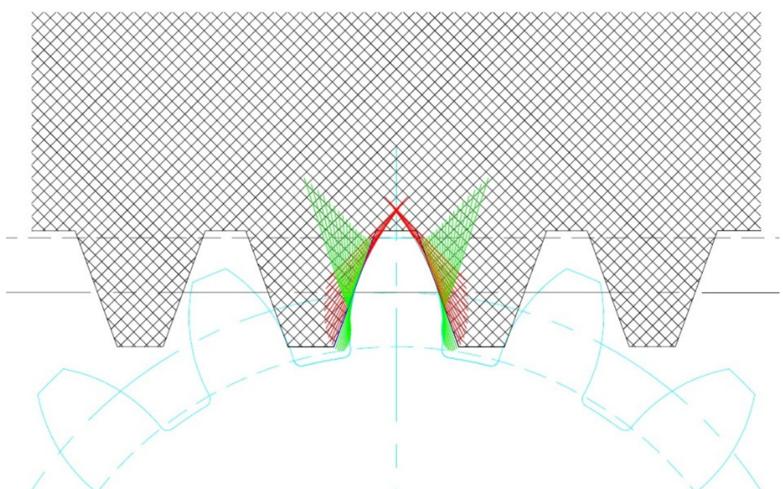
Gear Cutting – Home Engineering Style.

It is possible using AutoCad or similar drafting package to develop you own custom (as well as standard) gear profiles.
From this you can also make your own cutters and make the necessary compromises to suit.

Involute Gear Profiles.

I am only going to deal with metric (Module) involute gears and I'll leave it up to you to figure out that diametral and circular pitch are merely variations of the same theme (metric or imperial).

A basic gear profile represents the circular tooth profile that would be generated from a "Rack" vis :-



A MAAG gear shaper in fact planes gears by using a rack shaped cutter – with each cut the "rack" is advanced and the gear rotated – in so doing it generates a true involute curve.

https://www.youtube.com/watch?v=6UnrzoZyQsU

In my diagram above the green and red lines indicate the position of the cutter flanks as viewed from the perspective of the rotating gear in 2° rotation increments.

(A real MAAG cutter would have slightly taller teeth and corner radii to cut the clearance at the tooth root.)

The involute curvature is a constantly changing radius and is therefore difficult to make accurately (other than by generating using a MAAG or FELLOWS gear shaper – or using appropriately profiled cutters or hobs.

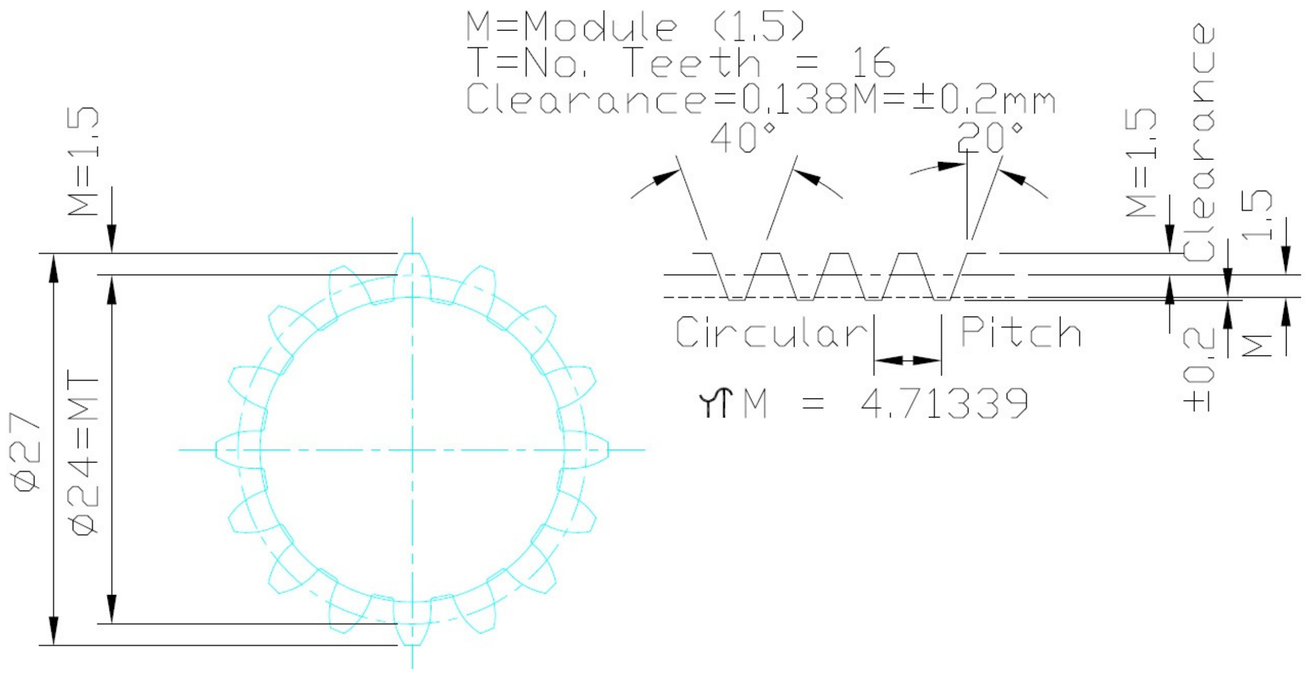
https://www.youtube.com/watch?v=fU01NlP-dNI

However in most cases a simple radius does very well – but there are limits.
The greater the number of teeth – the better the fit of a simple radius.
Typically for 16 teeth and over you will have no problem, 12 and lower tends to be problematical.
For smaller numbers of teeth you will find increasing incidence of interference and the need to use multiple radii which is somewhat outside the realm of home machining.

That said, for this tutorial I am going to make a pair of Module 1.5mm with the pinion being only 8 teeth and spur wheel 16 teeth. So the 8T is going to be problematical.

This was to repair a ride-on toy for my grandson who was delighted with the result (regardless of the slightly “grumbly” fit up of the gear. (Just to prove Grandad can fix anything.)

Basic Metric Gear Nomenclature.



For a standard Module gear the module is the height of the tooth above and below the centerline or pitch circle diameter – in this case 1.5mm so a tooth is approximately 2xM or 3mm in this case – there is also clearance which in almost all gear calculations is 0.138M or in this case ±0.2mm.

