Grinding Shaving Cutters and Rolling Dies by CBN Wheels

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1. Introduction

Shaving cutters and rolling dies are tools used primarily for finishing operations on automotive gears. An example of a shaving cutter used for finishing a gear for a truck transmission is shown in Fig. 1.

Tool steel or high speed steel shaving cutters and rolling dies have to be reground periodically throughout their working life.

The MAAG SD-36X gear grinding machine is particularly suitable for such regrinding operations because of the consistent accuracy of the tooth form produced by it. This machine and its essentially similar predecessors, the types HSS-30BC and SD-32X, are therefore used for this purpose by many companies.

The recent advent of cubic boron nitride (CBN or Borazon) grinding wheels has added a further significant advantage as the regrinding time compared with grinding with conventional carborundum or aluminium oxide wheels can be reduced appreciably. As shown by the nomogram in Fig. 2, the average cost saving exceeds 40 %.

The type of grinding wheels employed on the MAAG gear grinding machines lend themselves particularly to the use of CBN, as these wheels do not have to be profiled specially and only have to be provided with a thin and not very costly CBN layer.

2. Cubic crystalline boron nitride - a cost effective abrasive

Although the regrinding of shaving cutters by conventional grinding wheels is a well proven and widespread practice, it is intended to discuss here principally grinding with cubic crystalline boron nitride (CBN), which offers new and further advantages. This abrasive, also known under the name of Borazon, nowadays fulfils a quite generally important function in the grinding of hard and difficult to grind steels. Above all, it offers a very cost effective way of regrinding tools reliably to the specified form.

As the initial cost of CBN wheels is higher than that of conventional aluminium oxide (AL_2O_3) or silicon carbide (SiC) wheels, it is frequently assumed wrongly that the use of CBN is only justified where the technical ob; cannot be achieved at all or only with difficulties conventional abrasives. Due to the long life of the CBN wheels, the grinding wheel costs per workpiece are however relatively low, despite the high initial cost. With the small amount of stock removal customary during the regrinding of tools, the grinding wheel costs are even lower than when using conventional wheels (Fig. 2).

3. The 0° pressure angle grinding principle

On the 0° machines, whose principle is illustrated in Fig. 3, the workpiece rolls on the base circle of the involute. The involute tooth profile is produced by grinding wheels mounted in a fixed position and set at 0° or inclined at a few degrees to the tooth flank. The helix angle is formed by a helical motion imparted to the workpiece by the machine, composed of the axial feed and a proportional roll motion. This principle has also been used for more than two decades for regrinding shaving cutters.

The new 0° - K grinding method has enabled productivity to be increased by a further 20 to 30 %. With this method the machine set-up is optimised so that the tooth flank and grinding wheel are in continuous constant contact during the generating process, so that there is no tip overrun at the end of the generating stroke (Fig. 4) and shorter generating strokes and therefore higher feed rates can be employed. There is also a slight variation in the angle of contact of the grinding wheel between the tip and the root of the tooth during grinding of the profile. More grinding wheel grains therefore participate in the stock removal, which in turn increases the rate of the stock removal still further.

4. The CBN dish grinding wheels used

The dish grinding wheels used on the gear grinding machines consist of a body to which a relatively small volume CBN layer has been bonded. A section through such a grinding wheel mounted on a special flange is shown in Fig. 5. The maximum possible thickness at the rim U depends on the tooth space and the tooth profile. Wheels with a U dimension of 2.5 mm can be chosen for coarse pitches and the back of the grinding wheel can be of conical form. For finer pitches the back of the grinding wheel has to be made concave to suit the shape of the tooth space. For very fine pitches wheels with rims only 0.4 mm thick are used.

Both experimental work and practical experience have shown that for medium pitches B 107 (140-170 mesh) and for fine pitches (2 mm module) B 91 (170-200 mesh) represent the most suitable grain size for the grinding method discussed. The corresponding guide lines for the structure number are C 50 - C 100.

The MAAG dish grinding wheels shown here are particularly suitable for CBN coating for the following reasons:

1. The shape of the tooth flanks produced on the workpiece is not effected by grinding wheel wear, as both the tooth profile and the helix are produced entirely by the relative motions of the parts of the machine. The CBN grinding wheel therefore only has to be trued very rarely and only then when the change in shape has become relatively great. The long life of the grinding wheel results in very low grinding wheel costs per workpiece, which are appreciably less than those for the amount of conventional grinding wheels consumed.

2. The geometrical contact between tooth flank and grinding wheel does not change during the life of the CBN wheel due to the only small change in its diameter. For this reason the machine setting data, including that for the tooth flank modifications, can be employed without alteration for subsequent repeat grinding operations.

3. A further advantage is that one and the same grinding wheel can be used for different gears, i.e. for various pitches, numbers of teeth, helix angles etc. This enables the gear grinding shop to manage with a minimum number of CBN grinding wheels.

4. The CBN layer bonded to the grinding wheel body only has a small volume, as it only has to provide a narrow active rim and the diameter of the grinding wheel is relatively small. This keeps the initial cost low in comparison with CBN wheels for other grinding processes.

5. The grinding process

Due to the fact that on the one hand CBN wheels grind cool and on the other hand that they are resistant to high temperatures, dry grinding is overall to be preferred to wet grinding. This is particularly the case as the regrinding of shaving cutters only involves very little stock removal. The 0^{o} grinding machines therefore operate without coolant.

