Gear hobbing and MAAG gear cutting: a comparison of efficiency and quality

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Gear hobbing or MAAG cutting? The choice between the two processes is governed on the one hand by requirements arising from the workpiece (design features, accuracy) and on the other hand by the field of application, namely whether it involves small batch or one-off production, such as in the building of industrial plants, or mass production. While gear hobbing is indispensable in such fields as the automotive industry, the cost effectiveness of the universal MAAG cutting process for small batch production and the production of accurate gears is indisputable.
In recent years, MAAG cutting has become ever more widely accepted due to its greater cost effectiveness, particularly for the cutting of coarse pitch gears.

Some factors concerning the cost effectiveness and accuracy of the two processes, which frequently do not receive adequate consideration, will be examined more closely here.

Rate of stock removal

Gear hobbing is the most widely practised gear cutting process. The impression is therefore current that it is also fundamentally the most productive process. At first sight it does seem that due to its rotating tool, it must generally result in a higher rate of stock removal than MAAG cutting with its reciprocating movement.

In reality this only applies to gears of fine to medium pitch. Reference should be made in this respect to the paper by P. Bloch entitled "Analysis of gear cutting, performance of hobbing, gear shaping, MAAG cutting and milling".

The low rate of stock removal of gear hobbing compared with MAAG cutting on medium to coarse pitch gears is due to the tooling.

From the formula for calculating the gear hobbing time it is apparent that the rate of stock removal is determined by the cutting speed v, the hob diameter d_o, the axial feed s_x and the number of hob starts z_o:

$$t_H = (E + b + A) \cdot \frac{z \cdot \pi \cdot d_o}{z_o \cdot s_x \cdot v}$$

Where:

t_H = hobbing time

E = hob approach

b = workpiece face width

A = hob overtravel

z = number of teeth on workpiece

d_o = hob diameter

z_o = number of hob starts

s_x = axial feed

v = cutting speed

From this relationship it follows that the hobbing time increases as the hob diameter increases. The axial approach is also larger with large diameter hobs.

Where hobbing time is concerned therefore, the hob should have the smallest possible diameter (Fig. 1).

As the size of the teeth increases however, the hob diameter has to be larger for design reasons, so that the speed of rotation of hob and workpiece have to be reduced for a given cutting speed. With hobbing the pitch however has a quite appreciable effect on the cutting speed and the feed, as the specific cutting force increases with the size of the hob teeth. Both the cutting speed and the feed have to be reduced with increasing pitch, as can be seen in Figs. 2 and 3.

These graphs only represent guide lines, but the trends are clearly evident.

The rate of stock removal during gear hobbing compared with MAAG cutting is therefore necessarily reduced as the pitch increases.

By contrast, the cutting speed during the MAAG cutting process is not subject to any greater limitations for large pitches than for small pitches. With MAAG cutting the roughing and finishing times are primarily determined by the workpiece, the quality required and the machine's capabilities, but not by the tool dimensions.

The cutting time for MAAG cutting is calculated as follows:

$$t_G = (Z_e + z) \cdot \frac{s_p}{n} + z \cdot t_{ind}$$

Where:

t_G = generating time for MAAG cutting process

Z_e = number of pitches for cutter engagement

z = number of teeth on workpiece

s_p = number of strokes per pitch
(depends on pitch, machineability of material and number of teeth on workpiece)

n = number of strokes per minute
(depends on workpiece face width, helix angle, cutting speed and return speed)

t_{ind} = indexing time per tooth

As the distance required for engagement of the rack type cutter for coarse pitches is not significantly greater than for fine pitches, the ratio between cutting and non-cutting time is likely to improve in the case of large pitch gears, which also usually have a greater face width.

Although a hob rotates at uniform speed, its cutting action is not continuous, so that the cutting force also varies. With MAAG cutting by contrast, there is an uninterrupted cut during the working stroke, while the return stroke of the cutter on the modern MAAG machines takes place at increased speed.

The particularly rigid mounting of the rack type cutter and the short leverage between tool cutting edge and mounting also enable appreciably heavier cuts to be made than with a hob.

The following detailed time studies based on a practical example illustrate the cost effectiveness of the MAAG cutting process.

Production time comparison:

Workpiece data:

Module	25 mm
Number of teeth	150
Pressure angle	20^{o}
Tooth depth	2.25 module
Helix angle	0^{o}
Face width	600 mm
Material	cast steel, 700 N/mm^2 tensile strength
Grade	DIN 7

1) Machining data for MAAG SH-450/500 S cutting machine

Machining data	Plunge feed roughing	Roughing by generation 1st cut	Roughing by generation 2nd cut	Finishing by generation 1st cut	Finishing by generation 2nd cut
Cutter	stepped rack	rack type		rack type	
Cutter teeth z_o	3	3		3	
Ram stroke	630 mm	630 mm	630 mm	630 mm	630 mm
Plunge feed	0.25 mm	---	---	---	---
Strokes/pitch	88	36	20	30	18
Cutting speed	13 m/min	20 m/min	26/min	24/min	24/min
Strokes/min	14	18	21	20	20
Indexing time	0.26 min	0.25 min	0.25 min	0.25 min	0.25 min
Time/pitch	6.53 min	2.25 min	1.21 min	1.75 min	1.15 min
Time/gear	990 min	360 min	185 min	270 min	175 min
	16.5 h	6 h	3.1 h	4.5 h	2.9 h

Total MAAG cutting time per gear = 16.5+6+3.1+4.5+2.9h = 33 h
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The mode of operation of the stepped rack type cutter will be explained briefly, as it cannot be assumed that it is generally known. (See Fig. 4). This type of cutter is used for the initial roughing out of the tooth spaces by incremental radial infeed of the tool. An infeed takes place during each return stroke of the ram. The workpiece is indexed through one pitch when the full tooth depth is reached. As the stepped rack type cutter usually has straight flanks (or flanks with firtree profile), the involute profile has to be produced after the initial roughing by generation during one or several workpiece revolutions. The stepped cutter usually has 3 teeth with the tooth first engaging with the workpiece having a maximum root thickness and a minimum depth and

with the subsequent teeth having a somewhat smaller root thickness and a greater depth than the preceding tooth. The last tooth of the cutter entering into engagement therefore has the smallest root thickness and the maximum depth.
The total stock removal is therefore distributed substantially uniformly over the 3 cutter teeth with this arrangement. This shortens the individual effective cutting edges, particularly for large tooth depths, which is of advantage in the cutting process.