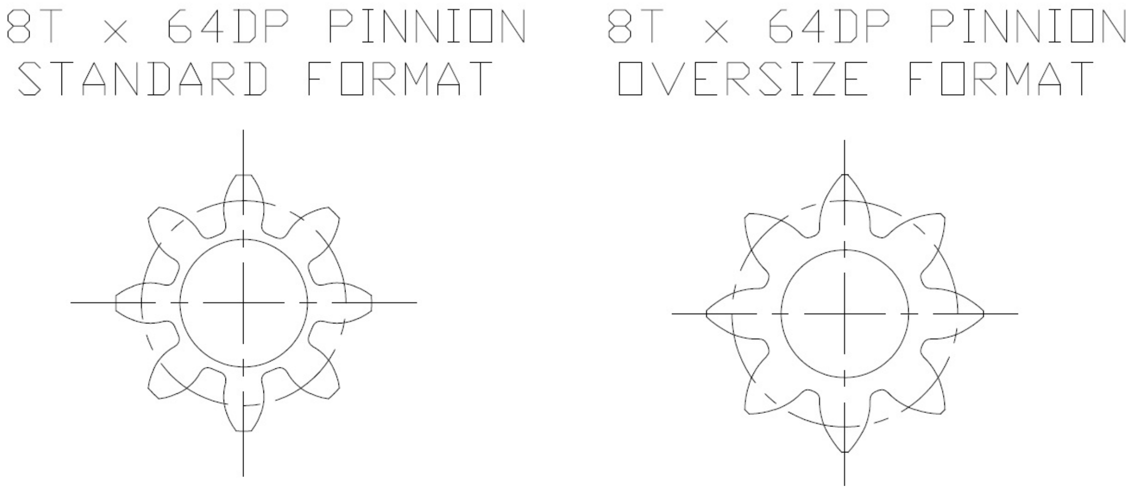
The pitch circle diameter is the module times the number of teeth (in this case Ø24.0) to which must be added a further two modules for the outside diameter (in this case Ø27.0)

The pressure angle for most gears is 20° (prior to WWII 14½° was commonly used – the greater the angle the greater the thrust between axles as the gears try to drive themselves apart – so in an attempt to limit this they tried to stay below the friction angle to eliminate this thrust – but with ballbearings and better lubrication and bearing materials this became less of an issue and 20° was adopted for its greater tooth strength and lesser interference problems with small tooth counts.)

What I Intend To Show.

I am going to show how to develop the tooth profiles using AutoCad (or similar).
Firstly I am going to approximate the spur wheel profile to the nearest cutter radius we might have to hand in order to make a cutter.
Then I am going to use the resultant compromised tooth profile of the spur wheel to generate the pinion gear profile and once again choose an approximate and convenient radius to make the cutter for the pinion.

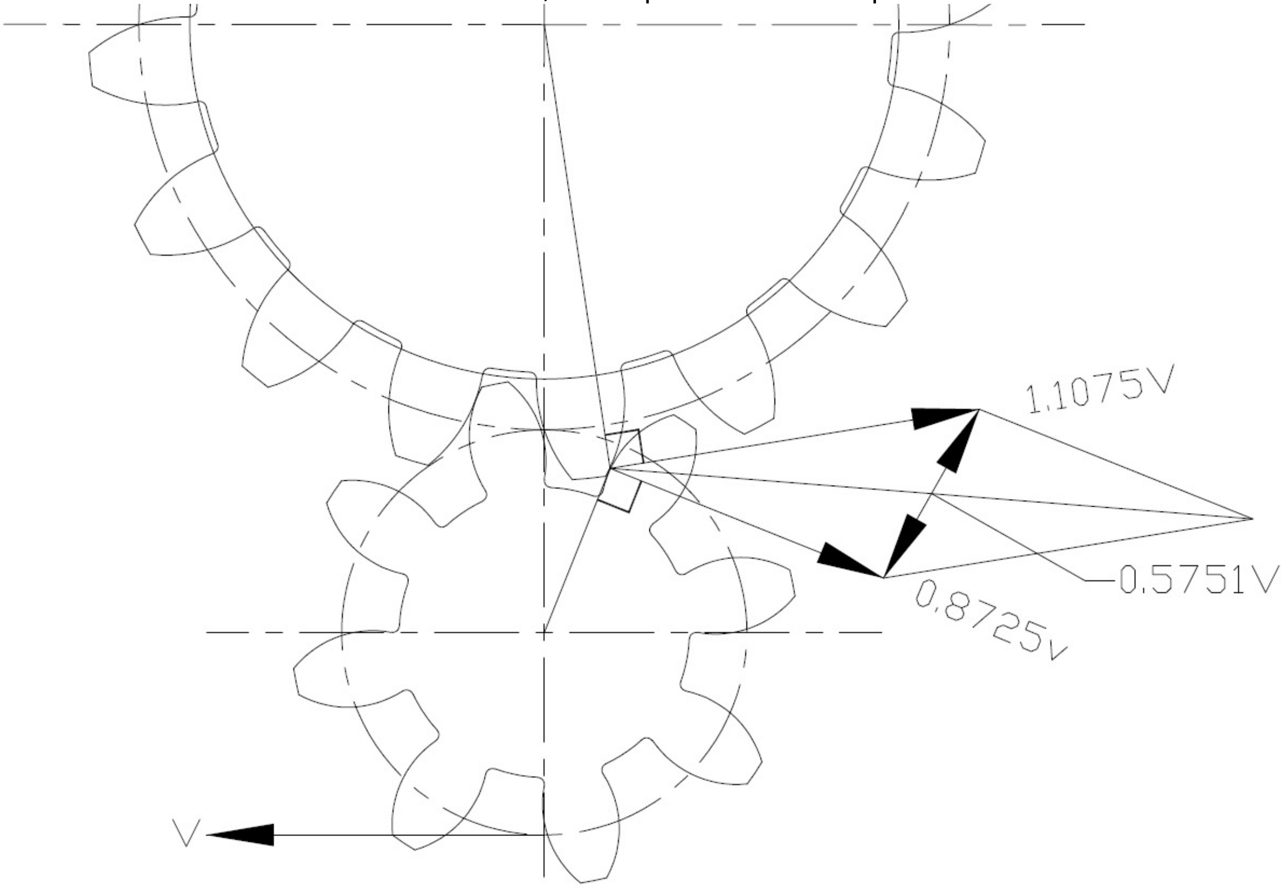
Whilst I have done this to demonstrate home engineering capability, the method can be used to accurately determine wire cutting paths for wire cut EDM and the method can also be used for generating non-standard gears – for example for matching centerlines that do not equate to the normal pitch or making a gear with a deliberately oversized PCD vis :-



The above small pinion gear used in Slotcar racing – leaves far too little material to the Ø2.0mm driveshaft bore so the pitch circle is made larger – results in a non-standard tooth profile – but it does work.

When you deviate as above you do introduce more sliding and therefore friction and wear problems – but it does work (see later).

Note: True involute gears “roll” over each other – but the velocities only match at the PCD – elsewhere there is sliding across the face of the gear – clearly at any contact point above / below the PCD on two different diameter wheels, it is impossible for the speeds to be the same.