The gear grinding machine shown in Fig. 6 is designed for workpieces ranging in diameter from 20 to 360 mm, modules from 1 to 12 mm, helix angles from 0 to 45^{o} and a maximum face width of 200 mm. The peripheral speed of the grinding wheels is about 22 m/s. This machine can be used for grinding gears (with vitrified bond grinding wheels) or high speed steel tools such as shaving cutters and rolling dies (with CBN or vitrified bond wheels). The changeover from one to the other process takes no longer than one hour.

The advantages of grinding with boron nitride derive primarily from the fact that the CBN wheel in comparison to conventional grinding wheels grinds off a much greater percentage of the infeed in a given time, so that the contact force is diminished rapidly (Fig. 7). On the other hand, a somewhat greater surface roughness (arithmetic mean $R_a \approx 0.3 - 0.7\ \mu m$) must be accepted. This however is not generally detrimental, as the life of the ground tools is not reduced thereby and only about 15% of the increased roughness of the tool flank is transmitted to the rolled or shaved workpiece. For grinding to ISO grades 2 or 3, the machine settings fall into roughly the following ranges:

Generating strokes per minute (i.e. complete to and fro reciprocations):		
a) without or with slight profile modifications		200 to 250 strokes/min
b) with large profile modifications		100 to 200 strokes/min
Axial feed rate		
a) without or with only slight profile modifications	roughing 1.0 to 2.0	finishing 0.4 to 0.8 m/min
b) with pronounced profile modifications	roughing 0.5 to 1.0	finishing 0.2 to 0.4 m/min
Number of grinding operations for a stock removal of 30 to 50 μm		4 to 6 operations
Infeed per grinding operation		
All roughing operations except the last		25 μm max.
Last roughing operation		0 μm
Finishing operation		2 μm

The machine settings can be determined easily with the aid of a computer once the gear tooth data and the quality specification have been entered.

6. Concave tooth flank modifications on shaving cutters and rolling dies

The tooth flanks of heavily loaded gears are usually modified by tip and root relief and crowning, so that shock free transmission and satisfactory load distribution are ensured.

As these modifications have to be produced by the tooth flanks of the tool, both underpass shaving cutters and rolling dies have to have tooth flanks with correspondingly concave modifications. This is also called negative tip and root relief and reverse crowning. When grinding very pronounced concave modifications, the grinding wheels are not set tangential ($\gamma_s = 0^o$) to the tooth flanks but are inclined at a slight angle. The required angle of inclination γ_s is calculated from the form of the modification and the gear tooth data.

6.1 Concave profile modifications

With the normal 0^o setting the cutting plane formed by the grinding wheel rim is set tangential to the involute, which is governed by the machine setting (generating pitch diameter). A zone on the profile with a pronounced departure from the basic involute into the tooth space towards the tip would therefore be ground away again, as can be seen in Fig. 8a.

A guide line for the angle of inclination $\gamma_s = \gamma_{sh}$, to which the grinding wheel has to be set to enable the profile to be ground without interference, can be established as follows:

1. Determine the point P on the profile where $\Delta C/(\Delta L . L_p)$ reaches a maximum value. $\Delta C/\Delta L$ can be determined from the slope of the profile trace.

$$L_p = L_a - L_{AP} = \sqrt{r_p^2 - r_b^2}$$

2. $\tan \gamma_{sh} = \Delta C \cdot r_b/(\Delta L \cdot L_p)$

Example: $\Delta C/\Delta L = 0.017$ mm/4.5 mm;

$L_p = 27$ mm (roll distance up to point P); $r_b = 108$ mm (base circle radius); $\tan \gamma_{sh} = 0.0151$; $\gamma_{sh} = 0.866^o$.

As the curvature of the involute has not been taken into account in this calculation, the angle calculated incorporates some margin. This is also the reason why slight positive modifications to the involute profile towards the tip of the tooth can in certain circumstances also be produced without grinding wheel inclination, i.e. with $\gamma_s = 0$.

6.2 Concave longitudinal modifications

As illustrated in Fig. 9, marked reverse crowning can only be obtained with a slightly inclined grinding wheel whose projection onto the pitch plane results in a curved (elliptical) line. A guide line for the angle of inclination required can be calculated from the following formula:

$$\sin \gamma_{sb} = C_b \cdot 4d_s \cdot \cos \beta_b \cdot \cos^2 \beta / b^2$$

b = face width; β = helix angle; β_b = base helix angle; d_s = grinding wheel diameter.

Example: $C_b = 0.020$ mm, $d_s = 220$ mm, $b = 27$ mm and $\beta = 0$. From this $\sin \gamma_{sb} = 0.241$ and $\gamma_{sb} = 1.38^\circ$.

This calculation does not take into account the additional reverse crowning which becomes possible due to the effect of the curvature of the involute and the vertical projection of the curvature of the grinding wheel rim. The calculated value of γ_{sb} therefore incorporates some margin, which is technically desirable.

When both γ_{sh} and γ_{sb} inclinations are required, then the greater of the two values rounded up to the next highest machine setting should be used.

7. Dressing and truing of the CBN dish grinding wheels

The CBN crystals are much harder than aluminium oxide and silicon carbide and therefore have greater wear resistance. The grinding wheels used for the processes described here therefore have an outstandingly long life. They therefore do not have to be trued after every workpiece or even in between the individual operations as conventional grinding wheels. Usually 300 to 700 shaving cutters can be ground before the grinding wheels have to be trued again.

