

## Working conditions during shaving process

Working conditions during shaving process includes many parameters that sometime have a reciprocal interaction. It is then necessary to carry out a careful examination of the whole picture of the situation before deciding how to work.

Of course certain items are taken for granted, such as the accuracy that you want to obtain on the gear, the preferred shaving method, which depends both on the workpiece shape and on the shaving machine available, the cross of axes angle and the table setting angles.

Let's examine in detail the following items, adding a few comments:

- *Shaving stock removal*
- *Stroke length*
- *Number of passes*
- *Cutting speed*
- *Cutting feed*

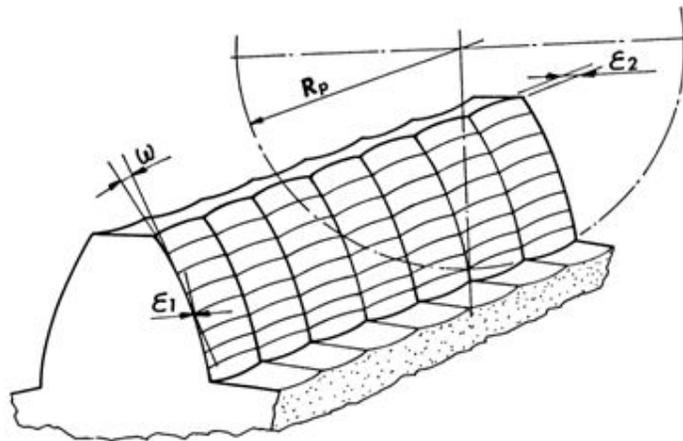
### Shaving stock removal

The gear can be hobbled or shaped.

The workpiece surface has a different look according to the system used for cutting and also the types of error are different.

It is a known fact, for instance, that shaped gears have indexing errors bigger than those of hobbled gears and, in general, can be considered less accurate as far as profile is concerned.

The surface of the hobbled gear has undulations as per figure N°1.



**Fig.N° 1-** *Hobbing scallops along tooth flank*

These undulations, commonly called *hobbing scallops*, have, after all, a positive effect on the shaving process, because they favour the penetration of the cutting edge into the material and then the chip formation.

The depth of these undulations, which mainly depends on the hob diameter and on the axial feed, determines somehow which must be the minimum shaving stock removal. It is obvious that in order not to leave any trace on the shaved gear, the stock removal must be bigger than undulations depth, but this is not enough. You need to take care of profile and helix errors too.

In practice, if a hobbled gear has big errors coming from hobbing, then the shaving stock removal must be bigger.

If shaving stock removal must be bigger, then the number of passes must be higher and, as a consequence, the shaving cycle time will be longer.

You will realise that you cannot consider the stock removal value indicated in table no.8 as strictly binding, since they only represent general statement, subject to possible variations (plus or minus) according to the hobbled gear status.

Table N°1 : shaving stock removal (in mm)

Module	Stock removal on the tooth	Stock removal on the flank	Module	Stock removal on the tooth	Stock removal on the flank
1,00	0,030	0,015	3,50	0,060	0,030
1,25	0,030	0,015	3,75	0,060	0,030
1,50	0,035	0,0175	4,00	0,060	0,030
1,75	0,040	0,020	4,50	0,070	0,035
2,00	0,040	0,020	5,00	0,070	0,035
2,25	0,040	0,020	5,50	0,075	0,0375
2,50	0,045	0,0225	6,00	0,080	0,040
2,75	0,050	0,025	6,50	0,080	0,040
3,00	0,050	0,025	7,00	0,090	0,045
3,25	0,060	0,030	8,00	0,090	0,045

Stroke length

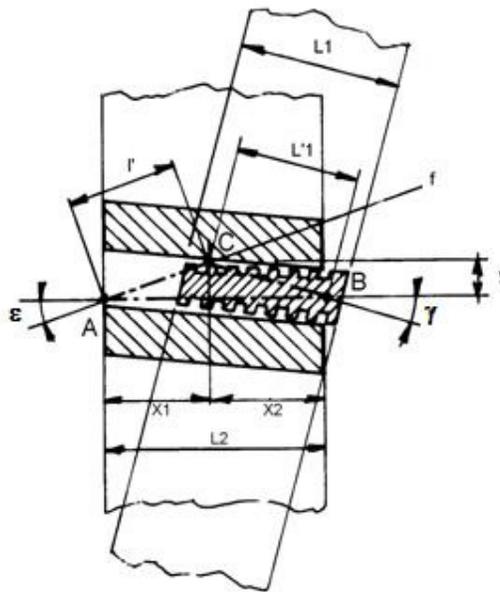
The table stroke length depends on the shaving method.

