, the credit and my thanks goes to Jerry for his time and ingenuity to develop this "modern means and method for wheel cutting" for today's 21st century clockmakers.

Tooth Forms

Some perspective on tooth forms and gearing principles from another respected gearing practitioner… Ivan Law:[1]

"There are two geometric curves that can be employed to give us the conditions we require for rolling contact. One curve is based on a shape called the cycloid and the second is based on the involute curve. Gears can be, and are, made to both standards but gears made to one standard must not be meshed with gears based on the other curve.

A cycloid is the curve which is described by a point fixed at the circumference of a circle when that circle is rolled in contact with a straight line

The involute curve as applied to gear teeth is a geometrical curve traced by a point in a flexible inextendable cord being unwound from a circular disc.

Gears based upon the cycloidal curve do maintain constant velocity between their two pitch circle diameters (P.C.D.) but this is only true so long as the two P.C.D's are touching each other. If, for any reason, the gear centers are opened out and their P.C.D.'s lose contact then the constant velocity condition will not be met. This means that if the wheel centers are not accurately set in the first place, or, as is more likely the wheel bearing wears, allowing the gear centers to spread, the constant velocity will be lost.

On the other hand, if the gear teeth are shaped on the involute curve then the constant velocity condition will not be affected by a small amount of spreading of the gear wheel centers, which means that any normal wear in the gear wheel bearings will not adversely affect the proper action of the gear teeth".

This condition "spreading of the gear wheel centers" as described by Ivan Law is most noticeable to us clockmakers in the form of the "egg-shaped" pivot holes that we encounter in our clock repairs and that require our re-bushing.

Involute: In the regular non-horolgical world of "gear cutting" is the involute tooth form. The curvature starts from the bottom (root) and continues to the top (addendum) of the tooth and is sized in diametrical pitch or "DP".
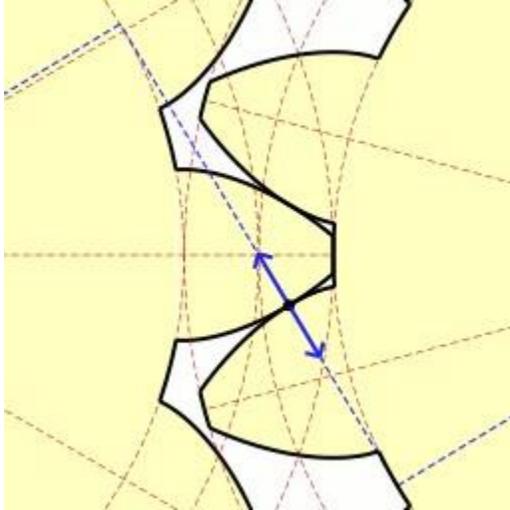
Two involute gears, the left driving the right: Blue arrows show the contact forces between them.
The force line (or Line of Action) runs along a tangent common to both base circles.
(In this situation, there is no force, and no contact needed, along the opposite common tangent not shown.)
The involutes here are traced out in converse fashion: points (of contact) move along
the *stationary* force-vector "string" as if it was being unwound from the left *rotating* base circle,
and wound onto the right *rotating* base circle
Source: Wikipedia
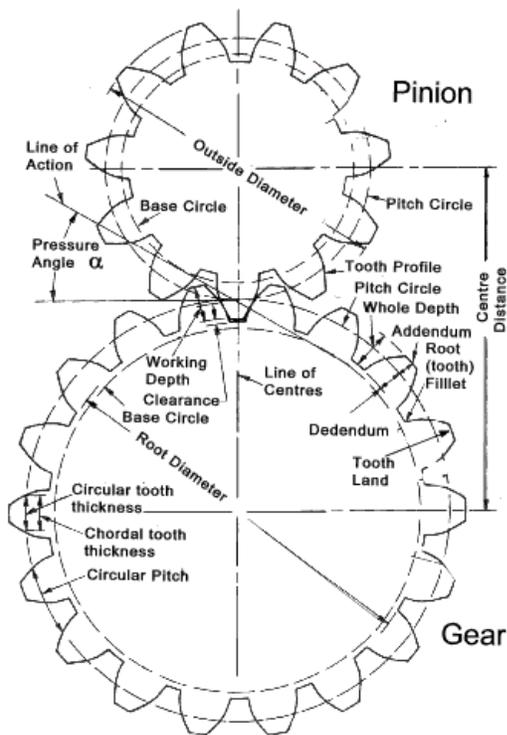
Here is some more involute gear information for the more inquisitive minded