Special, vitrified bond aluminium oxide dressing sticks enable the outermost layer of the bonding agent between the CBN grains to be removed if the cutting action has deteriorated. For this purpose the dressing stick is pressed against the rotating grinding wheel (Fig. 10) until it has been ground away to a depth of several millimeters. This exposes active crystals to the required depth and clears any loading of the wheel. Experience shows that this dressing of the CBN cutting face should be repeated after regrinding 10 or 20 shaving cutters.

When finally - after grinding an average of 500 shaving cutters - the form of the grinding wheel no longer meets the requirements, the outer diameter of the grinding wheel can be ground back radially by about 0.5 mm. This is normally carried out on a cylindrical grinding machine using an extremely soft, resin bond silicon carbide wheel with grains of approx. 120 mesh and a relative peripheral speed of 6 to 8 m/s. Normally the outer diameter is ground back by about 1 mm by traverse grinding with small incremental infeeds of 5 to 10 μm. A pair of grinding wheels, which for example have a usable radial width of CBN of 10 mm is then capable of resharpening 20 x 500 = 10,000 shaving cutters.

8. Setting time, grinding time, grinding quality, cost

The time required for the initial setting up of the machine and the tooth flank modification for a new cutter, including intermediate workpiece checks and adjustments, etc. is about 1 to 3 hours. For repeat operations, when all settings are already established and the cam plates or data carriers for the modifications are available and have been proved, the setting time is reduced to about 30 minutes.

Grinding time

The grinding time for a shaving cutter of about 250 mm diameter is 0.5 to 1.5 hours, depending on whether the teeth are to be provided with a slight or marked profile modification and whether they are to be ground to an average or high standard of accuracy. An average grinding time of an hour can be assumed. The grinding time for rolling dies is about 50 % greater.

Grinding quality

The grinding quality is affected by the grinding time. In particular, the surface roughness can be reduced by using low roll and feed rates. The following degrees of accuracy are typical in conjunction with medium roll and feed rates: Profile, circular pitch and helix errors up to 3 μm; arithmetical mean roughness height R_a approx. 0.6 μm.

Cost

The experience of a leading European car manufacturer has shown that the method described here enables the total cost to be reduced by at least 30 % compared with the hitherto adopted process (using vitrified bond grinding wheels).

Despite the relatively high initial cost of the CBN wheels, the grinding wheel costs per shaving cutter or per shaved or rolled part are negligibly small. The reason for this lies in the very long life of the CBN wheels. A long term investigation showed that 860 shaving cutters could be ground without truing or changing of the grinding wheels.

The daily output of the SD-36X machine averaged 7 shaving cutters with 2 shift operation. Here it has to be taken into account that one operator can serve 2 to 3 machines simultaneously (multi-machine operation).

9. Production examples

Two actual examples are given below.

9.1 Shaving cutter, number of teeth 47, module 5.21 mm helix angle 12°, face width 45 mm

The machine setting data is shown in Fig. 11, while the profile, helix and surface roughness charts are shown in Figs. 12 and 13. The fact that the profile as well as the helix have concave modifications can be seen clearly. The angle of inclination of the grinding wheels set on the grinding machine was $\gamma_s = 3^\circ$.

The grinding allowance of 0.05 mm on the flanks was ground off in five roughing operations and one finishing operation, which required a grinding time of 54.5 min. The tooth form achieved was accurate to within $\pm$ 2 μm with a mean surface roughness R_a of approx. 0.4 μm (Fig. 13).

9.2 Rolling die, number of teeth 152, module 1.35 mm, helix angle 20°, face width 19 mm

The tooth profile charts for the above rolling die after grinding on the SD-36X machine using the topological modification equipment are shown in Fig. 14. From this can be seen that both the form and the slope of the tooth profile changes along the face width.