In *parallel shaving* stroke length must be at least as long as the width of the gear to be shaved. Normally you establish a stroke 1÷2 mm longer.

In *diagonal shaving* depends on gear width  $L_1$ , cross of axes angle  $\gamma$  and diagonal angle  $\varepsilon$ .

With reference to figure N°2 you can use the following formula:

$$l_1 = L_2 \cdot \frac{\text{sen } \gamma}{\text{sen}(\varepsilon + \gamma)}$$

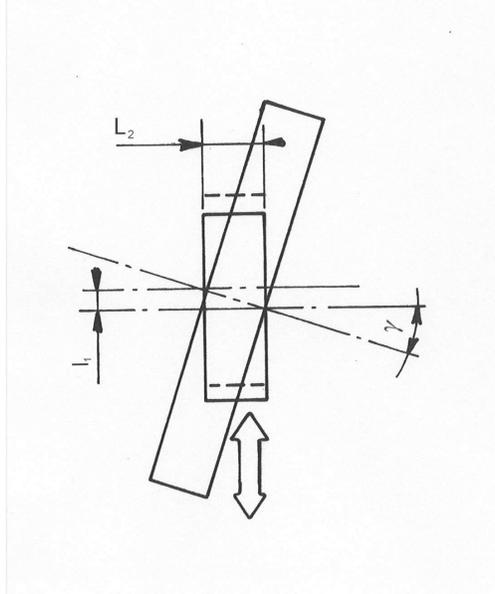


**Fig.N°2-** Indication for the calculation of stroke length in diagonal shaving

The length depends in reality also on the tooth working length  $L'_1$  because the *diagonal angle*  $\varepsilon$  must satisfy the relationship.

$$\operatorname{tg} \varepsilon = \frac{L_1' \cdot \operatorname{sen} \gamma}{L_2 - L_1' \cdot \cos \gamma} = \frac{\operatorname{sen} \gamma}{\frac{L_2}{L_1' - \cos \gamma}}$$

In *underpass shaving* the stroke length  $l_1$  can be calculated through  $l_1 = L_2 \cdot \operatorname{tg} \gamma$  as you can see in figure N°3.



**Fig.N°3-** Indication for the stroke length in underpass shaving

In *plunge shaving* the stroke length corresponds to the center distance reduction. You will first have a fast traverse and then the machine will go on till the final center distance is reached, and the stock has been fully removed.

### Number of passes

The number of passes depends mainly on the stock removal to be shaved off. If the gear has been poorly toothed and then we have to leave a thicker stock removal, number of passes will be higher as well as longer will result the cycle time.

We still have to consider that it is not too advisable to increase the number of passes, because the way the shavings are removed is more similar to a scraping than to a real cut.

This means that after each pass, especially if the feed rate is low, the tooth surface get more and more strained, thus causing an increasing in cutting edges wear formation speed.

As a general rule we could say that *in parallel and diagonal shaving you have to consider a pass for each hundredth of millimetre of stock removal on a flank*; then make a pass without increment, just to obtain a better surface. NB : for pass we mean one forward or one backward strokes. Normally at the end of each pass the cutter direction reverse.

The rule of the number of passes is not thoroughly valid when shaving underpass, where it is preferable to take the cutter to the finishing center distance and make only one forward and backward pass. But this rule does not always works fine because this shaving method normally considers very low cross of axes angle and sometime shavings removal takes place in a precarious way. In other words, it will be necessary to experimentally verify if it is better to work with one or more passes.

Plunge shaving requires a different dealing, since working cycle is totally different from the other methods. We will see an example further on.

### Cutting speed

The effective cutting speed during shaving, i.e. the speed at which each cutting edge is sliding on the gear tooth surface, can be represented by a vector whose module and argument change continuously during rotation.

The cutting speed vector  $\mathbf{V}$  is the resultant of three different vectors:

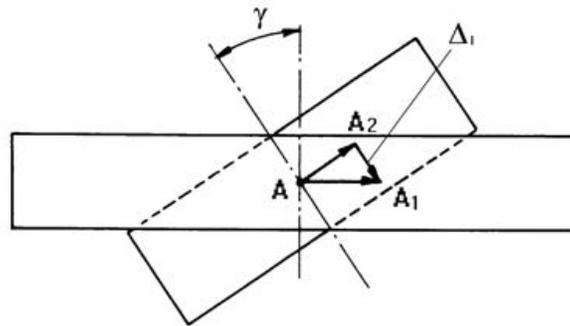
- $\mathbf{V}_l$ : sliding speed along the tooth longitudinal direction
- $\mathbf{V}_s$ : sliding speed along the tooth height direction
- $\mathbf{V}_a$ : sliding speed according to the table feed

Of course this component is present only in the Parallel and Diagonal methods. Moreover, it is much smaller, compared to the other ones and so we can forget it.

