# Working condition in shaping gears process

The shaper cutters for cutting both external and internal gears are always used in large quantities, although in recent years have made some pessimistic forecasts of the about their permanence on the market.
In fact, the total quantities of shaper cutters has been greatly reduced, but mainly due to the introduction of the coating with TiN that has multiplied the number of gears cut by a tool for 5 or 10 times.
Another important contribution to the performance of the shaper cutter was given by the improved HSS steel and the use of modern CNC gear cutting machines.
This has put in crisis many manufacturers of this tool even if it is still essential for many operations.
Working conditions for a disc shaper cutter, to cut external gear, are based on the following parameters:

- ➢ *stroke length;*
- ➢ *number of passes;*
- ➢ *cutting speed and (therefore) number of strokes per minute;*
- ➢ *radial feed;*
- ➢ *circumferential feed;*
- ➢ *cutting time.*

As in any other mechanical processing, also in this case it's possible to give only general indications about the choice of values to be assigned to each parameter, because they depend on a number of factors such as, for example, strength and workability of the material , the type and condition of the shaping machine, the type of steel of the shaper cutter and his eventual coating with TiN, the desired accuracy of the gear, etc..
The data that are reported below should therefore always be understood as a rough guide and should always be verified in practice.
Let us now examine the various elements that together constitute the working conditions.

## *Stroke length*
Stroke length **L** must be longer than the width of the gear tooth **H**. How much?
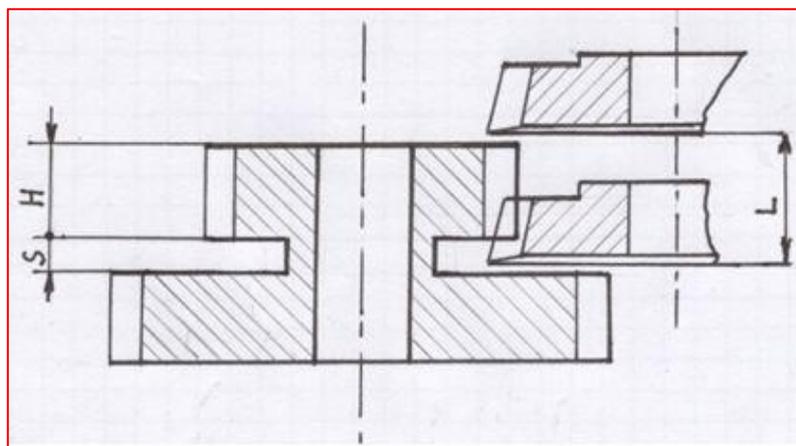It depends on the type of cutter and gear.



**Fig. N°1**

If we talk about disc shaper cutters for spur gear we can take as reference the diagram of figure N°2, that represents the equation: $L = 2{,}2 + \dfrac{H}{20}$

But if we talk about helical gears with a helix angle $\beta$, the real length of the stroke will be:

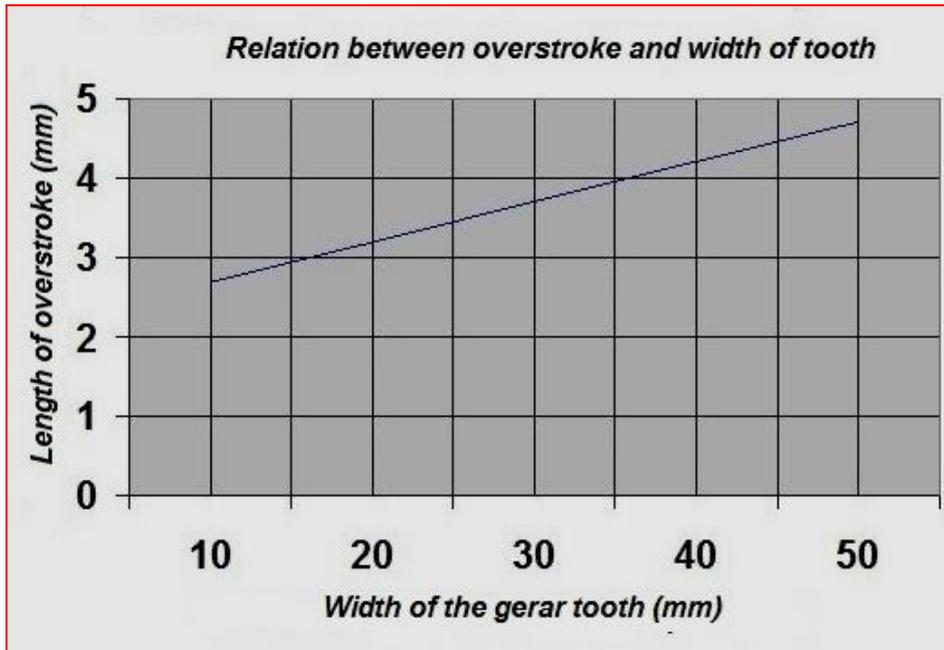$$L_\beta = \frac{L}{\cos \beta}.$$



**Fig. N°2**

Sometimes these values cannot be observed because the gear to be cut is very close to another gear or a shoulder.

With reference to figure N°1, the space S may be less than the above fixed.

In this particular case we consider that it is too dangerous to approach the shaper cutter at the of obstacle of the end of the stroke, primarily because there are dangers of collision with this obstacle and then chipped or broken teeth of the cutter, and secondly because the chips would be crushed between the workpiece and shaper cutter causing the breakage of the teeth, a fact that occurs quite frequently.

In these cases, the overstroke of the cutter should be as small as possible, assuming that the teeth the cutter should come out completely and must therefore take into account the inclinations of the cutting face (figure N°3).
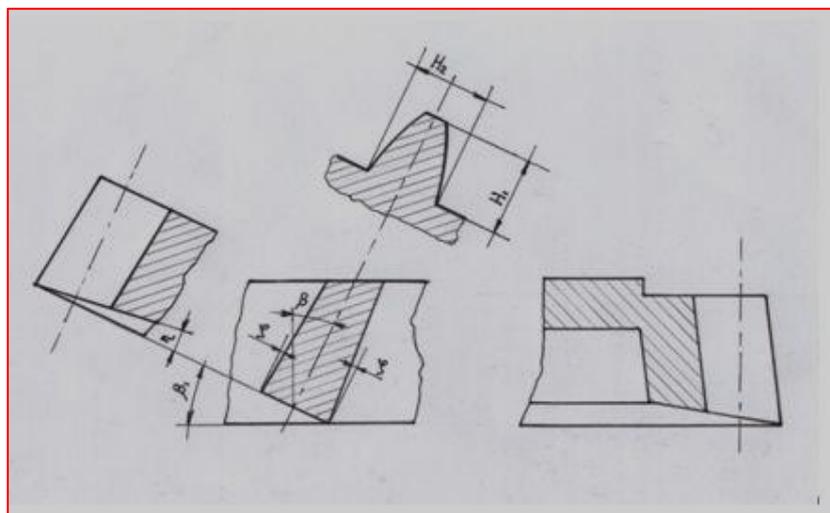


**Fig. N°3**

These values, imposed by the rake angle and relief angle are not always negligible.

If we consider for example a shaper cutter with a high helix angle ($\beta = 35°$), and remind ourselves that in general the surface of sharpening is orthogonal to the helix ($\beta_1 = \beta$), and if we suppose a cutter with a module of 2,5 mm and so has the value of $H_1$ = 6.5 mm (approximately), while $H_2$ is approximately = 6 mm, we obtain:

$$h_1 = H_1 \cdot sen5° = 6,5 \cdot sen5° = 0.566$$

$$h_2 = H_2 \cdot sen35° = 6 \cdot sen35° = 3,441$$

And therefore $h_1 + h_2 \cong 4mm$

If the space S has a value of about this entity, the situation is very dangerous.