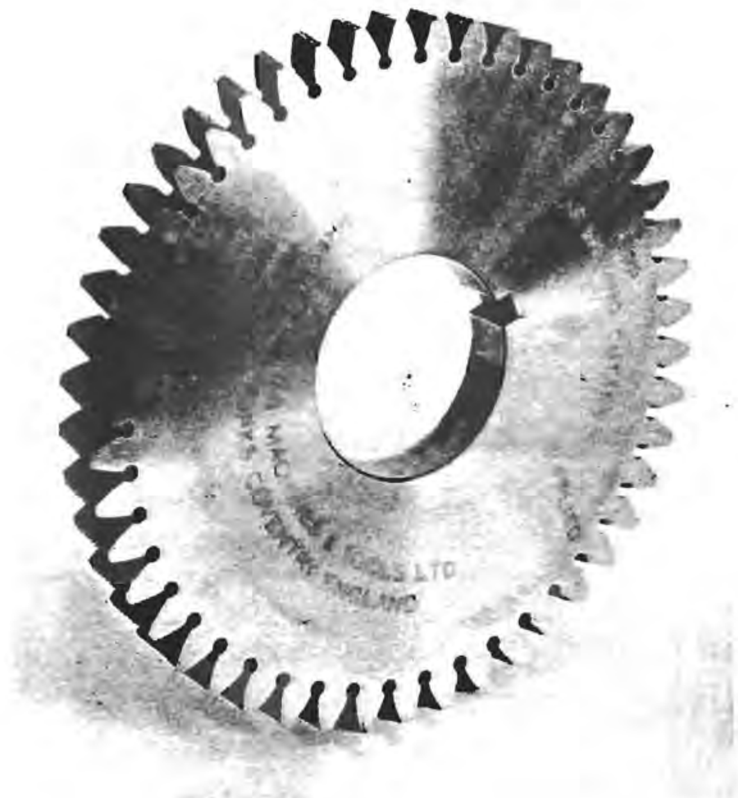
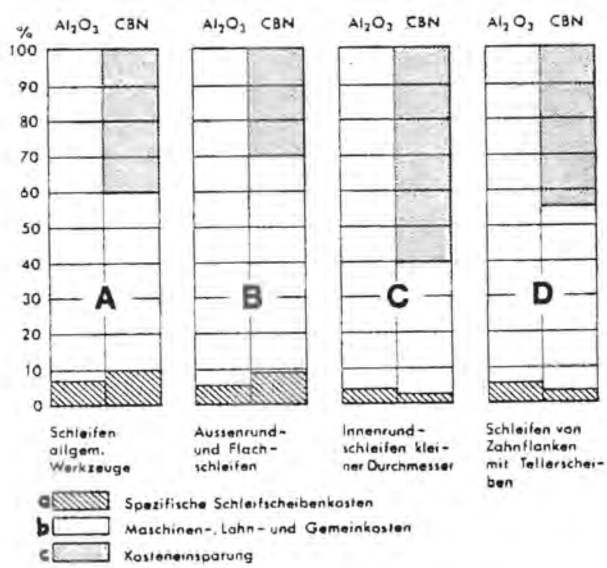


Fig. 1 Shaving cutter for finishing a gear for a truck transmission



a Specific grinding wheel costs

b Machine labour and overhead costs

c Cost saving

Fig. 2 Cost comparison between aluminium oxide and CBN grinding wheels for grinding high speed steel

A	B	C	D
General tool grinding	Cylindrical and surface grinding	Internal grinding of small	Grinding of tooth flanks with dish