With reference to figure N°4, calling  $\omega_1$  and  $R_1$ , respectively, the cutter angular speed and pitch radius, and  $\omega_2$  e  $R_2$  the gear angular speed and pitch radius, the point of instantaneous contact  $A$  after a time  $\Delta t$  on the cutter will have moved from  $A$  to  $A_1$ , while on the gear it will have moved from  $A$  to  $A_2$ .

The distance  $\Delta l$  connecting  $A_1$  and  $A_2$  is the value of the reciprocal sliding between the two points of the cutter and the gear that where coinciding in  $A$ .

The  $\Delta t/\Delta l$  ratio is the speed of this sliding.



**Fig.N°4-** Indication for the vectorial calculation of effective cutting speed

This speed depends on the cutter and gear rotating speed, and cross of axes angle, which is the difference between the two helix angles  $\gamma = \beta_1 - \beta_2$

You can then write:

- For spur gears  $V_l = \omega_1 R_1 \sin \gamma = \omega_1 R_1 \sin \beta_1$

- For helical gears  $V_l = \omega_1 R_1 \frac{\sin \gamma}{\cos \beta_2}$

The sliding speed along tooth height direction can be calculated with the formula

$$V_s = (\omega_1 + \omega_2) \cdot l_v$$

where, with reference to figure N°5,  $l_v$  is the distance between point W and point A considered (in this case situated close to the outside diameter) which in agreement with Henriot vol.1, chap 5°, can be calculated with:

$$l_v = \frac{d_{b2}}{2 \cdot \cos \beta_{b2}} \cdot (\operatorname{tg} \alpha_{e2} - \operatorname{tg} \alpha_{os2}) \quad \text{where}$$

$d_{b2}$  = gear base diameter

$\beta_{b2}$  = gear base helix angle

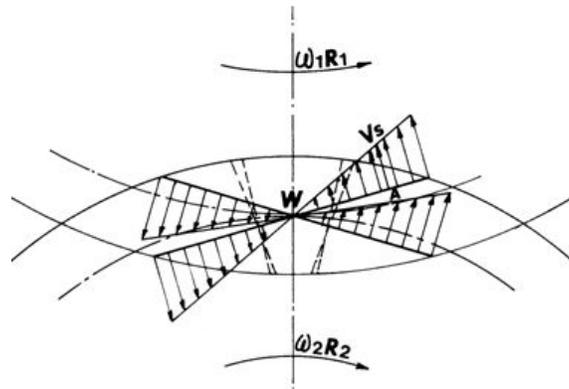
$\alpha_{e2}$  = pressure angle on gear outside diameter

$\alpha_{os2}$  = apparent pressure angle on gear pitch diameter

You can easily observe that  $v_r$ , and then the sliding speed in radial direction, much depends on the difference between the pressure angles in correspondence of the operating pitch diameter and of the point being considered.

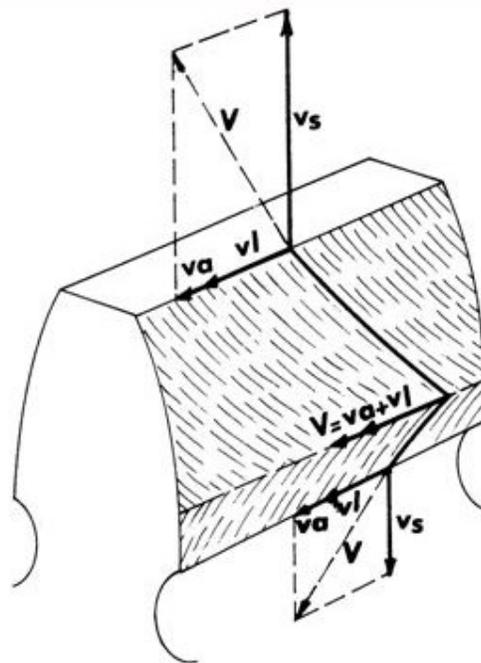
If the pitch diameter is chosen very low, i.e. closer to root diameter, you will have a noticeable vertical component close to outside diameter.