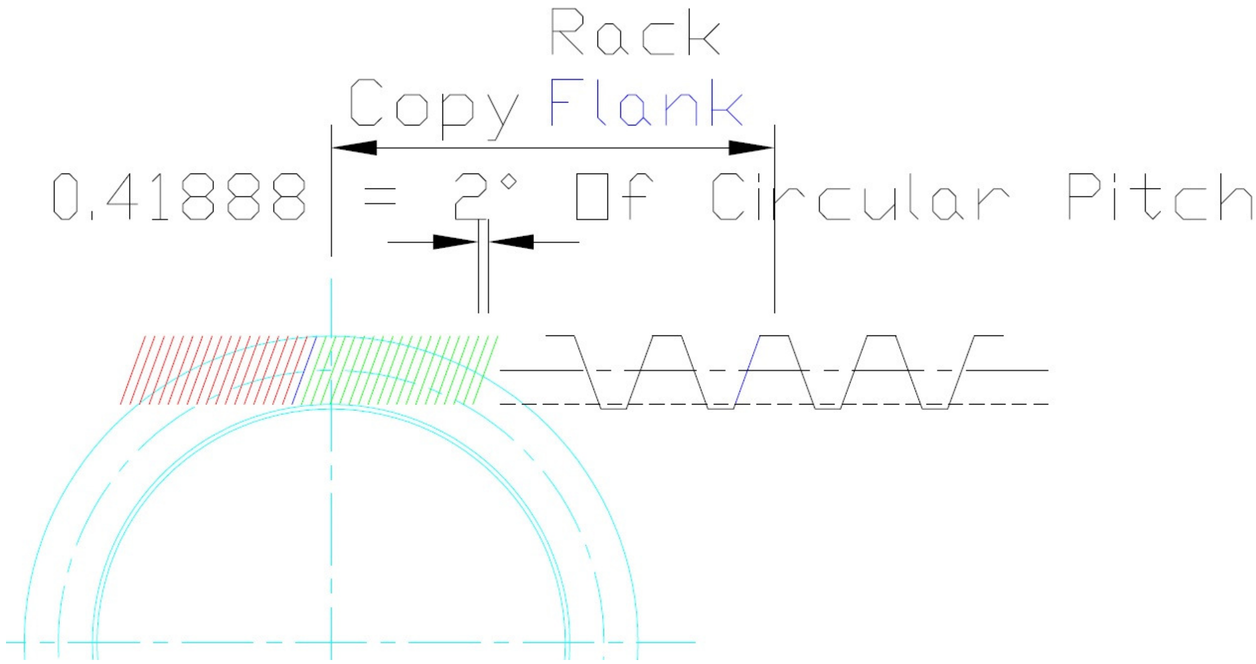


As the above vector diagram indicates the sliding velocity (at ½ tooth position) is as high as 57.5% of the Pitch Circle Velocity.

First Step – Generate Spur Wheel Profile.

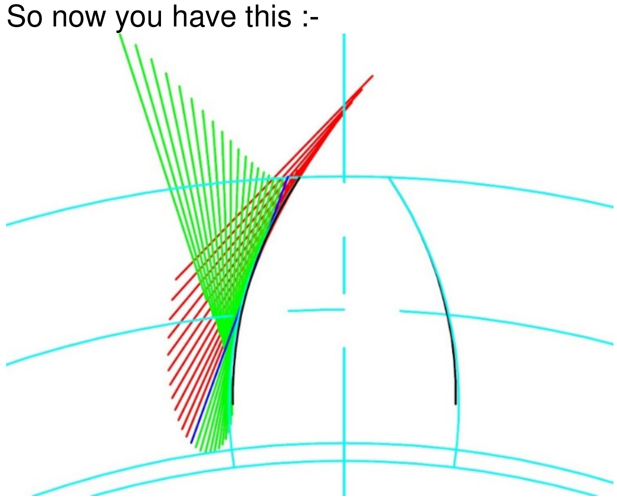
The illustration below demonstrates how to develop the tooth profiles using any CAD package.

Firstly draw the circular outlines of your gear and draw the rack adjacent to it vis:-

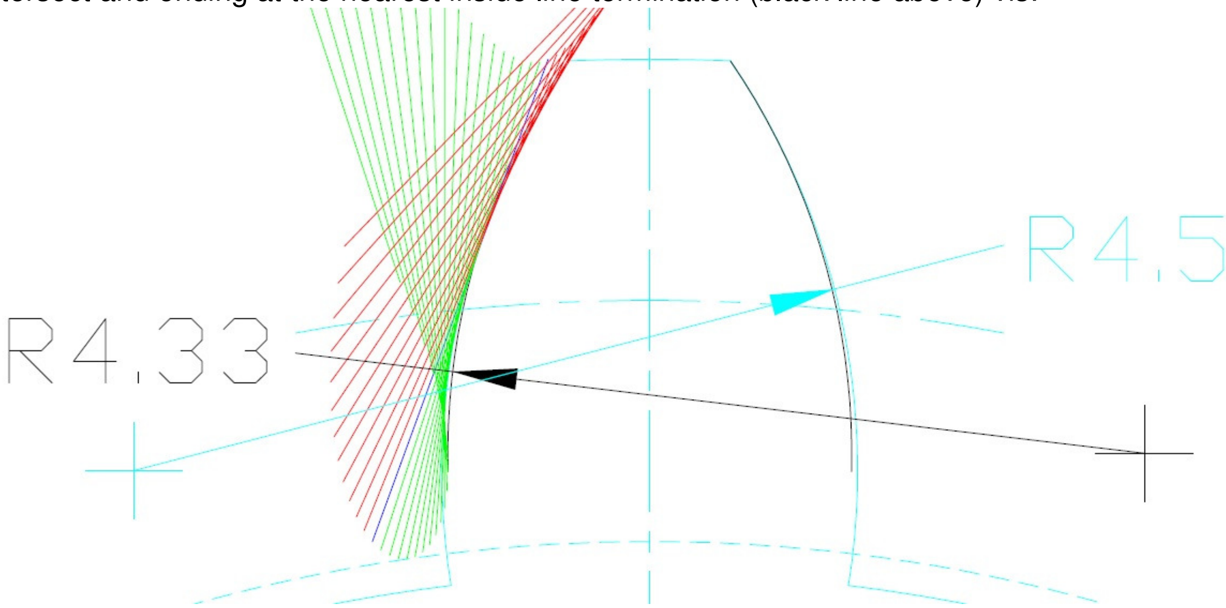


Copy a single flank (without clearance) from the middle of the rack crest to the centerline of your circular gear (In blue above).
Since this is a 16T gear, each tooth is going to occupy 22½°
We need to array rectangularly left and right at a pitch commensurate with a convenient angle.
I chose 2° of gear rotation which equates to 0.41887902mm of rack movement.
Next array a number of these lines to left and right (at this pitch) – I change the colour to keep track.
You could of course choose to array the flanks in say 0.5mm increments but then the rotation of each will be 2.387324° - you don't want to have to type that in at each rotate command – so stick to single digit degrees and let the array command take care of the horrible divisions.

Next rotate each of these lines individually about the gear center - the first green line 2°, the second 4° the third 6° and so on- Repeat with the red lines -2° and so on.
Repeat until you have sufficient lines defining the profile.
Sooner or later the lines start to disappear away from the profile indicating where the tooth starts to disengage.
So now you have this :-



Next draw a three point arc – typically starting at the outer diameter intersect, the pitch line intersect and ending at the nearest inside line termination (black line above) vis:-



On measuring this radius I get R4.33mm – note gap – radius does not perfectly emulate involute – don't worry at this stage we will (attempt to) fix that with the pinion.
Since I don't have a R4.33 cutter (although I could spin one down in a tool and cutter grinder) I go for R4.5 or Ø9.0 milling cutter that I will use to form my hob (see later).

Next, I redraw the arc using a SER (start, end, radius) method to draw the curve starting at the OD intersect plus any point you fancy and add the radius – this sounds a bit hit and miss – but play with it until you like the look of the fit – don't worry if at this stage that it crosses some of our projected rack lines (interference) we will deal with that problem with the pinion.