To improve a little the situation sometimes it's better to reduce of 7 - 8 ° the value of the angle of the cutting surface; in this way the cutting surface is no longer perpendicular to the helix.

Of course, this modification involves an adjustment of the profile at the design stage.

In this case, if it were $\beta_1 = 28°$ we would have: $h_2 = H_2 \cdot sen28° = 6 \cdot sen28° = 2,81$ mm with a decrease of about 0.6 mm compared to the initial situation.

This modification of the sharpening angle is sometimes carried out independently from the problem of space, as it makes a sharp edge of the tooth (the entry edge), making it easier the cutting action, especially in soft steels.

Completed the forward stroke, before starting the return stroke, the cutter is detached from the piece so as to prevent the friction of the rear edge against the freshly cut surface.

The detachment of the shaper cutter from the workpiece before the return phase is a parameter to be studied carefully; in fact is not enough that the cutter comes off only as much as not to touch the surface of the gear at the end of the stroke, but we must consider that the circumferential and radial feed is continuous.

This means that in the time that the cutter makes the forward stroke of the point at the beginning of the stroke has been advanced, and this also happens during the return stroke. So if the detachment is not enough the back edge collides with the workpiece.

In this case the shaper cutter is sometimes very badly damaged.

*Number of passes*

Normally in the production of gears for the automotive industry , ie modules from 1 to 3 mm, are performed two passes: one for roughing and a finishing. The cycle provides therefore the following steps:

> *Radial feed (with rotation) until reaching a center distance as to have a stock removal of about 0.3 to 0.4 mm per flank.*
> *Generation with circumferential feed for another complete revolution of the gear.*
> *Radial feed (always with rotation) until reaching the final center distance .*
> *Generation with radial feed for a complete revolution.*

The roughing and finishing phases have different speeds and feeds, in order to generate a piece in the best conditions of accuracy and surface finish in the shortest possible time.

In many cases however, the teeth are cut in a single step, especially where the teeth do not have the purpose of coupling with rotation, such as synchronizers, some sleeves, involute splines ASA on shafts, etc..

On the other hand however in some cases are made many steps such as of module greater than 5 mm on gears made in steel hardly workable.

In this case it is essential to carefully choose the total penetration for each pass.

Figure N°4 shown a possible subdivision of depth of cut, as a percentage of the total height of the tooth, for a number of passes from 1 to 7.
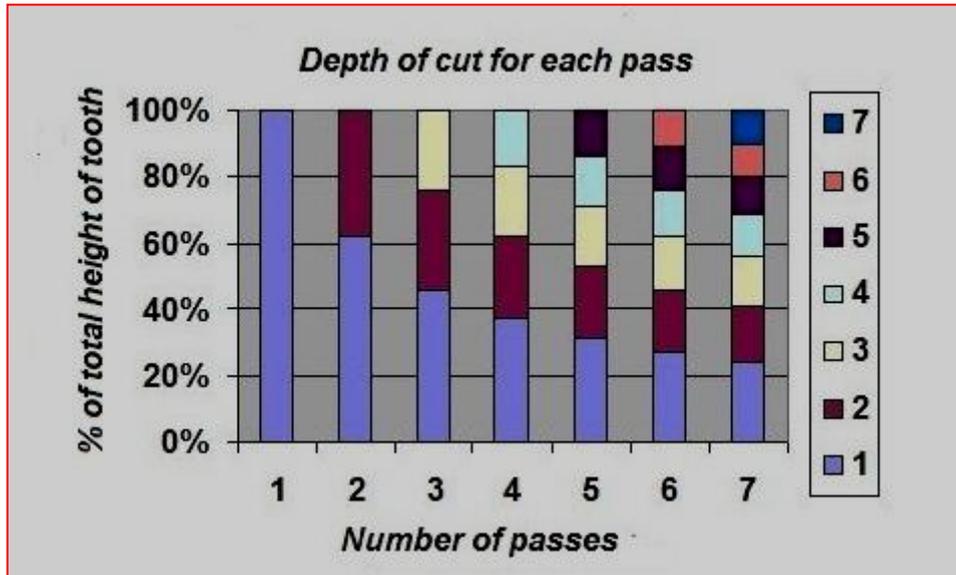
**Fig. N°4**

In the past years, the radial and circumferential feed and the number of passes were gave by cams or gearing, now all working data is managed much more effectively by numerical control.