In any case it appears evident that, since this distance is continuously variable (and also changes the sign), the vector resulting from the sum  $V_1 + V_s$  is variable both as module and as argument in every point of the gear tooth surface.



**Fig.N°5-** Indication for the calculation of cutting speed vector along the direction of tooth height

The most noticeable effect is that cutting speed, i.e. the way chips are removed, changes continuously as shown in figure N°6.



**Fig.N°6-** Speed vectors in the various point of the tooth

In correspondence of the operating pitch diameter the cutting direction will be only longitudinal, while, the more the point of contact moves far from the pitch diameter, the more oriented towards the radial component will be the cutting direction.

Tooth surface will then have different characteristics, sometimes showing a good finish only in one portion of the tooth and a worse situation in the other areas.

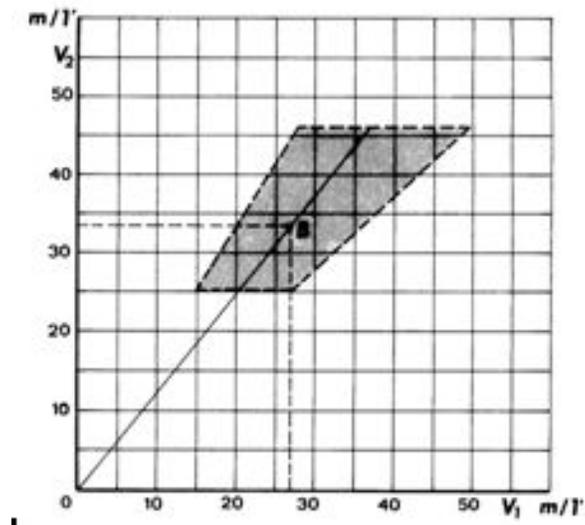
One of the operating inconveniences is caused by the direction of the cutting speed resulting vector being too much oriented in the vertical direction.

Sometimes it is sufficient to reduce the rotation speed values  $\omega_1$  and  $\omega_2$  so that  $V_s$  becomes smaller, but sometimes it could be necessary to increase the cross of axes angle - and then to increase the longitudinal sliding speed  $V_1$  - or design the cutter in such a way to limit the vertical sliding in the outer tooth areas.

It is not too simple, then, to advise an optimum cutting speed for shaving; this is the reason why the tendency is to state just the cutter RPM.

But it could also be interesting to know which is the order of magnitude of the effective cutting speed. Then it is advisable to look at the diagram of figure no.56, which in practice gives out the characteristics of the cutting speed vector.

If the point that represents the extreme of vector  $V$ , whose module is calculated with the formula  $V = \sqrt{V_1^2 + V_s^2}$  falls into the highlighted area of diagram as per figure no.56, then the cutting speed can be considered as good.



**Fig.N°7** Diagram for the correct establishment of cutting speed

This method, anyway is not easy to apply, therefore it is preferable to state only the speed on cutter pitch diameter, i.e.  $V_1 = R_1 \cdot \omega_1$ .

This approximated value must be chosen in function of the resistance of the material to be worked, and it is influenced, even if only a little bit, by the module.

In the following table N°2 you can find some values that can be recommended for the peripheral speed. Working on these data, and knowing the cutter outside diameter, you can obtain the cutter RPM value.

Anyway, in order to simplify the determination of RPM - no doubt the most widely used parameter in the workshop, we report in table N°3 the values calculated on the most common diameters.

The formula being use is the classic cutting speed one, i.e.

$$n = \frac{V_t \cdot 1000}{\pi \cdot d_o}$$

Table N°2: Recommended peripheral speed on cutter pitch diameter (m/min)

Steel resistance in Kg/mm <sup>2</sup>	Module = 2	Module = 4	Module = 6
50	200 – 120	180 - 110	160 - 105
60	180 – 115	160 -105	140 - 100
70	160 – 110	140 -100	120 - 90
80	140 – 100	120 - 90	100 - 80
90	120 – 90	100 - 80	90 - 70
100	100 – 75	90 – 70	80 - 60

Table N°3: number of RPM corresponding to a determined cutter peripheral speed

Peripheral speed m/min	7" Shavers (dia. 180 mm)	8" Shavers (dia. 200 mm)	9" Shavers (dia. 230 mm)	10" Shavers (dia. 250 mm)
70	124	111	97	89
75	133	120	104	96
80	141	127	111	102
85	150	135	118	108
90	160	143	125	115
95	168	151	132	121
100	177	159	132	121
105	186	167	145	134
110	195	175	152	140
115	203	183	159	146
120	212	191	166	156
140	248	222	194	178
160	282	254	222	204
180	320	286	250	230
200	354	318	264	242

### Feed speed

The table longitudinal feed speed - of course considering the parallel and diagonal methods - is normally included in the range 0.2 ÷ 0.7 mm/part revolution.