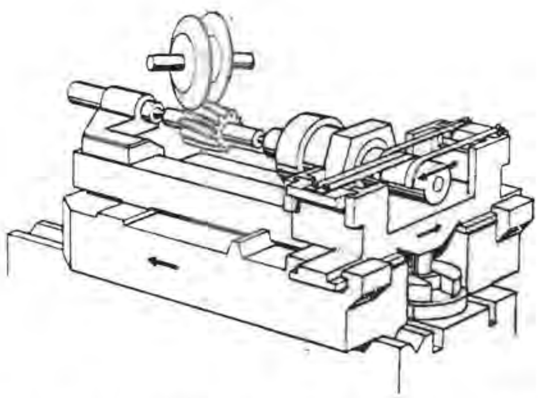


Fig. 3 Principle of MAAG 0^{o} grinding machines

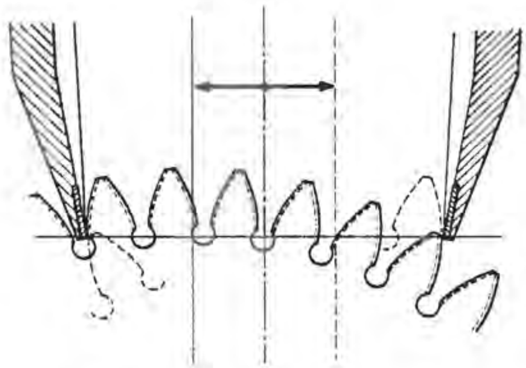


Fig. 4 0^{o}-K grinding method

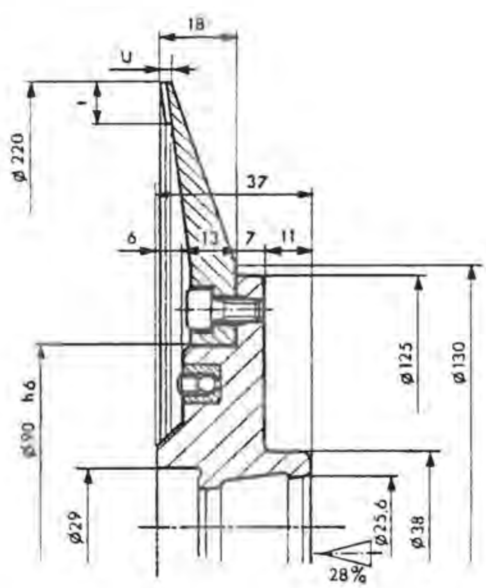


Fig. 5 Section through a CBN dish grinding wheel with flange

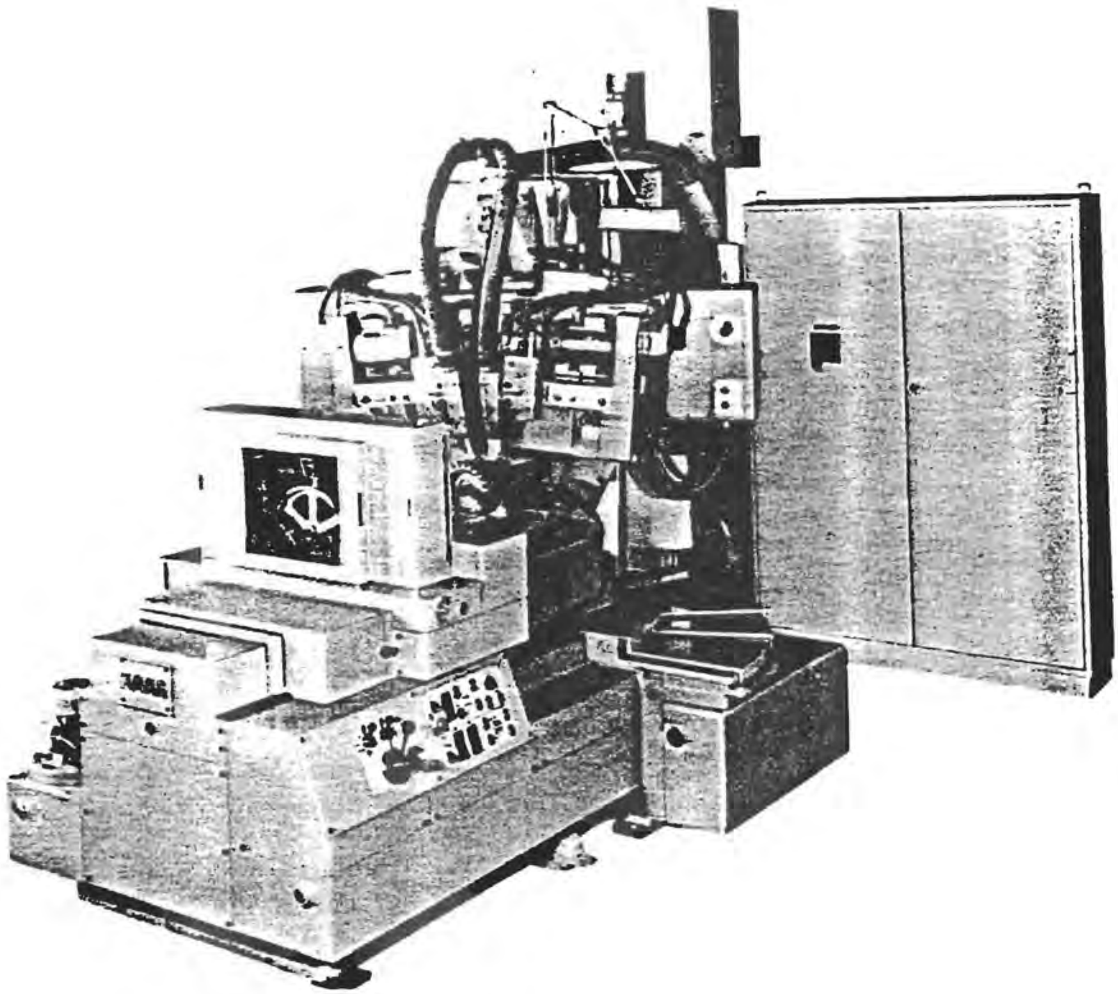


Fig. 6 MAAG SD-36X gear grinding machine

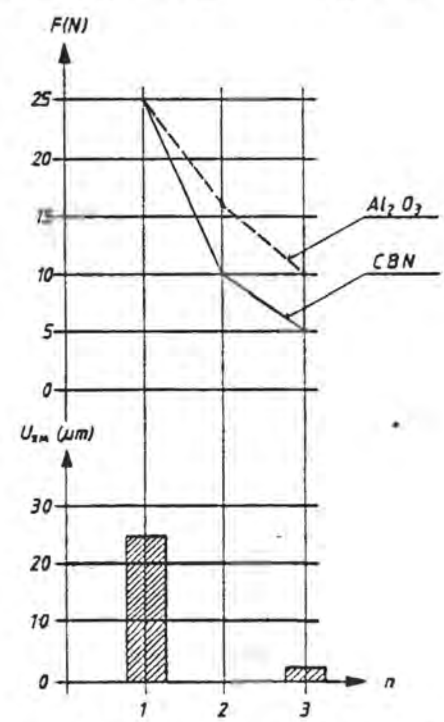


Fig. 7 Variation of grinding wheel contact force when grinding with aluminium oxide and CBN grinding

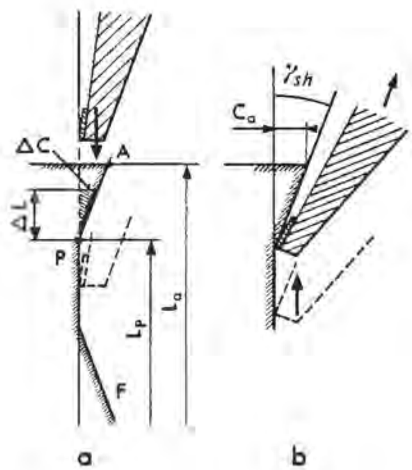


Fig. 8 Inclination of grinding wheels for the production of concave profile modifications

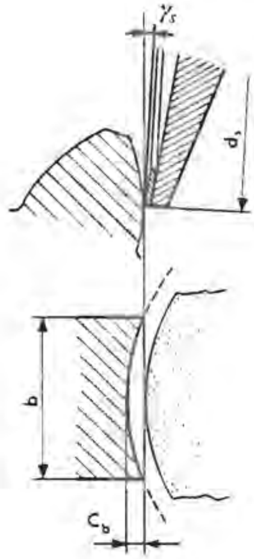


Fig. 9 Inclination of grinding wheel for the production longitudinal modifications