*Cutting speed and (therefore) number of strokes per minute;*
First is necessary to define what we mean by cutting speed, as the alternate movement of the shaper cutter is sinusoidal, therefore the speed start from zero, reaches a maximum and then decrease back to zero before starting the return stroke , or it can be almost constant if the slide where the cutter is mounted is controlled by a hydraulic cylinder.
In this case the trend of the speed of the slide, after a short acceleration reaches its maximum value and keeps up the short ramp and then reverse the direction of the return stroke with a rapid movement to the starting point.
A speed of this type can be also given by slides that are driven by a motor managed by Numerical Control.
In the case of sinusoidal motion, the instantaneous velocity in each section of the gear tooth is always different.
It is distinguished therefore an average cutting speed $V_m$ and a maximum cutting speed $V_{max}$. To understand how we obtained the expressions with which we calculate the values of these two speeds, you should refer to figure N°5.
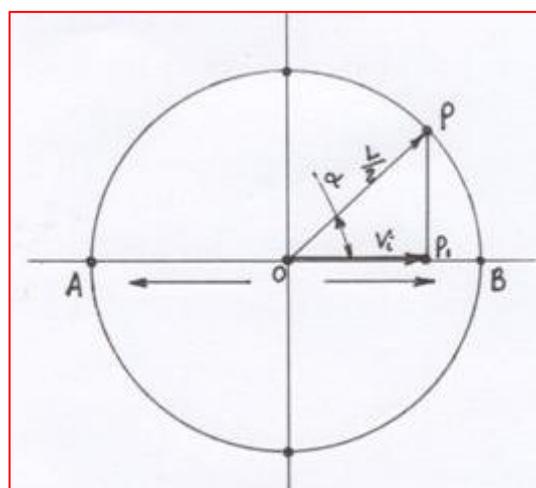


**Fig. N.5**

In this figure the diameter AB corresponds to the length of the stroke L.
If we consider a generic point P moving with uniform speed along the circumference , the cutting speed is the speed of the point $P_1$ on the diameter AB.
Then, using the following notations, we can calculate the two speeds.

$\overline{AB} = L$  (in mm)

N = number of stroke per minute  (a stroke is considered a complete cycle. Go and come back)

$V_i$ = Actual speed of $P_1$ on  AB

V = peripheral speed of the point P along the circumference (m/min.)

$V_{max}$ = maximum speed of $P_1$  (when  $P_1 \equiv O$ )

$$V = \frac{\Pi \cdot L \cdot N}{1000}$$

$$V_i = V \cdot \cos \alpha = \frac{\Pi \cdot L \cdot N \cdot \cos \alpha}{1000}$$

$$V_{max} = \frac{\Pi \cdot L \cdot N}{1000} \quad \text{(when } \cos \alpha = 1 \text{)}$$

$$V_m = \frac{2 \cdot L \cdot N}{1000} \quad \text{from which we obtain} \quad V_{max} = \frac{\Pi}{2} \cdot V_m$$

For the more general case, that is, helical gears, you have to replace L with:

$$L_\beta = \frac{L}{\cos \beta}$$

$V_{max}$ is the maximum speed that you must consider for the cutting edge life, although this concept is questionable, in the sinusoidal motion, because it is a condition that is very short, during which the cutting edge does not have time to absorb a lot of heat.
But this is valid in the case of hydraulic slide where, as mentioned above, the maximum speed is practically constant from begin to end of the stroke.
The average speed $V_m$  is used to calculate the cutting times.
The choice of the cutting speed, as has been said, must take into account many factors.