2) Machining data for pure hobbing on a modern, heavy duty hobbing machine.

Hobbing with 310 mm diameter heavy duty roughing hob:

$$\text{Roughing time } t_{H_V} = E + b + A \; \frac{z \cdot \pi \cdot d_o}{z_o \cdot s_x \cdot v}$$

$$= 120+600+20 \; \frac{150 \cdot \pi \cdot 310}{1 \cdot 2.5 \cdot 23\,000} = 1879 \text{ min} \approx \underline{\underline{31.3 \text{ h}}}$$

Finish hobbing with 12 gash, 320 mm diameter heavy duty inserted blade hob:

$$\text{Finishing time } t_{H_S} = 45+600+20 \; \frac{150 \cdot \pi \cdot 320}{1 \cdot 1.6 \cdot 32000} = 1957 \text{ min} = \underline{\underline{32.6 \text{ h}}}$$

Total machining time for roughing and finishing by hobbing =
$31.3 + 32.6 = \underline{\underline{63.9 \text{ h}}}$

3) Machining data for roughing with carbide type milling cutter with tooth-by-tooth indexing and finishing by hobbing on a modern, high productivity gear hobbing machine

Roughing with 400 mm diameter milling cutter (cutting speed 200 m/min):

$$\text{Roughing time: } t_M = \left(\frac{E + B + A}{s_M} + \frac{E + b + A}{s_R} = t_{ind}\right) \cdot Z$$

$$= \left(\frac{150+600+10}{300} + \frac{150+600+10}{500} + 0.5\right).150 = 683 \text{ min} \approx 11.4 \text{ h}$$

Where

E = milling cutter approach

b = workpiece face width

A = milling cutter overtravel

S_M = working feed

S_R = return speed

t_{ind} = indexing time

Z = number of teeth on workpiece

Finishing time t_{H_S} = 32.6 h (see 2)

Total machining time for roughing by milling and finishing by hobbing 11.4 + 32.6 = 44 h
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Summary of machining times for the three processes

MAAG cutting	time h	Hobbing	time h	Milling/hobbing	time h
Plunge feed roughing with HSS stepped rack type cutter	16.5	Roughing with HSS heavy duty hob	31.3	Roughing with carbide tipped milling cutter	11.4
Roughing by generation with HSS stepped rack type cutter	9.1				
Finishing by generation with HSS rack type cutter	7.4	Finishing with HSS inserted blade hob	32.6	Finishing with HSS inserted blade hob	32.6
Total machining time	33 ==	Total machining time	63.9 =====	Total machining time	44 ==

Tooling costs

An appreciable advantage of the MAAG cutting process is the comparatively low initial and maintenance costs of the tooling, which are a particularly weighty consideration in the case of coarse pitches and/or special tool profiles (e.g. for tip relief, tip chamfering, protuberance tool profiles, etc.)

The same rack type cutter is used for cutting both spur and right and left hand helical gears, irrespective of the helix angle and the number of teeth on the workpiece.

When hobbing gears with large helix angles by contrast, it is necessary to cut right hand helixes with right hand hobs and left hand helixes with left hand hobs. When hob and workpiece are of the same hand, the component of the main cutting force tangential to the circumference of the workpiece always acts in the direction opposite to the workpiece rotation. This ensures that the main cutting force keeps the index worm wheel in contact with the index worm. If hobbing is carried out with a hob and workpiece of opposite hands, then the component of the main cutting force tangential to the circumference of the workpiece acts in the same direction as the workpiece rotation. There is therefore the risk that the index worm gear is relieved from the index worm, which usually results in major errors on the gear (Fig. 5).

The use of the hobbing process therefore imposes limitations on the gear designer in respect of the gear dimensions due to the high initial cost of hobs. Instead of being able to design a gear offering the optimum solution to a problem, the designer is forced to make use of existing hobs.

Each time the tool cutting edges start a cut they are subjected to exceptionally high loads and as the MAAG cutting tool only enters and leaves the workpiece once every working stroke in contrast to hobbing, the interval between regrinds and the service life of rack type cutters are long and the regrinding costs low.

The use of a backing plate also permits maximum utilization of the rack type cutter, as the cutter can be reground until it is only a few millimeters thick (Fig. 6).

To illustrate the ratio between hobbing and MAAG cutting tooling costs, figures currently* applicable in Switzerland to the production example under discussion are given here.

* 1980

Tooling cost comparison:

Gear data:

Module	25 mm
Pressure angle	20^{0}
Tooth depth	2.25 module
Helix angle	0^{0}
Grade	DIN 7

1) MAAG cutting

Initial tooling cost:

3 plunge cut stepped roughing cutters m 25, $Z_o = 3$	@ SFr. 1,100.00	SFr. 3,300.00
3 generating roughing cutters m 25, $Z_o = 3$	@ SFr. 640	SFr. 1,920.00
3 generating finishing cutters m 25, $Z_o = 3$	@ SFr. 680	SFr. 2,040.00
Total initial tooling costs		SFr. 7,260.00

Utilizable thickness of the rack type cutters:

- plunge cut stepped cutter m 25 22 mm
- generating roughing cutter m 25 18 mm
- generating finishing cutter m 25 18 mm

Tool wear per gear:

- plunge cut stepped cutter: 4 regrinds of 0.5 mm each=2 mm
- generating roughing cutter: 2 regrinds of 0.4 mm each=0.8 mm
- generating finishing cutter: 2 regrinds of 0.3 mm each=0.6 mm

Tooling costs per gear:

- tooling costs for roughing with plunge cut stepped cutter: SFr. 1,100.00: 22 mm x 2 mm = SFr. 100.00
- tooling costs for generating roughing cuts with rack type cutters: SFr. 640.00: 18 mm x 0.8 mm = SFr. 28.45
- tooling costs for generating finishing cut with rack type cutters: SFr. 680.00: 18 mm x 0.6 mm = SFr. 22.70