Cycloidal: In the horological world of "wheel cutting" is the cycloidal tooth form. It has straight sides and a curved top (addendum) and is sized in "modules".
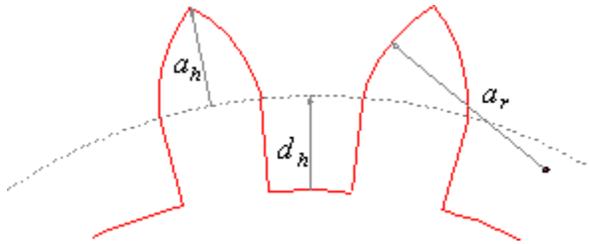
In figure 1, the *addendum height* a_h is the radial distance from the tooth tip down to the pitch circle. The *dedendum* d_h when used to denote a distance, is the depth of the dedendum part of the tooth measured radially from the pitch circle down to the base of the tooth.The *addendum radius* a_r is the radius of a circular arc that approximates the addendum curve. The *circular pitch cp* (not labeled) is the size of a tooth-space pair measured along the pitch circle. In most gear designs, the width of a space is equal to the width of a tooth.
Source: C.S. Sparks.
Note: The circular pitch (cp) does not equal the width of a tooth space. It is rather as stated above the (linear) distance along the pitch circle.

It wasn't always this way. Horological tooth forms have evolved over the centuries from whatever worked to today's cycloidal form. Clocks have been produced in one form or another since the late 1200's, and perhaps even earlier, and it wasn't until 1749, when Frenchman M. Camus first applied theory to horological gearing, that a basis for a standard tooth form even presented itself and you can imagine this development took time to become common usage. So what we have here from the first days of clockmaking to the mid-eighteenth century and, no doubt beyond, clockmakers of old using their own patterns for addendum constants, hand filing wheel teeth such that wheel and pinion teeth proportions vary tremendously from one clockmaker to another.[2] All this to say, that when one encounters such an old wheel, modern day cutters may not be a resource as a cutter and one may need to make a custom cutter. JK's means and method described herein will be an option for you

Some more perspectives…
- Module sizes within clocks: Typically, from JK's experience, the module is the same within a train. However, it is not unusual for the different trains (time, strike, chime) within the same clock to each have a different module.
- Through the passage of time and traditions, different labels have evolved, but from a functional perspective, gear cutting and wheel cutting are one and the same. It has become customary, traditional if you will, for each industry to refer to their different cutters by the module and DP labels.
- While today the primary horological tooth form is cycloidal, there still are a few applications for the involute tooth form. The involute form can be found in winding wheels in watches[3] and motion works in clocks.[4]

- In the geometry of teeth, the critical sections of the tooth are those sections that actually touch, make contact/roll. Specifically, contact is primarily in the area where their pitch circles meet. The rest of the tooth is designed for clearance.
- Involute gear cutters cannot be used to cut cycloidal tooth forms and vice versa. Said another way, DP cutters are not interchangeable with module cutters.

Finally, from George Daniels, is the best illustration and explanation I have found to help one visualize the cycloidal curve[43].

"The Cycloidal Curve"
"The most suitable addendum for watch train wheels is derived from the cycloid curve generated by a point at the edge of a circle rolling along a straight line. This is shown below in which the circle A has rolled along line B for the Distance CD and the point P has traced the cycloid E.[43]"