  ➢ Module of the teeth
  ➢ Workability of the material
  ➢ Length of the teeth
  ➢ Material of the cutter and his eventual coating with TiN
  ➢ Type and condition of the machine
  ➢ Type and quantity of cutting oil

Some of these parameters are difficult to define and therefore calculate the optimum cutting speed always has a certain margin of uncertainty.
First you must define the workability of the material that you want to work. This parameter is extremely important because they account for a significant effect on the maximum speed possible in a certain process.
Table N°1 lists the main steels with their tensile strengths, the hardness and workability index reported as a percentage of soft annealed steel C10.

## Tab. N°1 - Workability of most common steels

| Material Cod. DIN | Annealed steel | | | After heat treatment | | |
|---|---|---|---|---|---|---|
| | Strengthness N/mm2 | HB30 - Brinell Hardness | Workabilty % | Strengthness N/mm2 | HB30- Brinell hardness | Workability % |
| C 10 | 470 | 135 | 100 | 560 | 165 | 90 |
| C 15 | 490 | 145 | 95 | 685 | 200 | 60 |
| 15 Cr 3 | 570 | 165 | 90 | 790 | 235 | 50 |
| 16MnCr5 | 630 | 200 | 80 | 930 | 270 | 45 |
| 20MnCr5 | 730 | 210 | 75 | 1120 | 330 | 30 |
| 15CrNi6 | 770 | 220 | 65 | 1030 | 300 | 35 |
| 18CrNi8 | 810 | 235 | 60 | 1080 | 315 | 30 |
| 14 Ni 6 | 550 | 160 | 80 | | | |
| 14NiCr14 | 750 | 217 | 55 | | | |
| C 35 | 520 | 170 | 75 | 670 | 200 | 65 |
| C 45 | 580 | 210 | 70 | 730 | 220 | 60 |
| 30 Mn 5 | 750 | 217 | 65 | 825 | 240 | 55 |
| 34 Cr 4 | 750 | 217 | 65 | 885 | 260 | 50 |
| 41 Cr 4 | 750 | 217 | 55 | 975 | 285 | 45 |
| 37MnSi5 | 750 | 217 | 65 | 950 | 280 | 40 |
| 42CrV6 | 750 | 217 | 55 | 1150 | 340 | 35 |
| 25CrMo4 | 750 | 217 | 65 | 875 | 260 | 50 |
| 42CrMo4 | 750 | 217 | 60 | 1050 | 305 | 35 |
| 36CrNiMo4 | 750 | 217 | 50 | 1025 | 300 | 35 |
| 30CrMoV9 | 860 | 255 | 45 | 1200 | 355 | 25 |

If we consider:
- Tooth width 25 mm
- Steel of the shaper cutter M2
- Tool not coated
- Roughing pass
- Modern machine tool in good condition

If $L_{av}$ is the workability of the material in percentage, you can use the following formula to find the maximum speed:

$$V_{max} = \frac{L_{av} + 35}{2,6}$$

Found the maximum speed you must apply the following correction coefficients according to the characteristics of various other parameters:
- For every increase in the length of the tooth of 25 mm: multiply by 0.9;
- In the passes of semi-finishing: multiply by up to 2;
- In finishing passes, multiply up to 2-3;
- In the case of tool in steel powder of group F-AM (which is part of the famous ASP30): multiply by 1.1;
- With tools in steel. F-PM + TiN: multiply by 1.4;

Should always re-coating the cutter after each sharpening, otherwise the cutting speed should be reduced.
Normally, the cutting speed is fixed and, from this data we calculate the number of strokes per minute to set up shaping machine.

$$N = \frac{1000 \cdot V_{max} \cdot \cos \beta}{\Pi \cdot N}$$

In certain processes, where the tooth width is very small and especially with CNC machines, it may be that the maximum number of strokes per minute executable by shaping machine, is below that necessary to achieve the cutting speed determined.