Total tooling costs per gear for MAAG cutting: SFr. 151.15

2) Milling/hobbing

Initial tooling costs:

3 milling cutters tipped with carbide indexable inserts (cost of one set of inserts: SFr. 750.00) @ SFr. 5,100.00 — SFr. 15,300.00

3 heavy duty, 320 mm dia. inserted blade hobs, number of gashes = 12, grade "AA" @ SFr. 19,500.00 — SFr. 58,500.00

Total initial tooling costs SFr. 73,800.00

Tool life

- Life of carbide indexable insert for milling cutter totals 120 m

  Life of finishing hob 1,300 m

Tooling costs per gear:

- Total length of teeth on gear = z x b = 150 x 600 = = 90,000 mm = 90 m
- Tooling costs for initial roughing with milling cutters: SFr. 750: 120 m x 90 m = SFr. 562.50
- Tooling costs for finishing with hob: SFr. 19,500 x 1,300 m x 90 m = SFr. 1,350.00

Total tooling costs per gear for milling/hobbing = SFr. 1,912.50

This results in the following ratios of tooling costs for the production of this workpiece:

Initial tooling costs:	MAAG cutting relative to milling/hobbing	1 : 10
Tooling costs per gear:	MAAG cutting relative to milling/hobbing	1 : 12

The regrinding costs were not taken into consideration in this comparison, as they would hardly change the picture.

The calculation of tooling costs for pure hobbing (roughing as well as finishing by hobbing) has been omitted, as due to the appreciably lower rate of stock removal this process is hardly of interest for this example.

This comparison of tooling costs is based on tooling prices ruling in Switzerland in 1980.

Quality

The accuracy obtainable on MAAG cutting machines with standard MAAG rack type finishing cutters is shown in Fig. 7. During hobbing, tool wear and machine deformation and distortion (e.g. due to heat) only have an effect along the face width but not along the circumference of the gear. The pitch variation (adjacent pitch error) and the index variation (cumulative pitch error) obtained on first class gear hobbing machines are therefore of the same order, or even somewhat less for large diameter gears than those obtained on MAAG cutting machines. By contrast, the accuracy of tooth alignment guaranteed on MAAG cutting machines for wide gears can only be obtained with hobbing in air conditioned workshops. The tooth alignment is practically unaffected by tool wear and temperature variations during the MAAG cutting process. The effect of temperature differences is shown in Fig. 8.

Temperature variations therefore cause tooth alignment errors during hobbing and pitch errors during MAAG cutting.

As shown in Fig. 8, under identical conditions, i.e. with the same temperature variations, machines of the same size and the same finishing time, a MAAG cutting machine would produce a pitch error between the first and the last tooth of exactly the same magnitude as the tooth alignment error produced on a hobbing machine.

In practice, the pitch error produced on the MAAG cutting machine will be smaller, as the finishing time for MAAG cutting is always appreciably shorter than that for hobbing.

In the example cited, the final finishing operation takes only 2.9 hours for MAAG cutting, while it takes 32.6 hours for hobbing. Temperature variations, which can be caused by external factors during a period of 2.9 hours, are usually less of a problem than those which can occur in a period of 32.6 hours. For this reason it is frequently possible to operate even large MAAG cutting machines in workshops without air conditioning.

Tooling considerations limit the tooth profile accuracy attainable by the hobbing process. The base pitch error F_e of the hob has a decisive effect in this respect, as it reflects all individual errors of the hob teeth. The entire extent of the base pitch error F_e is transformed into a tooth profile error.

The base pitch error F_e, as well as the permissible individual errors are specified for various grades of hobs in DIN 3968.

If the permissible base pitch error F_e for top grade AA hobs is compared with the permissible tooth profile error for spur gears to DIN 3962, it is found that the hob base pitch tolerance and the permissible profile error for grade 6 spur gears (Fig. 9) are roughly the same. The inaccuracies of the machine, the errors of mounting the hob and the workpiece, the wear of the hob cutting edges as well as the deviation from the true involute of the enveloping cuts however have to be taken into consideration as further possible causes of profile errors.

The result is that a better tooth profile accuracy than grade DIN 7 can hardly be expected, even when using grade AA hobs.

An appreciable factor in the tooth profile accuracy of coarse pitch gears with small numbers of teeth is the number of enveloping cuts available for generating the tooth profile (Fig. 10). With hobbing, this depends on the number of gashes on the hob and the number of teeth on the work-piece.

The larger the number of gashes, the larger will be the series of tangential cuts and therefore the better the approximation to the ideal involute. The hob outer diameter however necessarily increases as the number of gashes is increased, on the assumption that the length of the tooth does not drop below the economic limit which allows a sufficient number of regrinds.

In this respect limits are set on the one hand by the machine dimensions (hob center distance and torque) and on the other hand by the demand for short hobbing times. Hobs in the 12 to 30 mm module region are therefore designed with only 8 to 14 gashes. Hob design considerations therefore conflict with product requirements. While coarse pitches necessitate a greater number of enveloping cuts for the precise generation of the tooth profile, the number of hob gashes actually has to be reduced.

With the MAAG cutting process the tool does not impose such limitations. The number of enveloping cuts for generating the profile can be chosen freely.

The index worm gear of MAAG cutting machines is only loaded lightly. It only has to move and position the workpiece. The rotary table is stationary during the working stroke and the generating motion only takes place during the return stroke. The generating mechanism is not affected by the cutting force and is therefore only subject to slight wear, so that the working accuracy of the machine is maintained for a very long time. By contrast, the index worm gear on a hobbing machine is subjected to the intermittent cutting force as it runs.