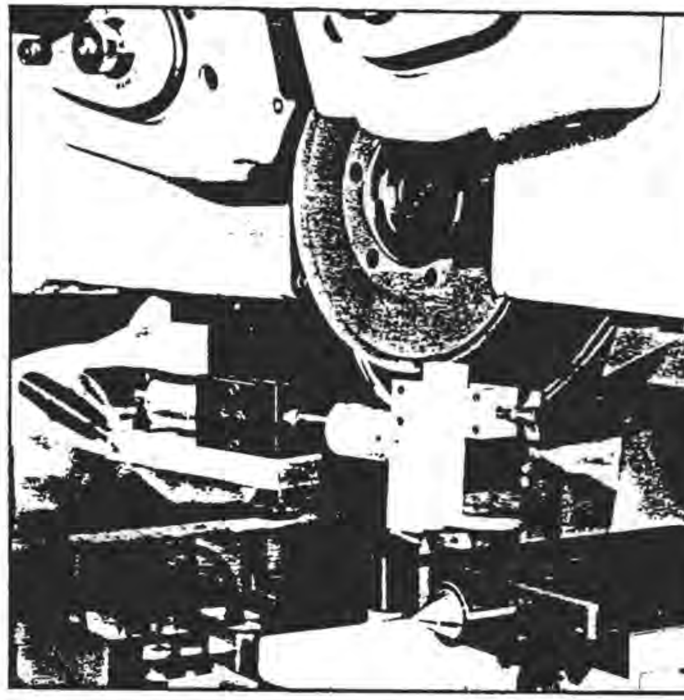
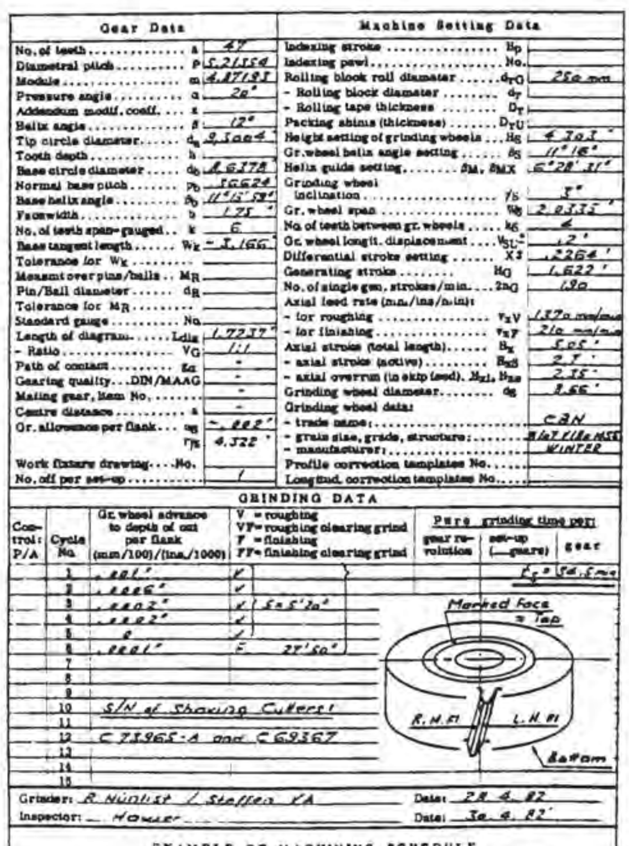


Fig. 10 Dressing of a CBN grinding wheel with dressing stick and special attachment



Gear Data		
No. of teeth	z	47
Diametral pitch	P	5.21554
Module	m	4.87193
Pressure angle	α	20°
Addendum modif. coeff.	x	
Helix angle	β	12°
Tip circle diameter	d_a	9.5004"
Tooth depth	h	
Base circle diameter	d_b	8.6378"
Normal base pitch	p_b	.56624"
Base helix angle	β_b	11°15'58"
Facewidth	b	1.75"
No. of teeth span-gauged	k	6
Base tangent length	W_k	3.166"
Tolerance for W_k		
Measmt over pins/balls	M_R	
Pin/Ball diameter	d_R	
Tolerance for M_R		
Standard gauge	No.	
Length of diagram	L_{dia}	1.7237"
- Ratio	V_G	1:1
Path of contact	g_α	-
Gearing quality ... DIN/MAAG		-
Mating gear, Item No.		-
Centre distance	a	-
Gr. allowance per flank	q_g	.002"
	r_{yt}	4.322"
Work fixture drawing ... No.		
No. off per set-up		1

Machine Setting Data		
Indexing stroke	H_p	
Indexing pawl	No.	
Rolling block roll diameter	d_{rO}	250 mm
- Rolling block diameter	d_r	
- Rolling tape thickness	D_T	
Packing shims (thickness)	D_{TU}	
Height setting of grinding wheels	H_S	4.303"
Gr. wheel helix angle setting	β_S	11°16'
Helix guide setting	β_M, β_{MX}	6°28'31"
Grinding wheel inclination	γ_S	3°
Gr. wheel span	W_S	2.0335"
No. of teeth between gr. wheels	k_S	4
Gr. wheel longit. displacement	V_{SL}	.2"
Differential stroke setting	X3	.2264"
Generating stroke	H_G	1.622"
No. of single gen. strokes/min.	$2n_G$	190
Axial feed rate (mm/ins/min):		
- for roughing	v_{xV}	1370 mm/min
- for finishing	v_{xF}	210 mm/min
Axial stroke (total length)	B_x	5.05"
- axial stroke (active)	B_{xB}	2.7"
- axial overrun (in skip feed)	M_{xL}, M_{xa}	2.35"
Grinding wheel diameter	d_S	8.66"
Grinding wheel data:		
- trade name:		CBN
- grain size, grade, structure:		B107 Y1Bo HSE
- manufacturer:		WINTER
Profile correction templates No.		
Longitud. correction templates No.		