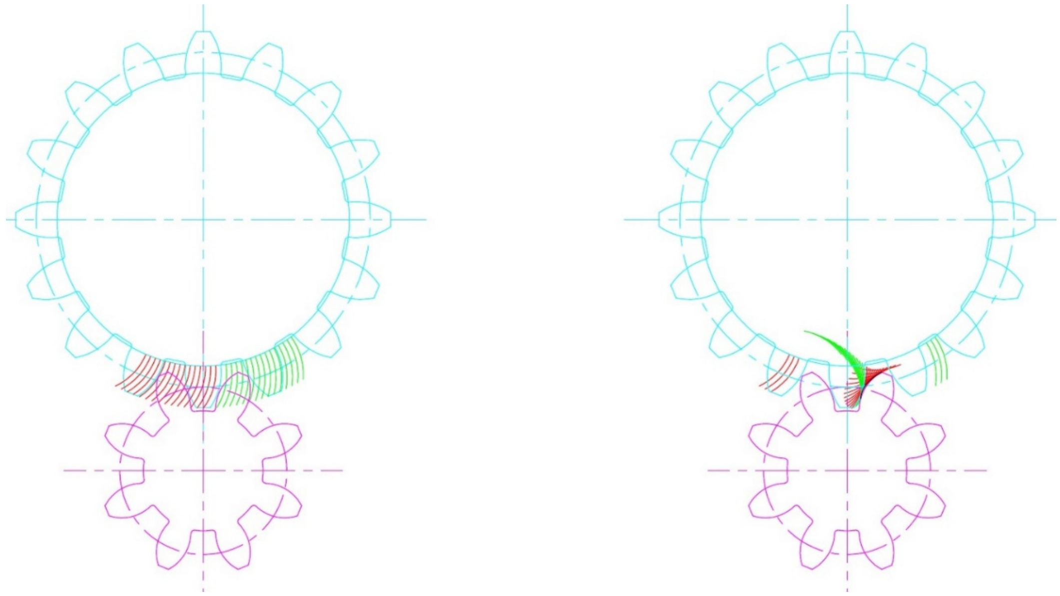
Note: For 16 teeth and upwards, you can normally draw an arc from the outside diameter intersect, via the PCD intersect and the inside diameter intersect and get near perfect fit up to the involute indicated by your generation lines.
In the 12T example above you can see that a simple radius does not work and you can also see the "interference" by the reentrant line ends (green) which cannot form a tangent to the curve. In a real gear this would be the tip corner of the rack "gouging" into the lower flank of its mating gear. In the above example I have simply pulled the radius clear of this interference and will worry about how it fits with its mating gear when I generate that.

Next add root and tip radii (if you want to) and complete the spur gear drawing.

Second Step – Generate Pinion Gear Profile.

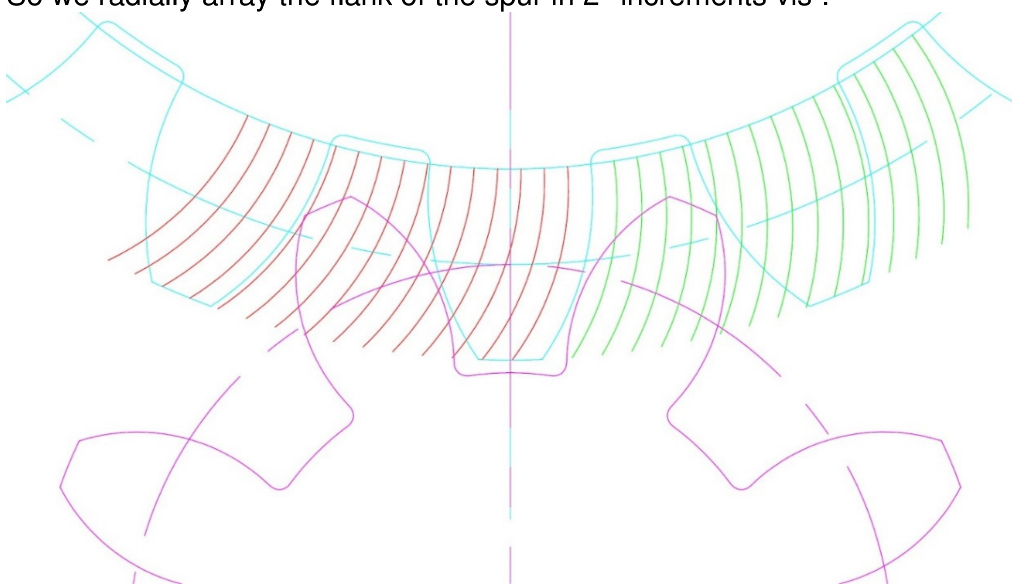
Now we use the profile we generated in the first step to generate the profile for the pinion - this way we take care of any imperfections in the spur gear and have a lot less interference to contend with than in the pinion – which with its smaller tooth count is always going to be more problematical.

So always generate the larger tooth count profile first and then use that to generate the smaller tooth count profile (except for annulus gear sets).



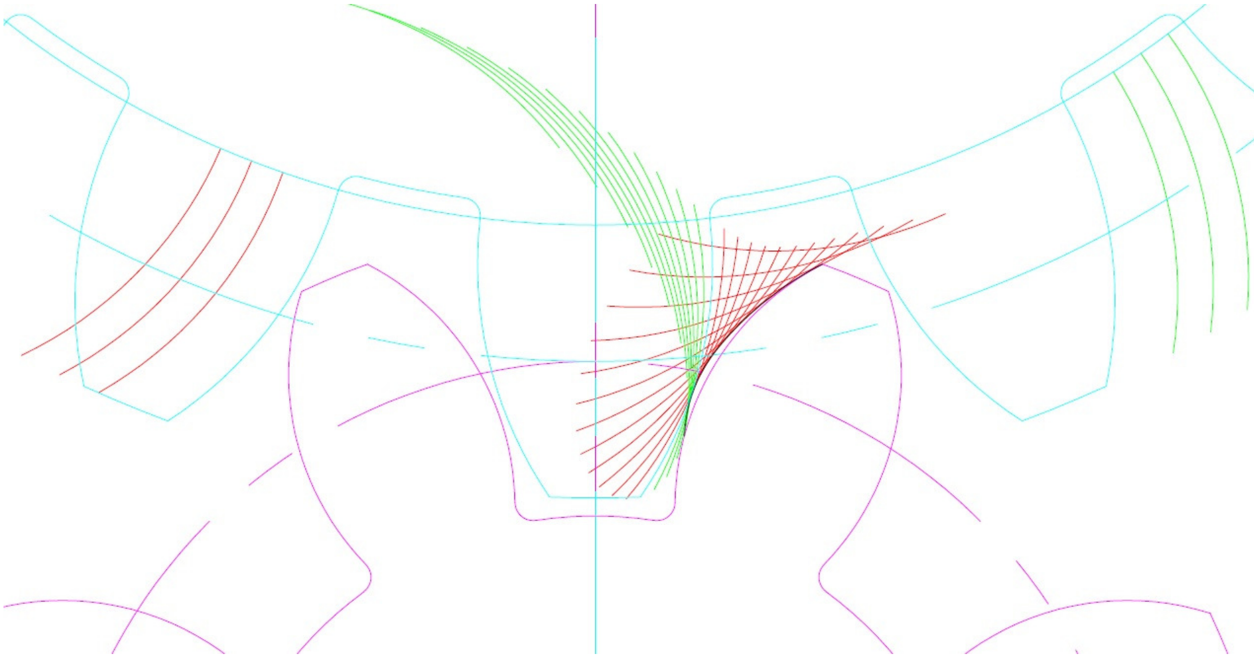
For the next profile generation we are going to do it radially – a'La a FELLOWS gear shaper where the cutter takes the form of a gear and planes the other gear in much the same way as the MAAG gear shaper only using a circular rotating cutter rather than a rack.

