MRR-based productivity decisions in hard machining

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Abstract: Machining procedures applied in the machining industry have been developing fast due to up-to-date tool materials, new machine-tool structures and automation solutions. This is why today a part's surface can be machined by more than one procedure having even completely different features. The potential procedures of a certain problem (machining a surface) are those that fulfill the accuracy and surface quality requirements specified in the drawing. The time parameters, the surface rate or the material removal rate can be parameters suitable for comparative analysis and ranking of the selected procedures. In this paper five machining procedures were chosen for machining hardened surfaces. Optimum cutting data, which can be recommended for real plant application as they fulfill the specified roughness and accuracy requirements of the part surfaces, were determined from machining experiments. Considering these data the machining times, operation times and the practical parameter of the material removal rate introduced by us were calculated. This differs from the widely applied theoretical value for material removal rate because it does not reflect just the theoretical time necessary for material removal but takes into account the actual manufacturing/machining times necessary for the machining of the component/surface. The analyzed surfaces are the various diameter and length bore holes of hardened gear wheels produced in large scale. Their efficiency parameters were calculated when the surfaces are machined by traditional bore grinding, hard turning (two procedure versions) and a combined procedure (two procedure versions). On the basis of these data a ranking was determined among the procedures.

Key-Words: Procedure selection, Hard machining, Grinding, Combined procedure, Material removal rate, Machining time

1 Introduction

In the context of the technical improvement of industrial machining procedures, technical planning and the determination of optimum values of cutting data remain just as important as earlier in increasing the efficiency of cutting operations. The extent of this increase depends on the concrete problem and the chosen solutions. The improvement in efficiency or the extent of savings can be considerable in large-scale production. To reach this aim, analysis of the changes in technological parameters directly determining the cutting process is not enough.

Other influencing factors connecting to the innovation have to be considered, such as the service time of machine-tools or the extra costs resulting from automation. Several costing methods are known for tracking efficiency [1, 2]. They differ from each other in their goals [3] and approaches [4, 5]. The basis of all these methods is a certain technical parameter [6, 7].

The material removal rate (MRR) characterizes the process efficiency well. Presumably this is the reason why a number of scholars have published results on the analysis of the material removal rate. These studies differ in the analyzed procedures and the manner in how the material removal rate is calculated. Ramana & Kumar performed steel turning experiments. Their goal was constructing a regression model to help in the determination of the material removal rate [8]. Tamiloli et al. applied the parameter in milling [9], while Das et al. constructed a regression model when machining aluminum alloy [10]. In these experiments the MRR was calculated by the weight and density of the removed material. Buj-Corral et al. carried out honing experiments and calculated the MRR value by the volume of removed material [11]. Other researchers applied the same calculation but their experiments were performed for electrical discharge machining (EDM) [12, 13]. Zeng & Blunt calculated the MRR by the multiplication of three parameters: the Preston coefficient, the contact pressure between the tool and the workpiece and the relative velocity of the tool [14]. Kumar et al. [15] and Mukherjee et al. [16] considered MRR as an input parameter in their studies These experiments aimed at the analysis of energy consumption and the connection between MRR and machining time. Budak & Tekeli calculated MRR for milling. Their formula included only cutting data [17]. Sardius et al. applied genetic programming; the MRR, which was the objective function, was calculated only by cutting data [18]. Several authors have published their results for turning when the material removal rate was analyzed. Hernandez et al [19] and Palacios et al. [20] intended to optimize the cutting data and Hernandez et al. analyzed the tool-life on the basis of the MRR [21]. All of them applied the theoretical MRR value. These authors calculated the material volume in cm^3 removed in one minute to determine MRR. Moganapriya et al. measured the mass and density of the removed chip to determine MRR (applied dimension: mm^3/min) and analyzed the effects of cutting data on MRR [22]. Yadav et al. measured the change in specific workpiece volume (dimension: mm^3/s) and calculated the material removal rate by the consideration of machining time. The determination of MRR was also supported by simulation [23]. During the multi-attribute optimization of cutting data Kumar et al. applied the removed mass of material in calculating MRR (dimension: g/min) [24].