Generating the cycloidal curve
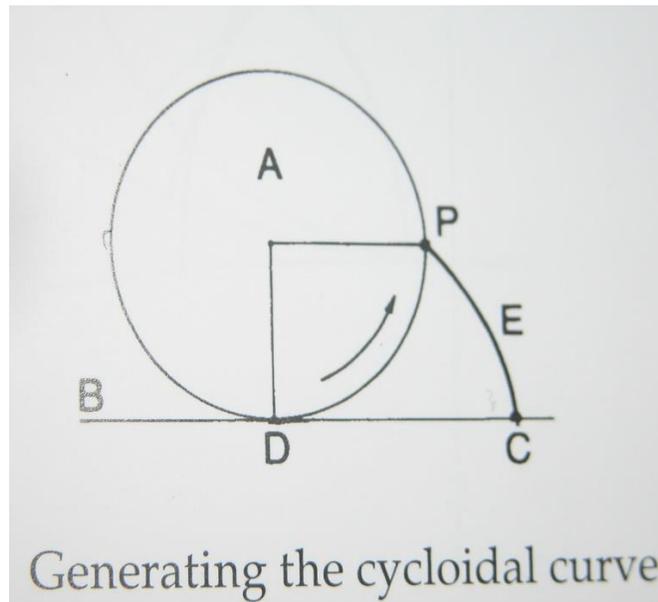
Cutters

Strict theory of cycloid curves…every change in wheel diameter and number of teeth would require a different curve and height of addendum and therefore every change would require a different cutter. However, less of the tip of the true curve is used and the constant addendum that results from using the same cutter is acceptable for the different diameter of wheels and number of teeth. Fortunately, for the same module, the difference in the theoretical tooth addendum curves is small enough to allow the use of the same cutter for different diameter wheels.[5]

The strict theory was recognized as impractical, not economically feasible and, as indicated above, not really necessary. So, at some point in time the gear and wheel cutting gurus got together and agreed upon certain standards and averages. This is the basis for today's commercial sets of involute and horological cutters.

Cutters for the horological world of wheelcutting and non-horological world of gearing share a design element whereby both are designed based on their number of teeth per inch. A key difference resides in their cutter sets. In the horological world, for the same module, one cutter representing an average, is used for the full range of wheel teeth i.e. different diameter wheels. This average curve is deemed to be an acceptable curve shape for the full range of wheel teeth within the same module. In the non-horological world, for the same DP, the involute gear has a different cutter for a given range of teeth. I surmise this difference is allowed because of the difference in their work environments. Clock wheel trains do not exert the amount of pressure that a gear's working environment would need to endure.

This difference is further illustrated below…

Commercial Cutters:

Involute tooth forms: Cutters for involute gears are sold in sets of eight for each diametrical pitch (DP). Cutter # 1 has almost straight sides and is designed to cut gears with 135 teeth to a rack. Cutter #8's addendum has a noticeable curve, profile and is designed to cut gears with 12 to13 teeth. See the chart below.

Here are two cutters for involute teeth. The # 1 cutter is on the left and a # 8 cutter on the right. Notice their addendum curves changing. Notice also the # 1 cutter for the largest number of teeth (135 to rack) has nearly straight sides.[6]

Non-horlogical (involute) gear cutter sets.[7]

Cutter # 1   135 teeth to rack
Cutter # 2   55 teeth to 134
Cutter # 3   35 teeth to 54
Cutter # 4   26 teeth to 34
Cutter # 5   21 teeth to 25
Cutter # 6   17 teeth to 20
Cutter # 7   14 teeth to 16
Cutter # 8   12 teeth to 13

Horological, cycloidal tooth forms: The horological cutter sets for a given module total seven cutters. See chart below. Cutters #1 – #6 are for the different number of pinion leaves and the # 7 cutter is for all wheels with teeth numbering 20 or greater (mobiles with less than 20 teeth are considered pinions). This explains Jerry's statement that a .60 module custom made form cutter using his means and methods will duplicate the existing tooth shape while a .60 module commercial cutter will not. Note that cutters are available in whole number modules and beginning with a certain size are available in increments of .50.
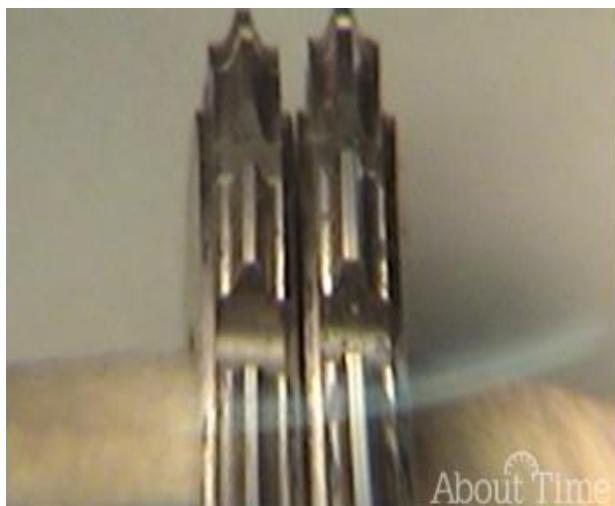

Here are two PP Thornton horology cutters for .30 module pinions.
A cutter for a 6 leaf pinion is on the left and on the right is a cutter for
an 8 leaf pinion. Again, notice their addendum curves changing. [8]