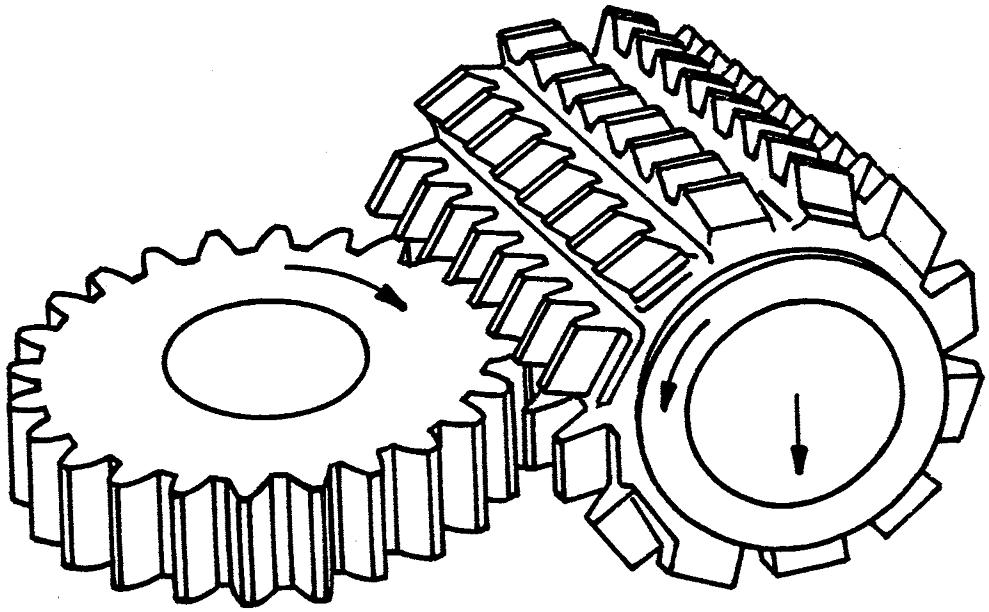
While the index worm gear during the MAAG cutting process only rotates once for each operation, the number of revolutions per hobbing operation is determined by the relationship between hob travel and the axial feed per revolution of the workpiece.

Note

Hobbing with carbide hobs was not taken into consideration. The first attempt to use carbide hobs (2 to 3 mm module) was made in the automotive industry about 12 years ago. Numerous experiments however did not produce successful results.

The relatively low ductility of carbide resulted in chipping and cracking of the hob. Coolant could not be used because of the quenching action. Chip removal from the cutting zone was therefore not ensured. Trapped chips resulted in chipping of the tool cutting edges. The severe heating of the workpieces made tooth alignment errors inevitable. A newly developed carbide indexable insert hob was introduced recently, which is primarily intended for roughing gears in the 8 to 20 mm module range. The initial cost of this hob is about 3 times as much as that of a heavy duty roughing hob of similar size. Experience under workshop conditions is not available yet.

Further appreciable savings in tooling costs with the MAAG cutting process can be expected confidently from extensive experiments with titanium nitride coated, high speed steel rack type cutters.