So we radially array the flank of the spur in 2° increments vis :-



We then rotate those 4° per division (because of the 2:1 ratio) about the <u>pinion</u> center line vis :-

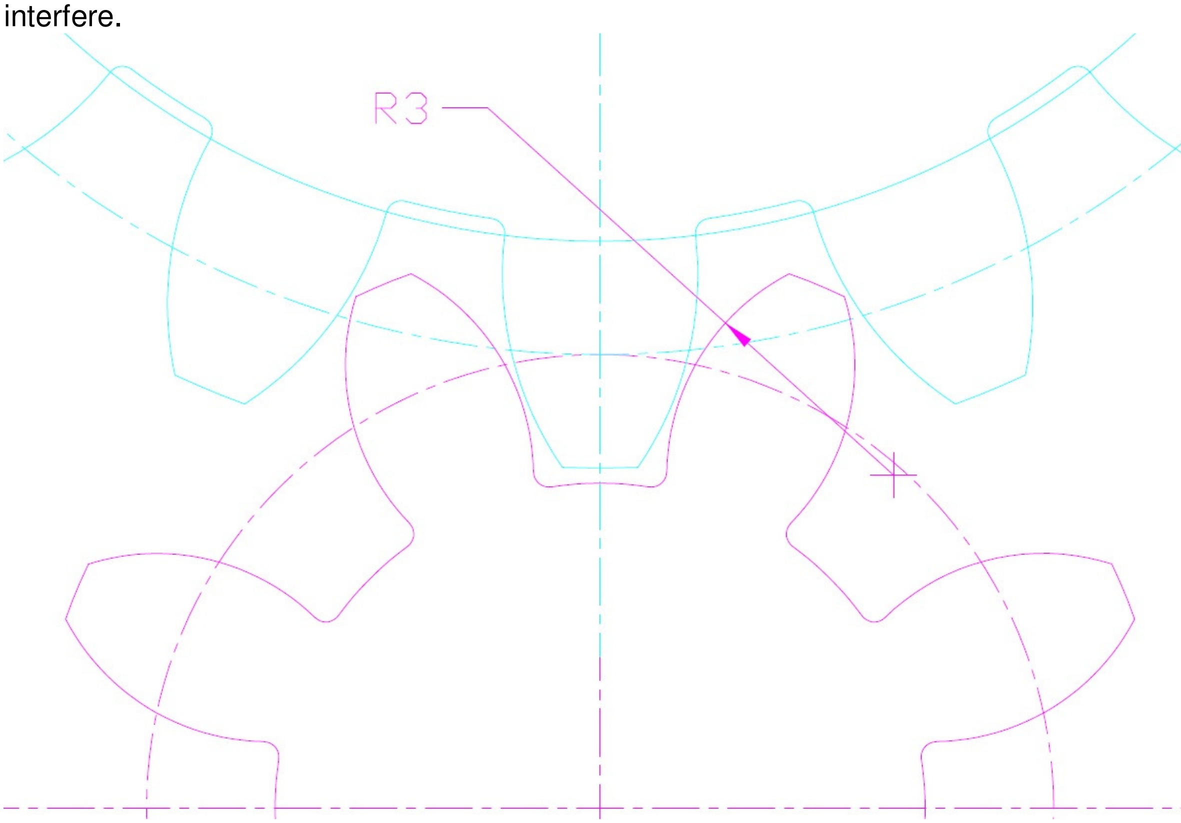
{Again, if we have odd ratios which will produce long decimal numbers then select a polar array value that will produce non-decimal numbers for each rotation command.}



Obviously you must adapt to suit the pitch you choose as well as the ratio being generated.

As you can see this does not produce a great fitting profile (black line) but we could still use a two radii approach and wire cut EDM the resulting profile. I did not rotate all the flank profiles as quite clearly we have left the tooth profile behind before we got to those.

No matter – we again look for the best fitting radius we can fit in using a cutter diameter we have to hand to get the best fit – only this time we cannot ignore interference points as they will actually interfere.



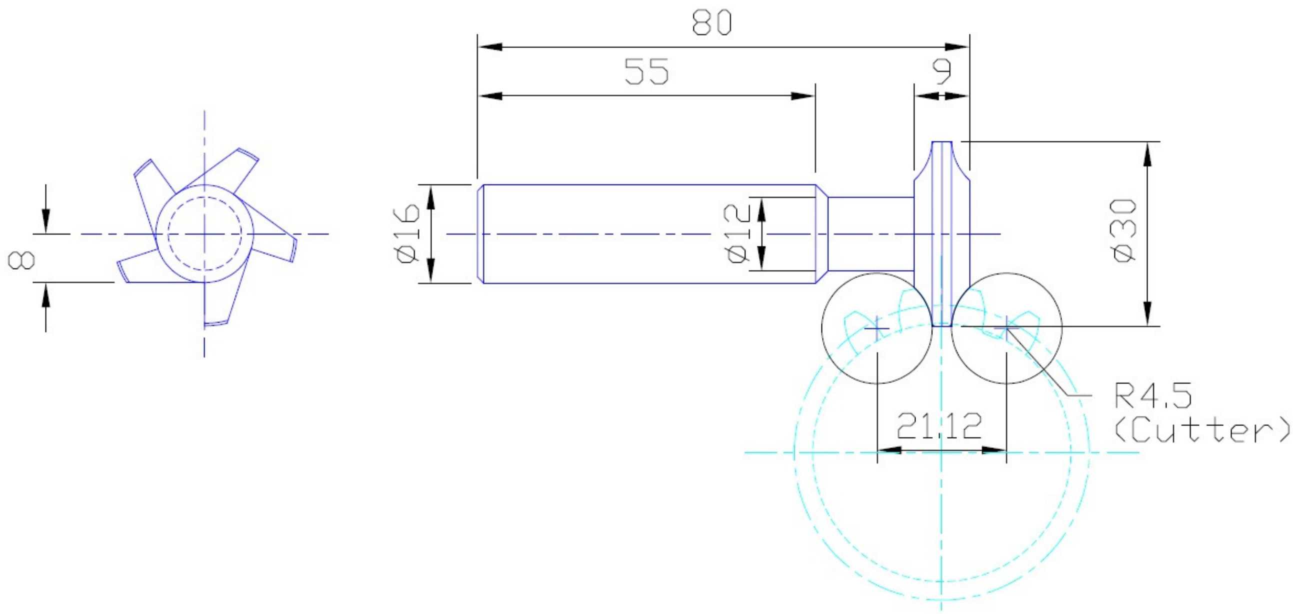
I have chosen R3 or a Ø6 cutter.
Yes there is clearance and this is going to be a bit “grumbly” but it will work.

I have chosen a rather small number of teeth as an example so its somewhat less than ideal but it does demonstrate the method whilst giving you the insight into the process of "generating" gear profiles as well as other problems such as interference etc. etc.

For a home machinist we could have used the ratio 12:24 using a 1.0M gear profile or smaller – which would give very much better results.

Making The Cutters.