In this case the cutting speed will be lower and therefore the cycle time will be longer.

We must also remember that in the shaping operation the tool cut with intermittent action; during each stroke the cutting edge receives a shock that is more intense if the feed is higher.

It is therefore not appropriate to use HSS steels with high hardness because would be easy generate chipping and even tooth breakage.

*Radial feed*

At the beginning of the cycle, the shaper cutter is radially approaching to the piece and begins to penetrate up to the desired center distance, ie until the final center distance if the piece must be finished in one pass, or deep enough to remain at each flank a specific stock removal for subsequent finishing operation.

The value of this feed $a_r$ depends mainly on the type of material being processed and, of course, on the type of machine and tool.

The choice of $a_r$ should take into account the actual workability of the material and not only its strength, however, in addition to what is said in talking about the cutting speed, the radial and circumferential feed allows more margins of choice.

This means that an increase, although significant of feed rate does not impact in proportion to the length of life of the shaper cutter.

A too high value of feeds, especially those of generation (circumferential) may cause chipping or breakage of teeth of the cutter or gear tooth surfaces with deep scratches.

You can take the same radial feed $a_r$ in the second approach, after roughing, although it is sometimes preferable to reduce a little its value to prevent the formation of deep scratches.

The table N°2 shows the values generally recommended for $a_r$ and, as can be seen, between the minimum and the maximum there is a significant difference.

It is clear that the optimal value should be determined after a series of tests also based on what you prefer to focus on: cutting time, tool life, product quality etc..

*Tab. N°2 – Radial feed rate (mm/stroke)*

| Hardness $HB_{30}$ | 135 – 185 | 185 - 220 | 220 - 280 | over 280 |
|---|---|---|---|---|
| Radial feed $a_r$ | 0,03 – 0,06 | 0,02 – 0,05 | 0,015 – 0,04 | 0,01 – 0,03 |

*Generation (circumferential) feed rate*

When the shaper cutter has arrived desired to the center distance it does not advance more radially, but continues to run in a circumferential direction, that is rotating.

The meshing between the tool and the gear (virtual) to generate occurs at a speed precisely equal to the feed rate of $a_c$ per stroke of the cutter, conventionally calculated on the nominal pitch diameter.

It is evident that from the value of this parameter depends the thickness of the chip and therefore the mechanical stress on the cutter.

It is true that the choice of the value of $a_c$ can be made within the large limits without affecting dramatically the cutter life, but if the chip thickness is very large, it is evacuated with greater difficulty and, in case the tooth width is large, the chip (rigid in case of large $a_c$) easily gets blocked at end of the stroke, especially if in this area there is not a wide space between the cutter and shoulder.

Another phenomenon not to be overlooked when working with high $a_c$ of low strength material, is the formation of a large burr on the output side of the cutter.

The removal of this burr can be difficult if you do not have specific machines.
The table N°3 shows the recommended values of $a_c$, (mm/stroke) (it is always understood as a double stroke) as a function of the module and hardness of the steel of the gear.
Lower values are to be used on machines of the old type not in perfect condition.
The higher values are applicable on modern CNC machines.

*Tab.N°3 – Generation feed rate ( mm/stroke) for roughing operation*

| Module | Hardness $HB_{30}$ | | | |
|---|---|---|---|---|
| | 130 - 180 | 180 - 220 | 220 – 240 | 240 – 300 |
| Up to 1,5 | 0,30 – 0,40 | 0,25 – 0,35 | 0,20 – 0,28 | 0,15 – 0,25 |
| 1,5 – 2,5 | 0,50 – 0,65 | 0,40 – 0,60 | 0,30 – 0,40 | 0,25 – 0,35 |
| 2,5 – 4,0 | 0,50 – 0,65 | 0,45 – 0,60 | 0,35 – 0,45 | 0,30 – 0,40 |
| 4,0 – 6,0 | 0,60 – 0,75 | 0,50 – 0,60 | 0,40 – 0,50 | 0,30 – 0,40 |