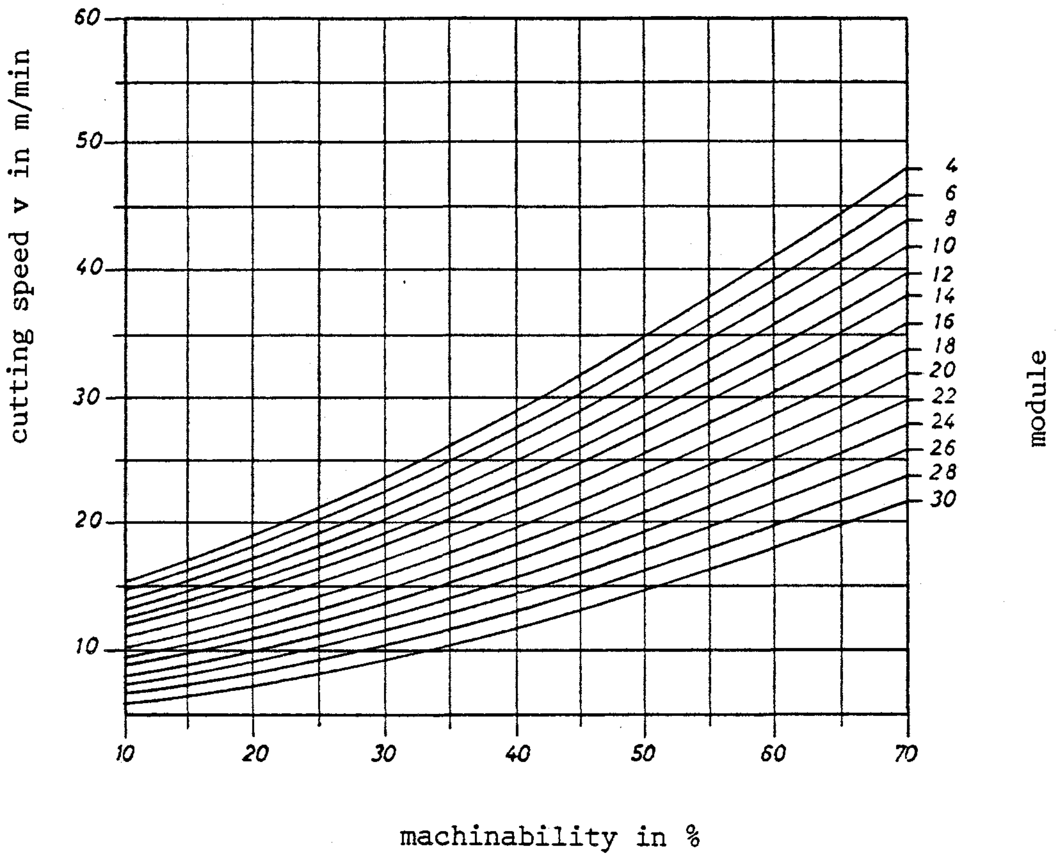
$$n_o = \frac{v}{d_o \cdot \pi}$$

n_o = Hob rpm

v = Cutting speed

d_o = Hob diameter

FIG. 1: Influence of hob diameter on hobbing time



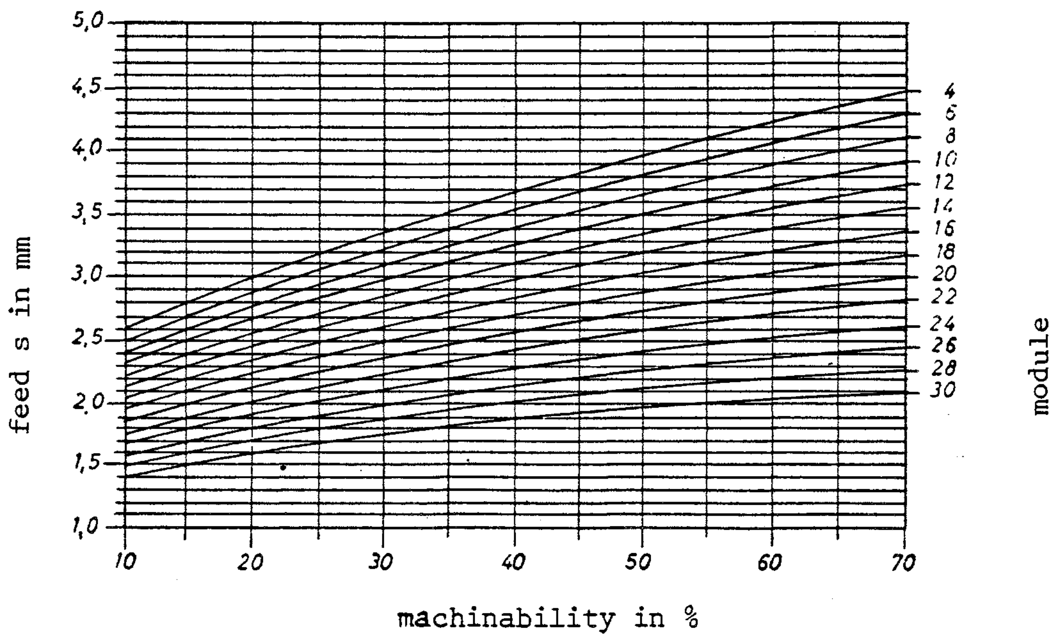


FIG. 2: Cutting speed and feed for roughing hobs

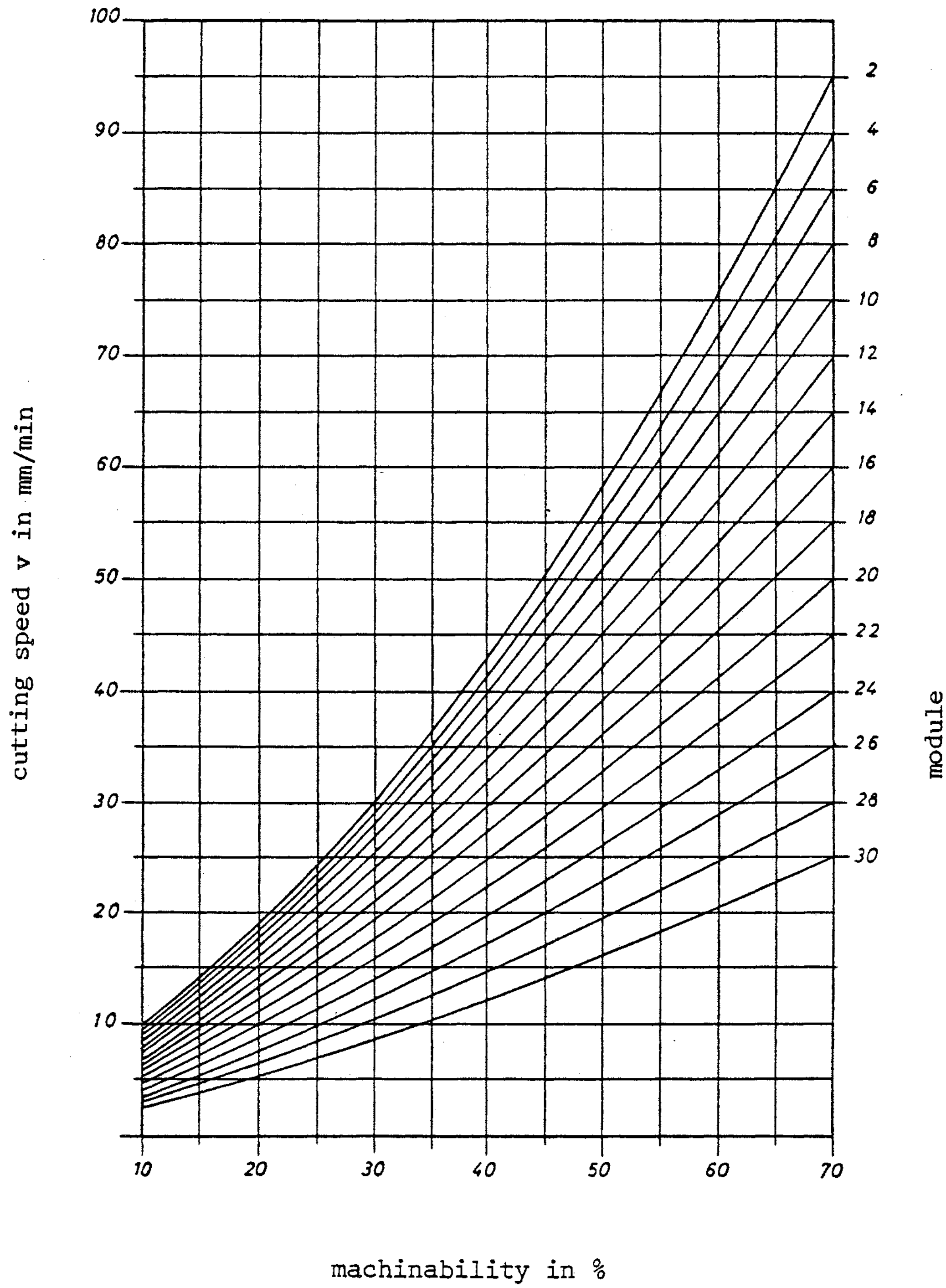


FIG. 3: Cutting speed for finishing with hobs with inserted tooth

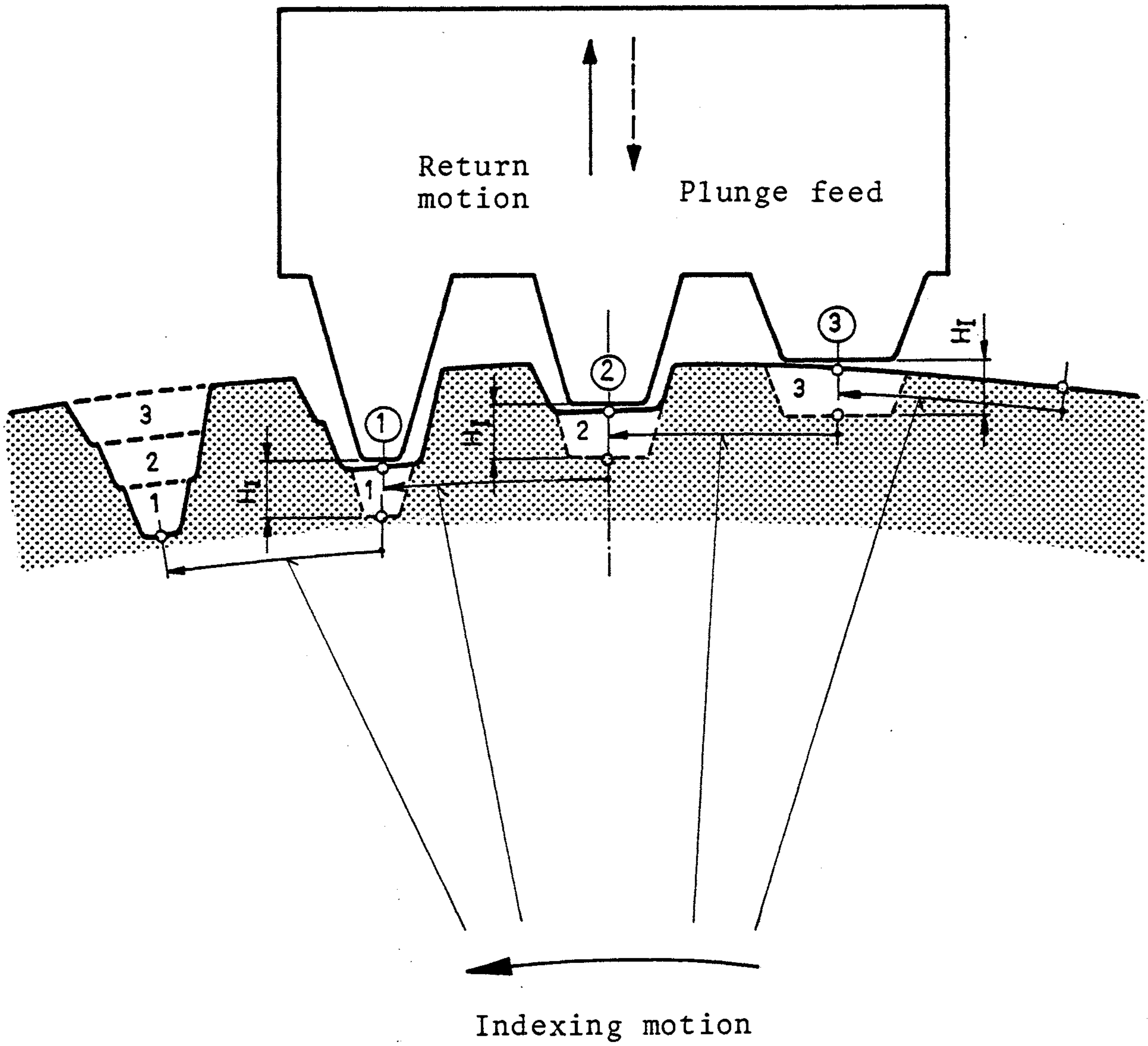