For the spur cutter we chose R4.5 vis:-



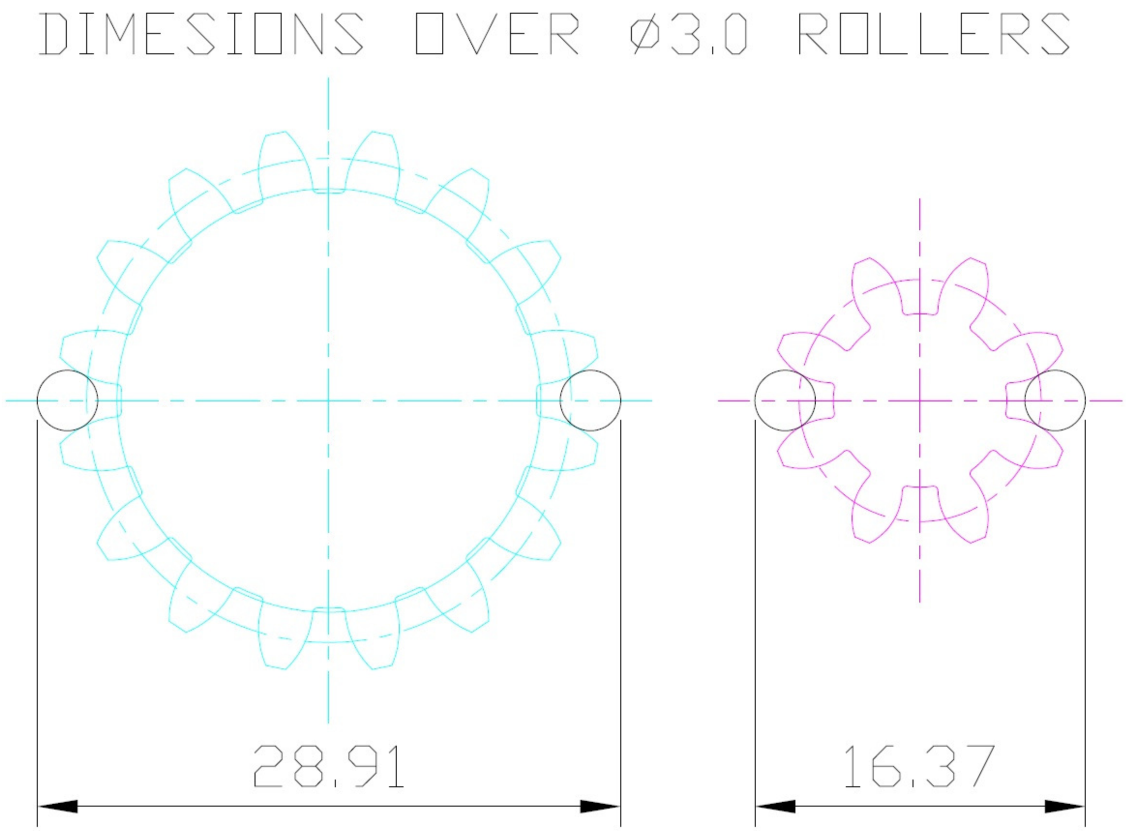
Turn the blank and in a dividing head or rotary table, mill the radii using the correctly sized cutter (Ø9 in this case) – then gash the teeth – as per dimensions determined from your drawing.
Make shank to suit whatever you are going to hold it with.
Material will depend on what you want to do with it – I use silver steel and harden it and use it without tempering. For limited use you can use a case hardening steel and case harden it.

Note: In the above illustration the gashing is on centreline – therefore zero° rake. You can adjust to get rake but this will change the radius (read up on form tool correction) – you can use this correction to your advantage but it's a lot of extra PT, I generally don't bother.
There is effectively no side clearance so the tool will rub slightly at the cutting edges. Use lubricant when cutting.

Below a photo of a "home made" hob.

Cutting The Gear Teeth.

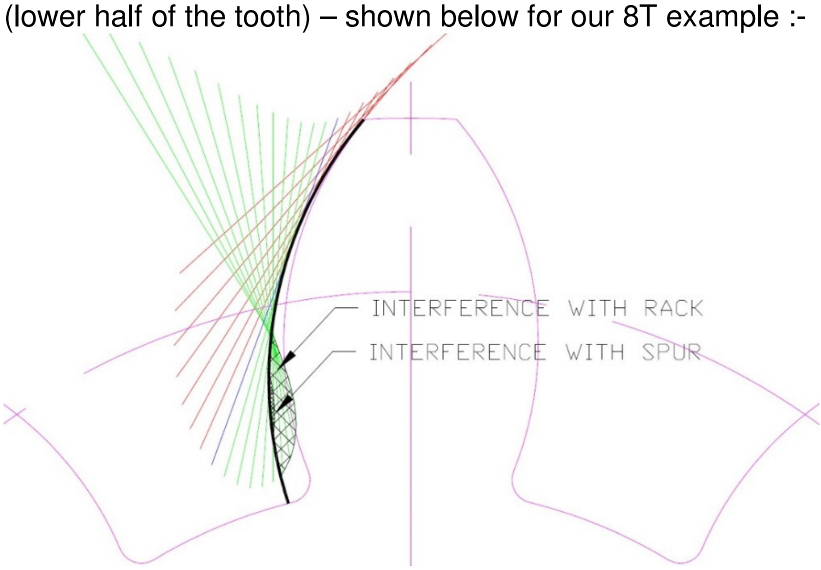
Since nothing you are doing is standard – you can't rely on standard calculations – sure you can simply work to depth of cut – but it is going to be far better to establish some "over roller" dimensions within your drawing vis :-



Pick a roller diameter that you have that will protrude above the teeth – offset adjacent flanks by the radius and add roller – for odd numbers of teeth you will need to use a three wire method.
I use dowel pins, drill shanks and drill rod that I have to hand. Insert actual rod size into your ACAD drawing – drill shanks are typically smaller than drill size, dowels are larger than nominal and drill rod (silver steel) is normally spot on to microns undersized.

Interference.

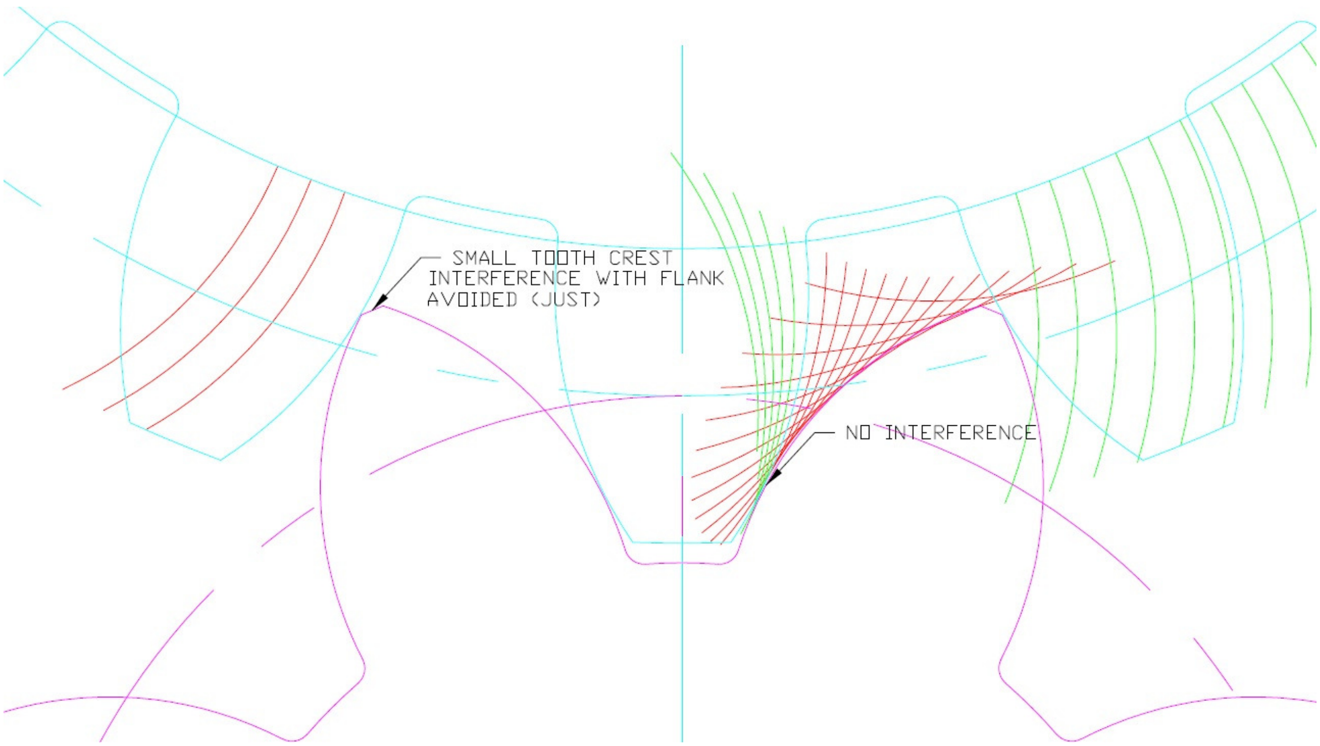
As the tooth count goes down, there is increased interference and undercutting of the dedendum (lower half of the tooth) – shown below for our 8T example :-