Horological (cycloidal) wheel and pinion cutters sets. [9]

Cutter # 1   Six (6) leaf pinion
Cutter # 2   Seven (7) leaf pinion
Cutter # 3   Eight (8) leaf pinion
Cutter # 4   Ten (10) leaf pinion
Cutter # 5   Twelve (12) leaf pinion
Cutter # 6   Sixteen (16) leaf pinion
Cutter # 7   Wheel

Bergeon has a set of 26 cutters, each of which covers 3 - 4 different modules. For example, cutter no. 3 is for mod 0.24, 0.25, 0.26, and 0.27. There is enough overlap that a 0.25 module cutter could be used to cut a calculated module of 0.27. I don't feel it would be necessary to purchase every single cutter for every single module. A starter set of a few of the more common ones would be worthwhile. Then you could purchase specific cutters as the need arose. [10]

Here it is in drawing form. The cutter on the left is for a 6 leaf pinion and the one on the right is for an 8 leaf. The cutter for the 6 leaf pinion will cut a slightly shorter leaf than the cutter for the 8 leaf pinion. The 8 leaf pinion will also have flanks which are slightly more vertical. The space between leaves will be slighter greater on the 8 leaf pinion than the 6 leaf.[11]
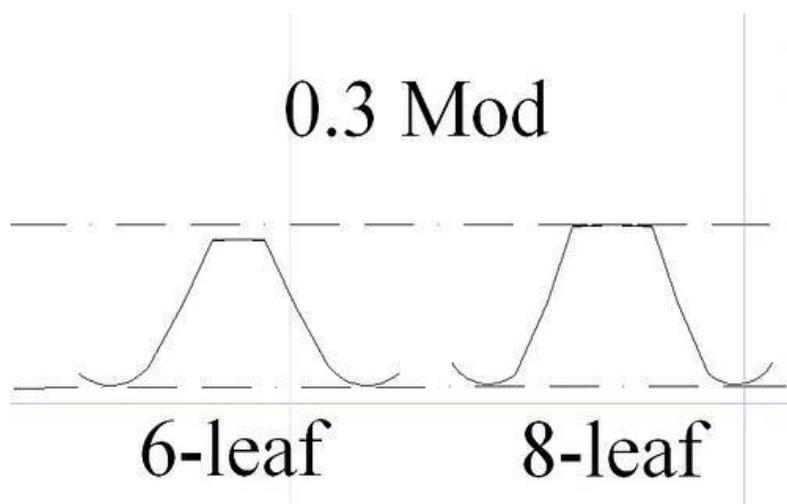
Flanks of the pinions change similar to how the addendum changes in the tooth…however…

For the same module, when increasing the number of leaves on a pinion i.e. 6-7-8-10-12-16. the flank of the pinion changes shape similar to how the tooth addendum changes shape when the number of wheel teeth are increased. This characteristic, however, is a more significant matter with pinions than with wheels as evidenced in the design of commercial cutter sets. Instead of having only one cutter for pinions like they do for wheels, there is a different cutter for almost every change in number of pinion leaves…proof, if indeed we need it, that the flank changes in the pinion present a larger issue with friction, required clearances and rolling contact then the addendum changes do with teeth. For a deeper read on this, refer to Claudius Saunier's "Treatise on Modern Horology". In the "Depths" section of his text, Saunier discusses this characteristic at length, referring to it as "uniformity in the lead".

Custom Single Point Cutters:

When needing to cut an involute gear or a horological wheel, home shop machinists have essentially two choices…they can either purchase a commercial cutter or make a custom single point cutter, otherwise known as a fly cutter. Jerry's method for making a custom single point cutter is really what these writings are all about. It is where his modern day machining breaks away from the clockmaker traditions of the past.

Variety of custom single point cutters I've machined the JK way

There are a number of advantages to making a JK custom cutter vs. commercial cutter:

- With an existing wheel, one is certain the original tooth shape functioned properly. Thus, making a cutter exactly like the original tooth form ensures the wheel will mesh with its mating pinion.
- Tooth will look the same as its mates. That said, teeth that are not exactly like the original can and do work, they mesh if you will. Just the same, one needs to target good workmanship.
- They are very cheap to make (once one has made the investment in the right machine tools ☺). Conversely commercial cutters are very expensive and usually do not emulate the original shape of the tooth form.
- It is very easy to sharpen. Lay the flat side on the oiled India Stone and rub it back and forth for 30 seconds or so. Conversely, commercial cutters are difficult to sharpen and require an investment in more expensive sharpening tools.
- These JK designed cutters are very sturdy and not subject to breakage such as oftentimes occurs with some types of homemade single point cutters.[27]

- After hardening, one can very readily remove the carbon. It comes off easily during the sharpening process. Conversely, removing carbon from intricate areas, such as are present in other fly cutter designs, is difficult at best. Even though I would use powdered boric acid as a protective covering, carbon still gets into intricate areas and is difficult to remove. Thus, another advantage of JK's cutter design.