GRINDING DATA

Control: P/A	Cycle No.	Gr. wheel advance to depth of cut per flank (mm/100)/(ins./1000)	V = roughing VF = roughing clearing grind F = finishing FF = finishing clearing grind		Pure grinding time per: gear revolution	set-up (— gears)	gear
	1	.001"	V			t_g =	54.5 min
	2	.0006"	V				
	3	.0002"	V	5×5'20"			
	4	.0002"	V				
	5	0	V				
	6	.0001"	F	27'50"			
	7						
	8						
	9						
	10	S/N of Shaving Cutters:					
	11						
	12	C 73965-A and C 69367					
	13						
	14						
	15						

Grinder: R. Hünlist / Steffen YA Date: 28. 4. 82

Inspector: Hower Date: 30. 4. 82

EXAMPLE OF MACHINING SCHEDULE

Fig. 11 Shaving cutter and grinding machine setting data

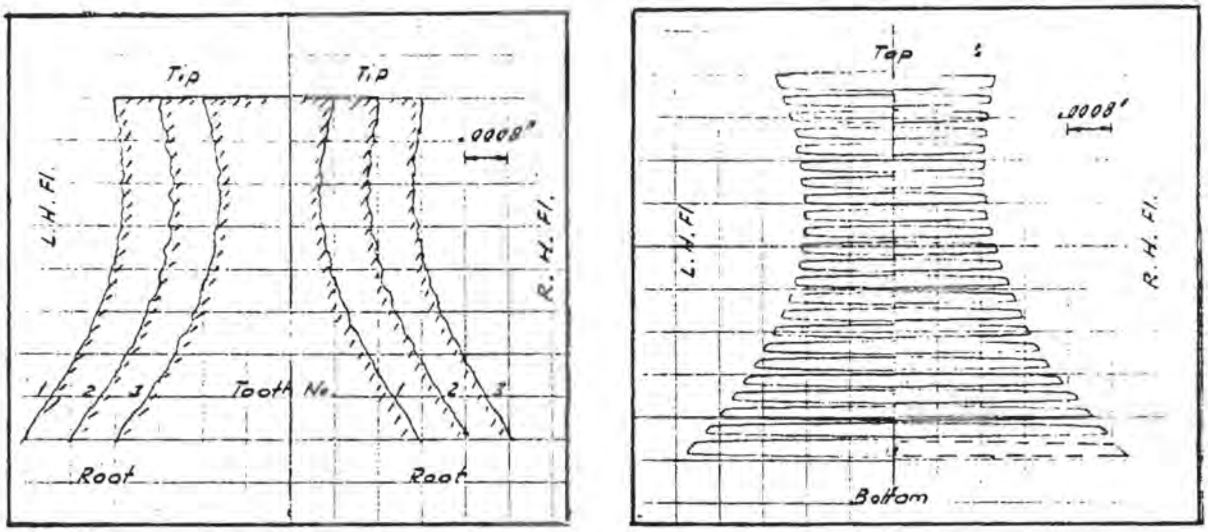
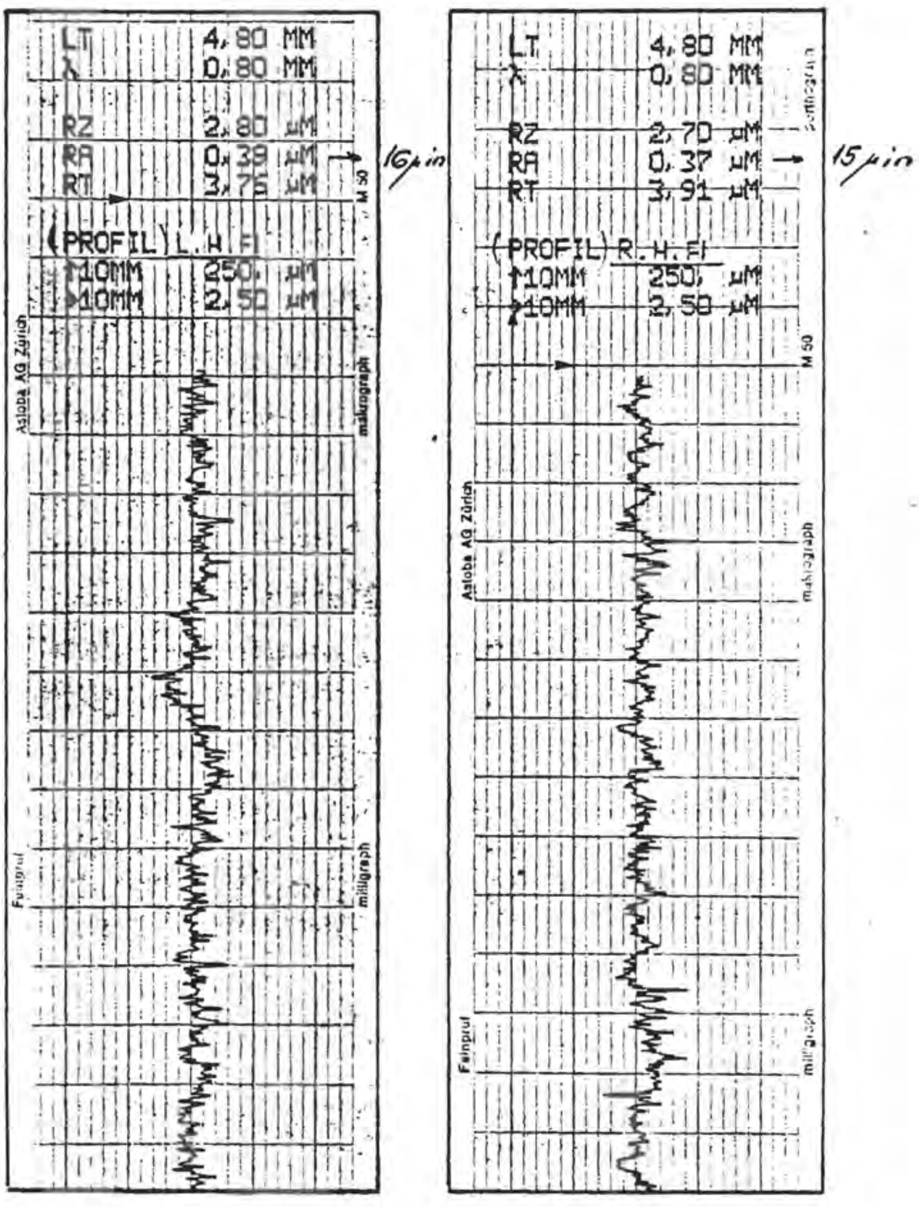