The value to be chosen depends both on the shaving method and on the number of teeth of the workpiece.

For a low number of teeth you can choose a low feed rate, while for a high number of teeth you can go for a higher value.

As an example , in parallel shaving:

Gear with Z=12 you can have Ag = 0.3 mm/part revolution.

Gear with Z=40 you can have Ag = 0.6÷07 mm/part revolution.

In diagonal shaving you always have to take into account the cross of axes angle  $\gamma$  and the diagonal angle  $\varepsilon$  . The feed, in this case, has to be calculated with the following formula:

$$A_{g1} = A_g \cdot \frac{\text{sen}(\gamma + \varepsilon)}{\text{sen } \gamma}$$

With the latest NC machines it is possible to modify the feed speed at each pass and then you can determine bigger feeds for the initial passes and then reduce the final feeds at the last pass.

If the surface finish is not acceptable sometimes it is sufficient to slightly alter feed speed to obtain better results. This depends on the fact that in certain conditions cutter serrations traces are not correctly offset. In other words, feed rate per revolution is such that on each tooth the serrations trace falls onto the previous trace. All you have to do to leave this situation is simply to increase or decrease the feed.

Also the *approaching speed* - i.e. what could be defined as the cutting depth - has its own importance.

The radial approaching values for each pass range from 0.02 and 0.05 mm, considering the smaller values for the finishing stage.

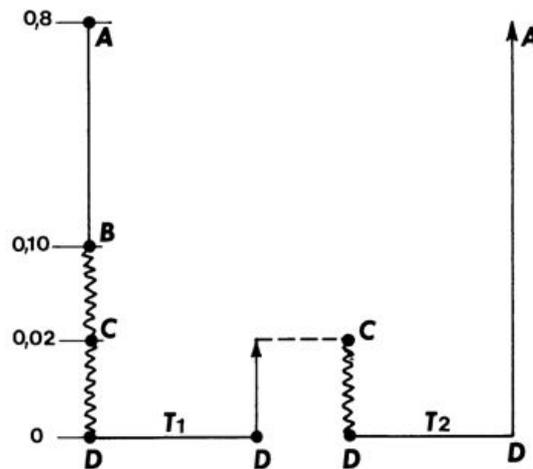
Sometimes it can be advisable to perform the last pass idle, i.e. without feed. This generates a smoother surface, but if cooling is not effective, there are risks of sticking.

A thoroughly different picture has to be drawn for the plunge shaving.

Plunge shaving technique has developed thanks to the NC shaving machines, which allow practically any choice, with no limits, of the reciprocal movements between cutter and workpiece.

This possibility is fully exploited in the special feed cycle usually considered for plunge shaving.

If you consider a typical gear module  $2 \div 2.5$  mm, you can use the feed scheme indicated in figure N°8.



**Fig.N°8-** Feed scheme in case of plunge shaving

- Point A: Meshing size. (Center distance 0.8 mm bigger than the final one).
- Point B: Cutter/gear contact size. (Center distance 0.1 mm bigger than the final one).
- Point C: End of roughing size. (Center distance 0.02 mm bigger than the final one).
- Point D: Final center distance.
- From A to B: Fast feed 200 mm/min.
- From B to C: Roughing feed  $1.5 \div 2$  mm/min.
- From C to D: Finishing feed  $0.75 \div 1$  mm/min.
- $T_1$ : pause time ( $2 \div 5$  seconds) only with rotation and no feed.
- From D to C: fast return and rotation direction reversal.
- From C to D: Finishing feed  $0.75 \div 1$  mm/min.
- $T_2$ : pause time slightly longer than  $T_1$ .
- From D to A fast return to initial meshing size.

You can note that, first of all, the stroke is quite short and that shaving times are extremely reduced. The mere working time, considering the pauses, is approx. 12 seconds, more or less 4 times smaller than the other shaving methods. Of course this is the main reason for the success of this shaving system.

The second consideration is that you can rationalise the strokes, feeds and times in function of the results you want to obtain, also in relationship with the initial conditions of the gear.

It is important to specify that finishing feed must never be lower than 0.02 mm for modules  $m \leq 2$ , while for  $m \geq 2$  the bottom limit for feed is as many hundredths of mm as the value of the module. For instance, for a module 4, you must always keep to have this feed per revolution rate value lower than 0.04 mm.