FIG. 4: Method of operation of the MAAG stepped rack type cutter

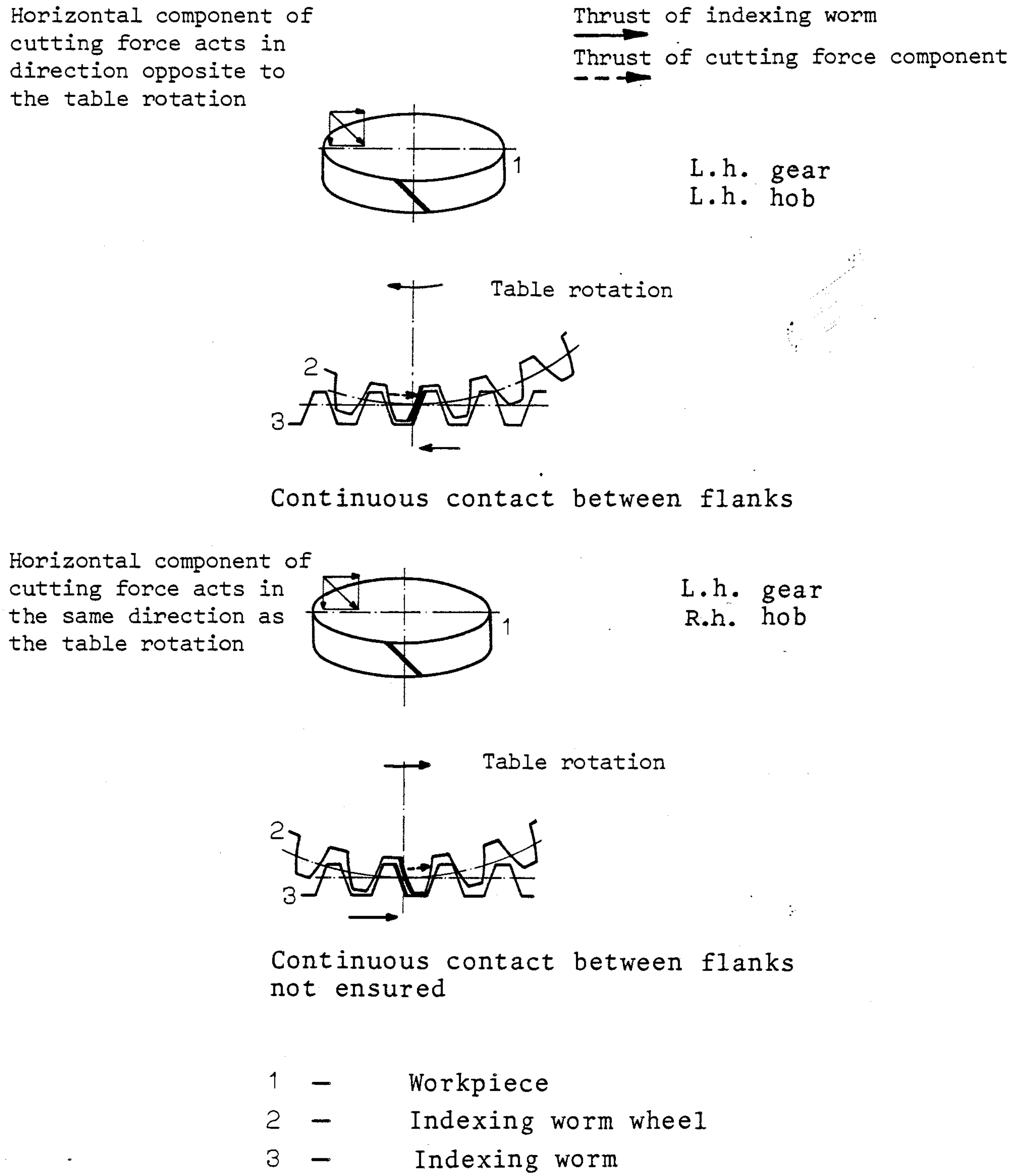


FIG. 5: Effect of the hand of the hob on the accuracy of hobbed helical gears

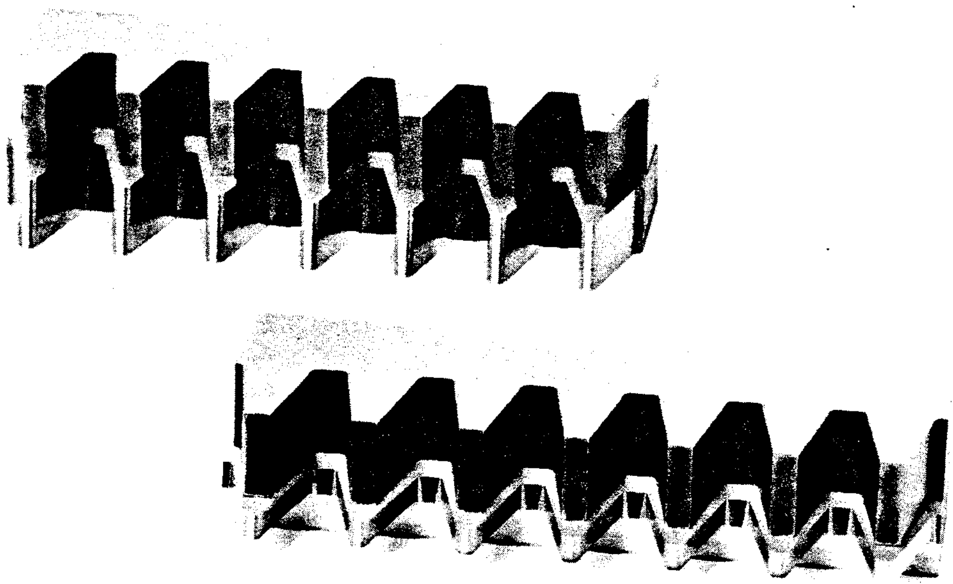


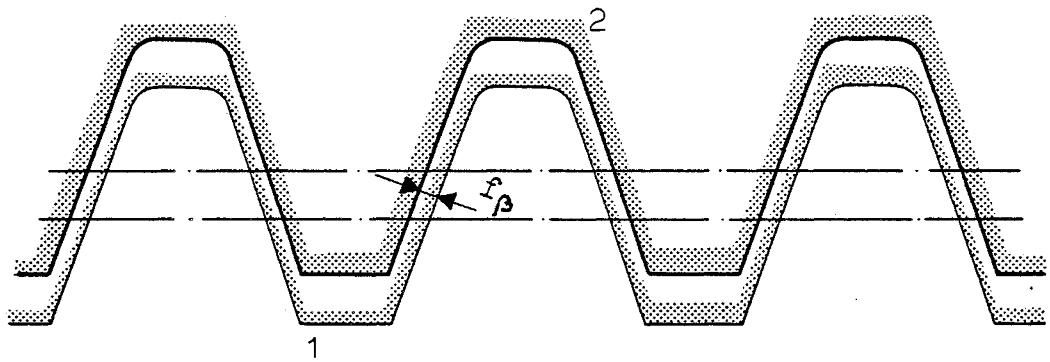
FIG. 6: A new and a multiple reground MAAG rack type cutter

Average working accuracy of MAAG cutting machines when using MAAG rack type finishing cutters to DIN 3962 (1978).