Fig. 12 Profile and helix charts for the underpass shaving cutter detailed in Fig. 11



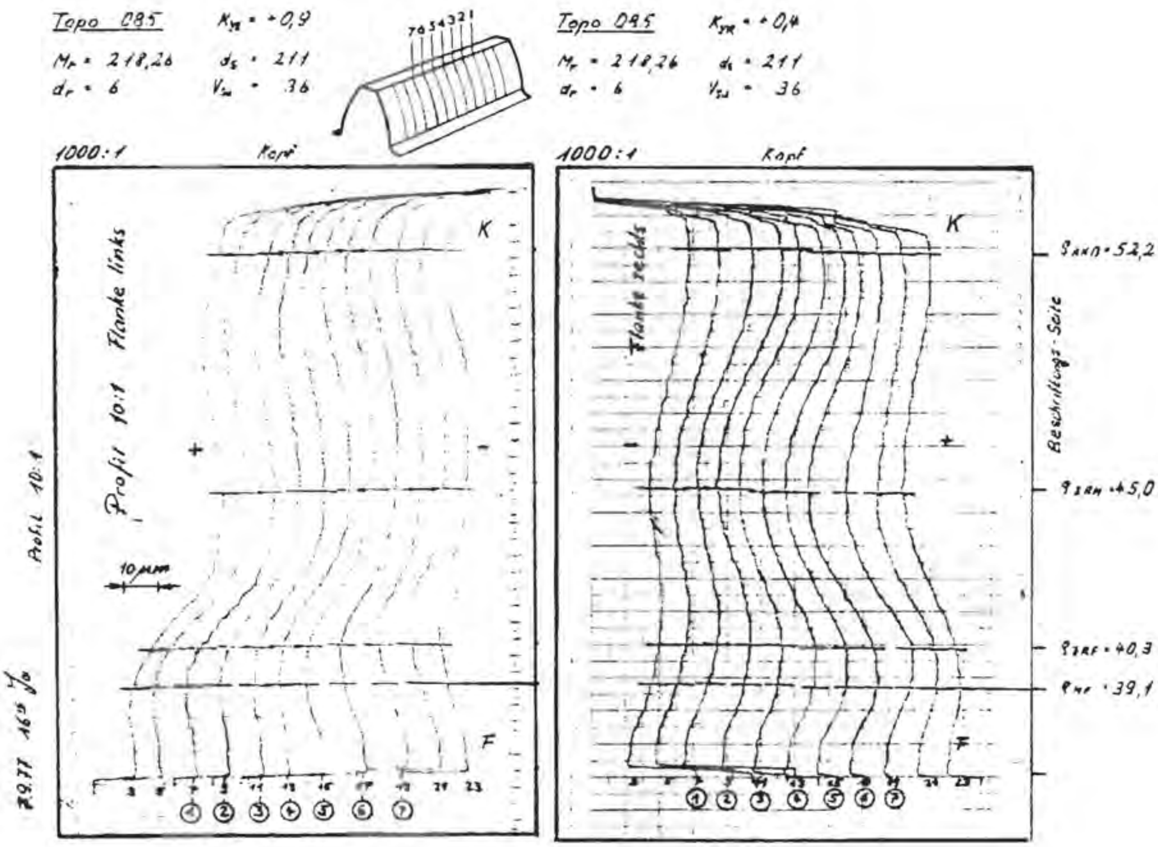


Fig. 14 Profile chart for a rolling die with varying profile modification along the face width ground on the SD-32X grinding machine with the ES-421 topological modification system.