In finishing these values can be increased, because there is no risk of damaging the tool, the only factor to consider is the accuracy and surface finish of the workpiece.
As mentioned above, it is intuitive that the chip thickness increases with increasing circumferential feed rate, but it should be noted that the shape of the chip is very complex and it is difficult to give a clear definition of its thickness.
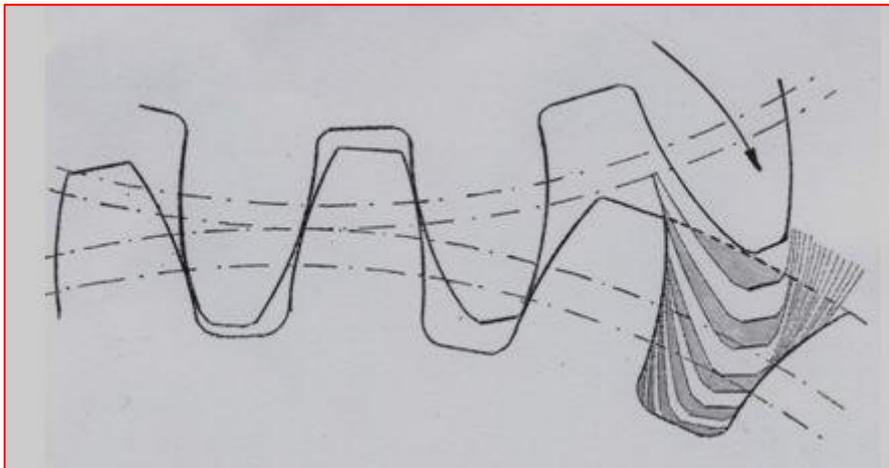


**Fig. N°6**

Just look at the figure N°6 to understand, first, that this is not the usual chips, but has a section with three sides, difficult to detach and roll up.
Secondly it is much larger at the entry side of the cutter , falling almost to zero at certain points of the opposite edge.
All this affects the wear of the cutter , which is concentrated near the edge of the entry, close to outside diameter.
All this affects the wear of the cutter , which is concentrated near the edge of the entry, close to outside diameter. In fact, this is a great disadvantage because it reduces the efficiency and life of the cutter itself.
In order to avoid this problem, in modern machines you can choose some variants of the working cycle.
The first is to cut the gear turning with the cutter in a clockwise direction and then working the next revolution in the opposite direction.
In this way is better distributed the wear on the cutter with its higher performance.
Another method is to change the phase of radial feed extending it to a full revolution and coming up to the final center distance. In this way the trajectory of feed is a spiral achieved by the combination of the radial feed with the circumferential feed.
The effect is a reduction of chip thickness in the entry side and an increase on the opposite side and thus the wear on the cutter becomes a little more balanced.

Also spiral feed can be constant, ie the radial component has the same value for each stroke until the end of the cycle or the radial component of the spiral feed may decrease gradually as you approach to the theoretical center distance.
It is evident that in any case, when the penetration is finished and the cutter arrived at final center distance, you must run at least another tour without radial feed to get all the gear teeth with same size.

*Cutting time*
The calculation of the cutting time is important to determine in advance the cost of the operation and the cadence of the shaping machine, with implications for its integration into production lines.
The method for its determination is quite intuitive since the first is to calculate, for each phase, how many strokes are needed to finish the radial infeed and one revolution of the gear and then divide this number by the number of strokes per minute.
So the data required are:

- $a_{r1}$ = radial feed rate in roughing  (mm/stroke)
- $a_{r2}$ = radial feed rate in finishing  (mm/stroke)
- $a_{c1}$ = generation feed rate in roughing (mm/stroke)
- $a_{c2}$ = generation feed rate in finishing (mm/stroke)
- $p_1$  =  radial infeed in roughing (mm)
- $p_2$  = radial infeed in finishing (mm) ($p_1+p_2$= height of tooth)
- $D_p$  = pitch diameter of the gear (mm)
- $\Pi \cdot D_p$ = length of the pitch circle (mm)
- $N_1$  = number of strokes per minute (double stroke) in roughing
- $N_2$  = number of strokes per minute (double stroke) in finishing
  .