  For reference, the use of powdered boric acid is based on John B. Moore's July 16, 1916 patented method[12] for using powdered boric acid for the hardening process. This method discusses the use of water or heat to get the powder to stick to the metal. Archie Perkins refers to this method in his book "The Modern Watchmakers Lathe and How to Use it", though he suggests the use of heat rather than water to get the powder to stick to the metal. Actually using water instead of heat worked better for me. By the way, this method is great for hardening pallets as it leaves minimal to no scale on the pallet surfaces. My actual process is: dip the part into water, dip the wet part into the powder, heat to cherry red, plunge into water. The powdered boric acid becomes glass hard hot during the heating process and explodes off when it comes into contact with the water, leaving the part's surface with minimal to no scale. Ergo its reputation as a "protective coating".

  A little more background: Heating metal pulls the chemical element carbon out of metal. This is known as "decarbonization". The carbon in this state is known as "scale" and is visible on the metal surface and typically is hard to remove. Horologists vary in their means and methods to contend with this condition.

A little More About DP and Modules:
Neither the information on DP nor the information on Modules are essential knowledge for cutting wheels via the "JK Modern Means and Methods", however, knowing this information satisfies the curiosity and is simply good information for clockmakers to become familiar with. I was even able to draw some keen perspective after having added these formulas to the "Wheel Cutting Worksheet" (to be discussed later). It became apparent, that even though the Outside Diameter and Pitch Diameter (all to be discussed shortly) could be off a few thousandths using the calipers (dial, digital, Vernier) measuring method discussed below, it did not have an impact on the DP or module calculation. Interpret that as the few thousandths error wasn't sufficient to change the round up or round down result. This was a helpful perspective, given that it is easy to be a bit off with the calipers (dial, digital, vernier) because of tooth wear, a bent wheel or just presenting the calipers at the wrong angle. Even placing the caliper jaw tips on tooth tips can be a bit fiddly. Knowing this, one can seek to mitigate the error by taking several readings with several opposing teeth, bend the wheel straight or straighter, etc. Remember if one is replacing teeth or replacing a whole wheel, something is seriously wrong with the wheel to begin with and repeated readings will contribute to good, repeatable outcomes.

One would need to know the Module or DP to purchase commercial cutters as all manufacturers use Modules or DP to identify the different cutter "sizes". Recognize, however, that neither the DP nor the Module are an actual "size" per se…Rather it is a relationship between the number of teeth and the pitch diameter. In the non-horological world, when gearing is calculated in inches, DP represents the number of teeth per inch of pitch diameter. When wheels are calculated in millimeters, Modules represent pitch diameter in millimeters divided by the number of teeth. To convert one to the other...Remember 25.4.

For the longest time, I understood the module and DP numbers to be the size of the tooth space a/k/a width of the tooth space. Instead these numbers represent a ratio relationship i.e. the # of teeth per inch.

> In those instances where one is making a clock from scratch and has no original wheel or clock to use as a guide, the "module" is, in essence, a by-product of the clockmakers intended design i.e. their intended BPH, tooth count, center distances, duration, etc. That once one designs a clock they use these design configurations to then calculate the modules. [13]
>
> Many old clocks have calculated modules that are not available as current wheel cutters, the manufacturers simply did what they wanted to do. It is handy, however, to use a design that allows one to use commercially available cutters so as to avoid the need for making fly cutters. [14]
>
> While the module is not necessarily a choice or criteria for designing configurations, one would do well to be mindful of the commercial cutter module sizes available when designing clock trains for ease in wheel cutting. More to the point, as a matter of practical application, machinists and gear cutters use the "diametrical pitch system" as a reference point to design gears i.e. they work to the diametrical pitch. [15] This is understood to be the same for modern day horological design and wheel cutters. Not so much for clockmakers of old. As stated above and in many other references, they just did what worked. This fact speaks directly to the value and significance of Jerry Kieffer's modern means and method. As you will see from these writings, Jerry teaches the concept of how to machine a custom single point cutter for any horological tooth shape and size. This, as you will discover, is the key to successful wheelcutting.