You can see why cutting with the profile of the actual spur will eliminate much of this undercutting. Since the contact between gears and/or rack is always tangential to the pitch circle, the involute shape will be the same (black line).

Expanded Pitch Circle.

Using the same approach I have expanded the pitch circle from Ø12 to Ø13.5 a 12½% increase. This is about as far as you can push it before the tip crest becomes a point and the tooth height begins to get shorter.



The good news is that this has eliminated the interference and the modified tooth profile also more closely approximates a radius.
The bad news is that it has increased the effective pressure angle and therefore the forces driving the gears apart. It also introduces increaced sliding motion of the gears introducing wear and friction.

Purists (myself included) will throw up their hands and tell you that you should never do this.

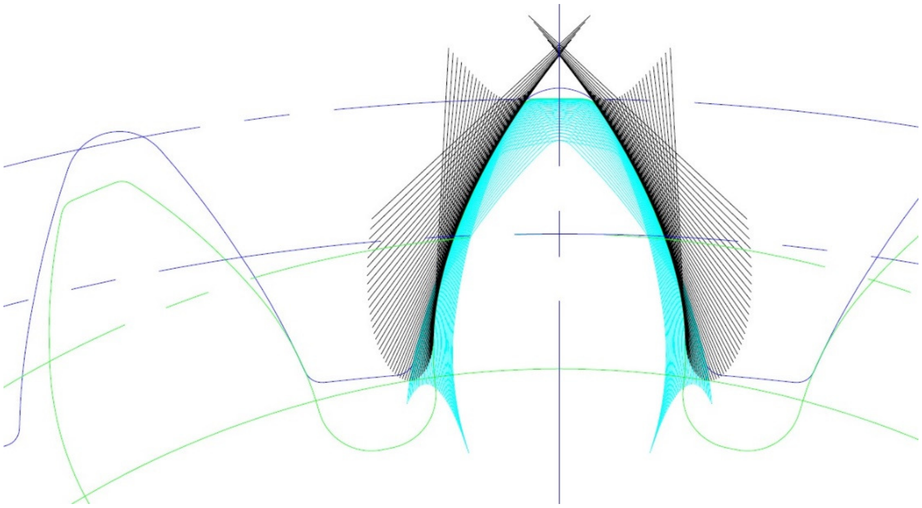
My advice is avoid if possible – but sometimes circumstances dictate otherwise !

I my other hobby – Slotcar Racing – we use expanded gears at insane rpm's and relative power outputs (like 50 Watts at 80000 rpm via a 72 DP 7T pinion which is so tiny it would not allow the Ø2.0 motor shaft – so we use expanded versions that do)

So I know from personal experience it works well.

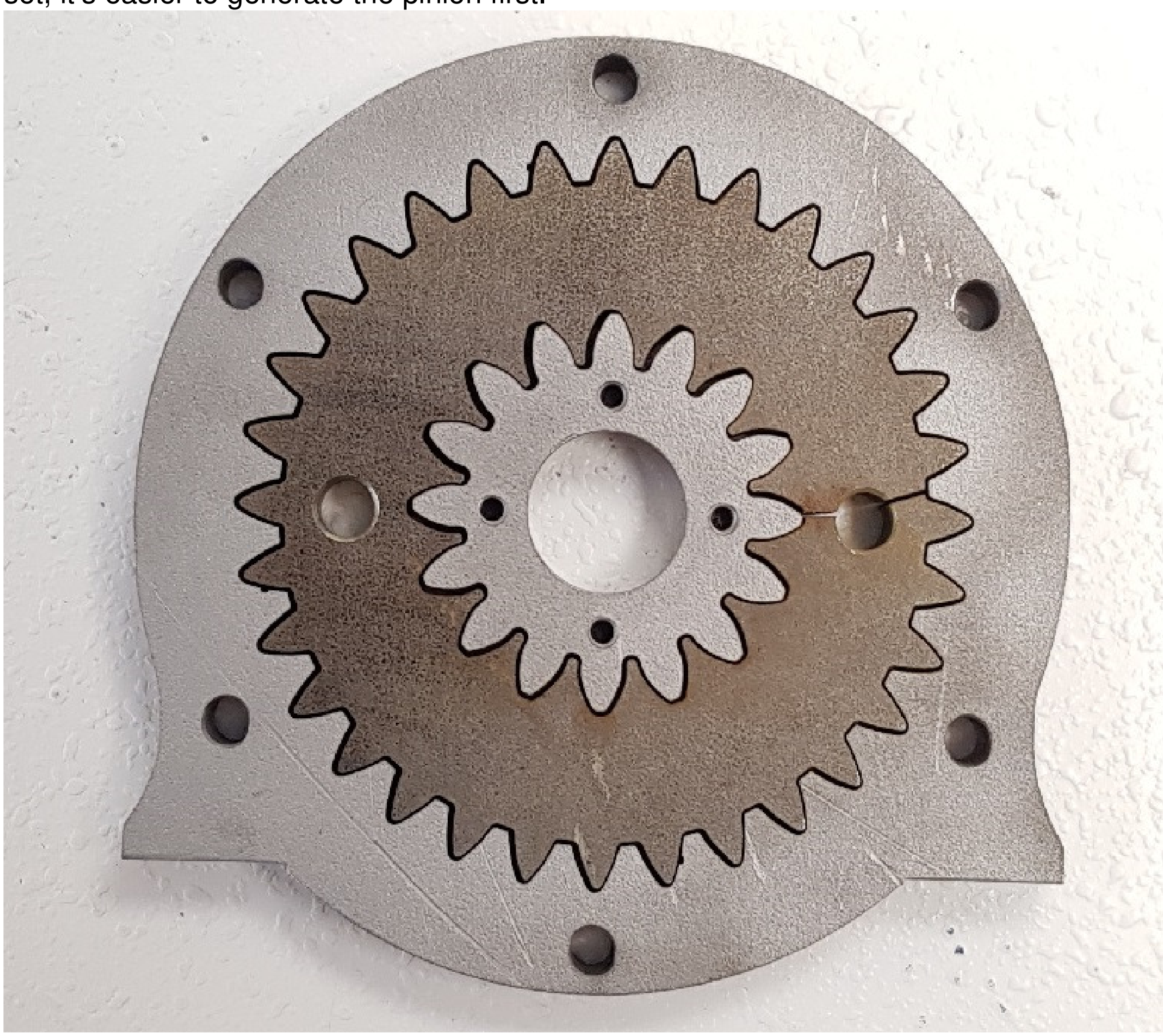
Some Examples.