Error	Grade of gear
Total tooth profile error F_f	5
Pitch variation (adjacent pitch error f_p)	5
Tooth-to-tooth spacing variation (difference between adjacent pitches) f_u	5
Total index variation (max. cumulative pitch error) F_p	5
Total tooth alignment error F	5

Fig. 7: Working accuracies of MAAG cutting machines

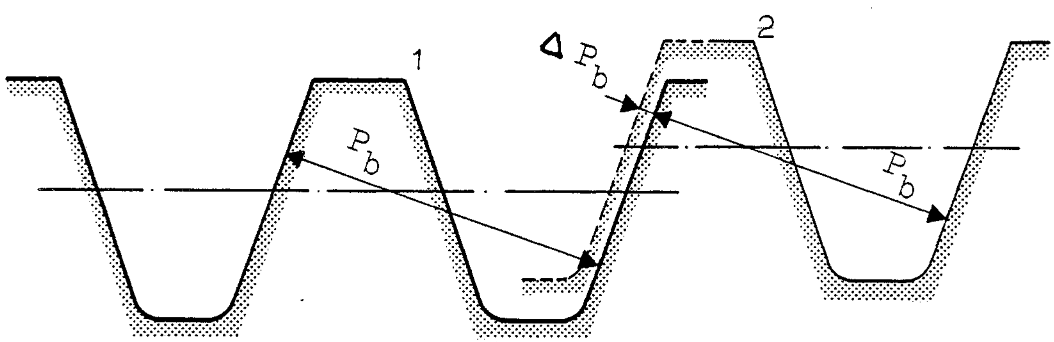
Hobbing:



1: Workpiece hot
2: Workpiece cold

f_β : tooth alignment error

Planing:



p_b: Base pitch
Δp_b: Base pitch error

FIG. 8: Effect of temperature differences on gear tooth accuracy

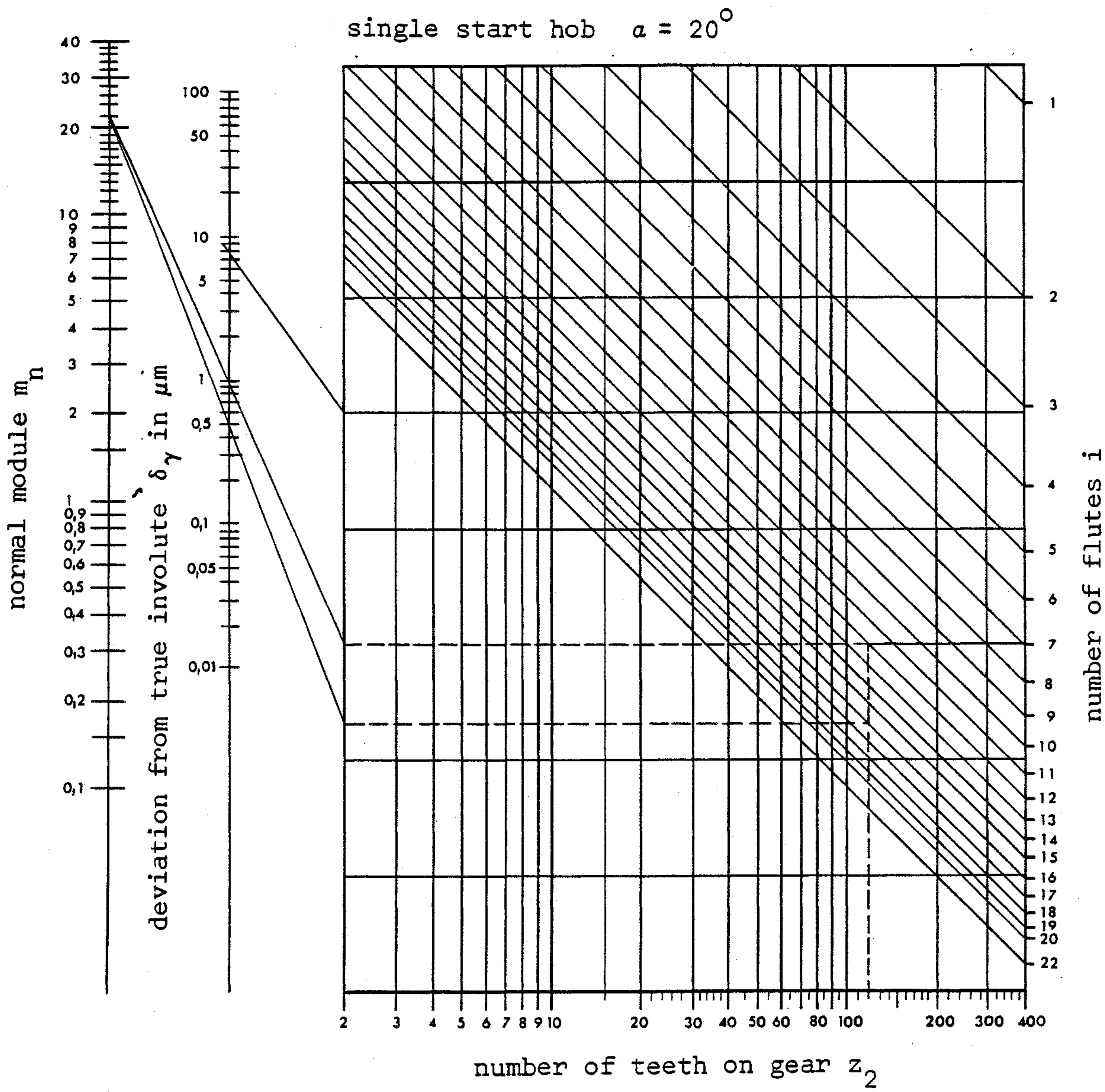
Tolerances for a single start hob for
involute spur gears to DIN 3962.

Error	Grade of hob	Tolerances in µm (=0.001 mm) for modules						
		1.5	3	5	8	>10-16	>16-25	>25-40
Base-pitch error F_e	AA	8	10	12	16	20	25	32
	A	14	18	20	25	32	40	50
	B	28	36	40	50	63	80	100

Tolerances for spur gears
to DIN 3962 (1978)

Error	Grade of gear	Tolerances in µm (=0.001 mm) for modules						
		1.5	3	5	8	>10-16	>16-25	>25-40
Total tooth profile error F_f	6	8	10	12	16	22	28	36
	7	12	14	18	22	28	40	56
	8	16	20	25	32	40	56	71

Fig. 9: Comparison of permissible base pitch error F_e of hobs with the permissible total profile error F_f for various grades of hobs and gears.



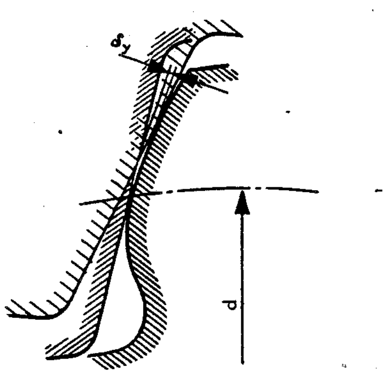


FIG. 10: Deviation of enveloping cuts from true involute in gear hobbing