Mixing and matching cutters

- Involute cutters - there is some flexibility for mixing manufacturer's involute cutters. JK says it best…"commercial wheel and pinion (involute) cutters for high speed heavy loads, such as a large truck rear end, are generally designed in sets that are best purchased from the same manufacturer. However, for non-critical, slow speed loads such as a garden tractor transmission, brands with the same DP designation can generally be mixed without issue".[16]

- Horological cutters – "because of the vast variation of tooth forms in horological movements, all cutters should be visually compared to existing teeth to be duplicated". [17] Of course, therein lies the challenge as typically the cutter you need is not in your tool box and instead needs to be purchased. It is hard to compare when the cutter you need is in a distant state or maybe even a distant land and they are not cheap. This would be another advantage of developing the skill set of making your own single point cutters in your shop. Note also that commercial cutters for wheels and pinions are intended to be made as matched pairs. Thus, ideally, one would purchase them together.

Helpful tips for micro milling:

- Lighting workpieces on mill table i.e. using reflective lighting. I'm not exactly sure what lighting principle is at work here but if you've ever shined a light directly on the workpiece, you'll find it is hard to see. Using reflective light mitigates that situation. Try this: [18]
    - Place stiff white paper of appropriate size behind the saddle
    - Shine light on the paper
    - Light reflects back onto the workpiece

- Milling machine terminology and parts
    - "X" axis is the table and is controlled by the "X" handwheel
        - Clockwise handwheel turns: table moves right to left
        - Counterclockwise handwheel turns: table moves left to right
    - "Y" axis is the saddle and is controlled by the "Y" handwheel
        - Clockwise handwheel turns: saddle moves to the back away from the operator
        - Counterclockwise handwheel turns: saddle moves to the front towards the operator
    - "Z" axis is the headstock/spindle controlled by the "Z" handwheel
        - Clockwise handwheel turns moves headstock/spindle down
        - Counterclockwise handwheel turns moves headstock/spindle up
    - All three axis can move in .001" increments

- Before machining, establish a habit of locking all axis (table, saddle and headstock) that will not be moving. This is especially needed on a cutting task with a lot of force.
    - The Sherline mill has a particularly helpful feature in this regard. When needing to do precise machining make use of the brass lock lever on the "Z" axis. Move the lever to the almost lock position. Snug it up if you will. This eliminates the backlash for the task at hand.

- Machining process and results are improved with:[19]
    - Sharp end mills
    - Rigid, stable end mills
    - Cutting fluid, particularly for steel, but also for brass
    - Locking all axis not moving before machining.

- Milling any part brings with it significant cutting forces. Given this, items need to be very secure and the machining process needs to be planned so as to produce the least amount of force. In our instance of the cutter blank…its positioning in the center of the vice and the guidance to progress the table from right to left so that the end mill progresses across the top of the cutter blank are all intended to ease the stress on the workpiece and the machine. Ultimately the workpiece (cutter blank) stays secure and results in a better finish.

- An overall JK bit of advice…"if you don't seem to grasp a particular tools and procedure concept, move on to a different approach to achieve the same result, we all learn differently".

- Horological wheel cutting makes extensive use of measurement tools. Thus, a couple of points to make with regards to caliper measuring tools such as dial calipers, digital calipers or Vernier Calipers. First, in each instance, these tools are only accurate to within .001"- .002". There are occasions in wheel cutting whereby one needs a more accurate reading. An example would be a wheel's center hole. In such instances, one should use gage pins a/k/a pin gages instead of the calipers inside diameter jaws. For accurate outside diameters, one should use a micrometer. This is mentioned throughout the article. Note that these remarks are intended for diameters of ½" or less. At least for me, as beyond that calipers become the more practical tool and the .001" - .002" is of less consequence. For certain distance measurements the calipers are the only practical tool. An example would be a wheel's outside diameter. In those instances, recognize that the caliper is only accurate to within .001" - .002". Secondly, for the reader's clarity, I only own a dial caliper, thus the readings throughout will refer to dial calipers. This should be understood to mean that references related to dial calipers are also intended to include digital calipers or Vernier Calipers.