Below is a gear profile I developed for a model Hypocycloid engine – which I had wire cut EDM.



Basically a Module 2 gear profile with a 24T annulus and a 12T pinion. The resultant Ø48mm pitch circle of the annulus is therefore the stroke of the cylinder of the Hypocycloid engine.

I generated the pinion tooth form from a rack (black lines a'La MAAG shaper) then used that tooth form to generate the annulus (cyan lines a'La FELLOWS shaper). Because this is an annulus gear set, it's easier to generate the pinion first.



Above: The actual wire cut gear (the colour contrast is a different patina on the reverse side – so I flipped the "scrap" which makes it more visible). Link to the running engine below.
Special note for EDM: The start and finish points should be in the middle of accessible tooth crests for access to "de-pip" the part – as in the above photo.

https://www.youtube.com/watch?v=sPblQfnNu-0&feature=emb_logo

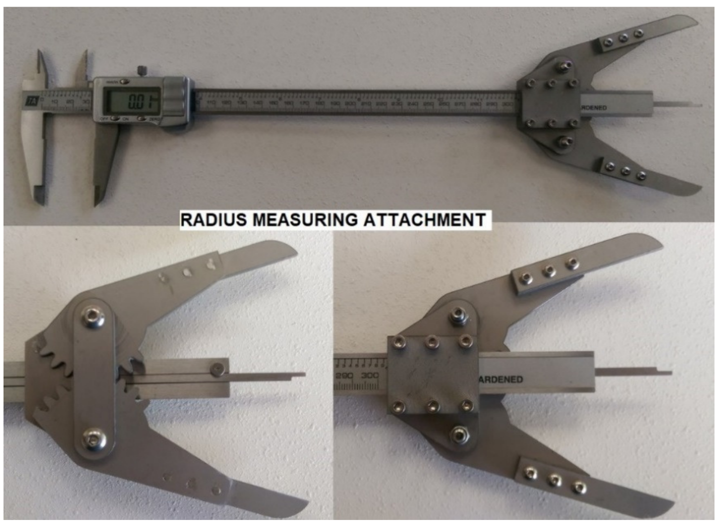
Sometimes an iterative approach can help refine the process – i.e. generate the pinion from a rack form, from that generate the annulus and from that regenerate the pinion – this can help where low tooth counts are generating interference. I didn't need to do that here.

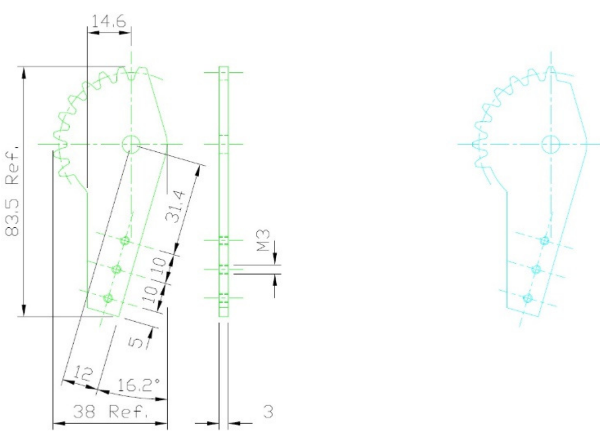
I found the standard 20° pressure angle a bit too "coggy" for my liking and changed to 25° as shown above.

The root radius and clearance is non-standard – I developed this with the intention of water jet cutting the gear and M2 is the smallest module you can accomplish with a waterjet's Ø1.2mm kerf.

My friend's waterjet machine had problems and I ended up getting them wire cut on another friend's EDM.

Below an example of a waterjet cut stainless steel M2 quadrant gear used on my Vernier caliper radius gauge attachment.





Those jaws were waterjet cut directly from the drawing data of the profile above – they meshed perfectly without any dressing or fiddling with the fit up – Eureka – it works !

Why Develop Your Own Profiles ?

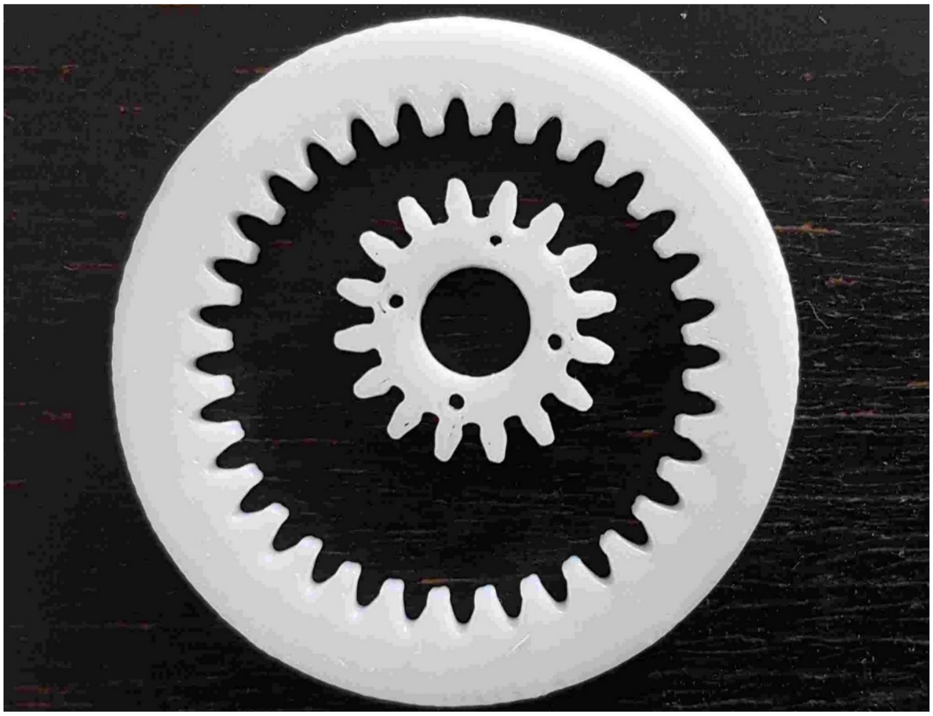
Clearly you should use standard gears and cutters whenever you can – it's considerably less trouble.

(In fact as a professional engineer I have a great hatred for using non-standard gear profiles – but that's another story.)
Having the ability to generate your own profiles allows you to peer into the dynamics of your gear set – it is particularly adept at demonstrating interference problems, it also allows you to use non-standard pitches, pitch circle diameters and pressure angles.

The nice thing about generating your own profiles is you can play with it to your heart's content and then use the database to cut it (or make cutters).

Besides there is a great sense of accomplishment (and grandson's admiration).

You can also use the data for prototyping – as in the 3D gear print (obviously not a functional part) below :-



This is a 20° pressure angle – I did not like the way it fitted up – too "coggy" - and changed the design to 25°

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Ken Irwin – 11th August 2020

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