It is thus easy to calculate the contact time of the shaper cutter in the case of cut with two passes  with:

$$T = \frac{p_1}{a_{r1} \cdot N_1} + \frac{\Pi \cdot D_p}{a_{c1} \cdot N_1} + \frac{p_2}{a_{r2} \cdot N_2} + \frac{\Pi \cdot D_p}{a_{c2} \cdot N_2}$$

It emphasizes that this is not the time cycle, but only the contact time of the tool and then we must add to **T** the time of approach and return, time for locking and unlocking of the workpiece and loading and unloading times.

*General recommendations*
In order to obtain a good result in shaping gear operation, in addition to a correct choice of cutting conditions, you must meet some basic conditions relating to mounting and maintenance of shaper cutter, the correct clamping of the workpiece and the choice of an appropriate cutting oil.
First, it is recommended to verify the eccentricity of the shaper cutter in the machine, it should not ever exceed 0,005 mm and the same value is required for planarity.
The clamping of the cutter must be done using spacers and flanges which support the largest possible diameter of the shaper cutter, so you have a reaction force as close as possible to the teeth of the shaper cutter.
The shaper cutter must be sharpened properly before the wear takes values too high: a limit value may be between 0.3 and 0.5 mm.
Particular care must be taken for the respect of sharpening angles. Any deviation of these angles from to the design inevitably causes an error on the tooth profile.

To get an idea of how can influence a mistake on the frontal rake angle $\eta$ (which is normally standardized to $\eta = 5°$ - see figure N°3) on the variation of pressure angle, we can apply the following formula:

$$\Delta\alpha_n \cong -tg\,\zeta \cdot \frac{\cos^2 \alpha_n}{\cos^2 \eta} \cdot \Delta\eta$$

where:
$\alpha_n$ = *normal pressure angle*
$\zeta$ = *side clearance angle*
In case of $\zeta = 2°15'$ ; $\eta = 5°$ ; $\alpha_n = 14°30'$ ; there are:
$\Delta\alpha_n \cong -0,037 \cdot \Delta\eta$
If the pressure angle was 20° would be obtained:
$\Delta\alpha_n \cong -0,035 \cdot \Delta\eta$ .
These errors are quite significant, so the tolerance recommended for this angle is
$\Delta\eta = \pm 15'$
The roughness of the sharpening surface should be around Ra = 0.5 microns, keeping in mind that a higher roughness generates an irregular cutting edge that reduces the life of the cutter and the quality of the machined surface.
In addition, a high roughness of the sharpening surface causes a more difficult flow of the chips and an easier formation of the build-up edge.
Finally, it is evident that during the re-sharpening should be avoided, in the strongest terms, the overheating of the cutting edge, something that would drastically reduce the life of the cutter.
It is also imperative that the shaper cutter after sharpening is again coated with TiN (or with another type of film) , this in order to keep an efficiency similar to the new cutter.
So it would be appropriate that both sharpening and the new coating should be performed by a qualified service center.
Another important note concerns the clamping of the workpiece to prevent movement in any way, under the cutting force, or slip in the direction of rotation.
This would create the large profile and helix errors and possibility of breakage of the cutter.
Finally there is the cutting oil that besides the important function of cooling the contact zone between the workpiece and the tool must be sufficiently fluid to clean continuously the work area to prevent building up of chips in dangerous areas.
The cutting oil must also be added with components EP (Extreme Pressure) that prevent, as much as possible, the welding of chips on the cutting edge of the tool and the formation of the build-up edge.
This phenomenon, to be honest, today is quite limited by the TiN coating, but there still remains a danger.