It can be seen from the literature review that almost every machining procedure has been studied. Our method differs from these results in the extension of the MRR calculation for the real operation time connecting to manufacturing. This is necessary for the realistic evaluation of the material removal efficiency, i.e. a determination of its value that reliably reflects reality. Material removal was analyzed on the basis of the actual machining time in this paper. This method is considered appropriate for comparing the various machining procedures [25, 26].

In this paper we intend to highlight that even an incremental improvement in the cutting data or a high-degree modification in technology requires a high level of reliability of efficiency parameters. A modification is considered as high degree if an applied procedure is exchanged with another one. This means that the machining procedures that are suitable for a certain machining task are analyzed and the one which ensures the most efficient material removal is chosen and then applied. Here we define ‘suitable’ as a procedure applicable for satisfying the specifications of the surface/part accuracy, the surface roughness and the adequacy of the surface for the operation requirements. In this paper the data of time analysis of a manufacturing process carried out among real operating circumstances were considered. In our research the values of cutting data, by the application of which the surface of the component can be machined in the same quality in case of all the analyzed procedures, were determined from experiments. After this the actual time and efficiency of manufacturing were analyzed when machining hardened surfaces for the actual production process in which the cutting data were applied. Hardened surfaces and finishing precision machining were chosen for the analyses because the surface quality [27], accuracy [18] and the wear resistance are ensured in the finishing operation. In precision machining this is particularly valid [29] because keeping strict accuracy and quality parameters is expected in the planning of every machining procedure [30]. Abrasive machining, mainly grinding, has been applied as finishing for long time. The appearance and spread of hard turning [31] extended the range of potentially procedures by new possibilities; first of all in machining disc-feature components that incorporate internal cylindrical surfaces [32].

Five variants were analyzed from the available tool and procedure versions from economic efficiency point of view. In our analyses the infrastructure and knowledge necessary for machining were considered as available. A lack of these would require the consideration of procurement and development expenses in the decision of procedure selection.

2 Experimental setup

The objective of the experiments is the analysis of the material removal efficiency of five procedure versions capable of machining hardened surfaces.

3.1. Procedure versions

Five different hard machining procedure versions were compared to analyze the machining efficiency of hardened internal cylindrical surfaces of gear wheels:

- Traverse bore grinding – a corundum wheel was applied both in roughing and smoothing passes (TBG).
- Hard turning – a standard insert was applied in both roughing and smoothing passes (HTS).
- Hard turning – a wiper insert was applied in roughing and standard in smoothing passes (HTW).
- Combined procedure – hard turning with the application of a standard insert in the roughing pass and in-feed bore grinding with the

application of corundum wheel in the smoothing pass; both passes were carried out in one clamping (CPS).

- Combined procedure – hard turning with the application of a wiper insert in the roughing pass and in-feed bore grinding with the application of a corundum wheel in the smoothing pass; both passes were carried out in one clamping (CPW).

With all these versions the accuracy and surface quality requirements specified in the drawing can be fulfilled. This condition is the basis of the comparability of the procedures. The comparison of the procedure versions was carried out on the basis of the machining time and the operation, which characterizes the manufacturing of the whole lot, and the practical material removal rates were calculated by these time parameters. Traditional traverse bore grinding was considered as the basis and the calculated values of the parameters were compared to those of grinding.

3.2. Applied tools and machine tools

The following machine tools and tools were applied for the three procedures. The traverse grinding was carried out on the grinding machine type SI-4/A. Both for roughing and smoothing a type 40×20×16-9A80-K7V22 corundum wheel was used. The hard turning procedures were carried out on the lathe type Pittler PVSL-2. For roughing a standard insert type CNGA 120908S-Lo CBN was used in the HTS procedure and a wiper insert type CNGA 120408 GSW2 in HTW. In both procedures a standard insert type CNGA 120408 7020 was used for smoothing. The combined procedures were carried out on the machine tool type EMAG VSC 400DS. For the roughing passes of the procedure versions the tools of the hard turning procedures were used and for smoothing corundum wheel type 40×40×16-9A80-K7V22.

3.3. Workpiece material surface geometry

The material of the gear wheels incorporating the analyzed surfaces is case hardened steel type 20MnCr5. The hardness of the material after hardening is 62±2 HRC. The accuracy of the surface in all four cases is IT5; the surface roughness is specified by the Rz parameter Rz=5μm.

In the study hard machining of four gear wheel bores was analyzed. The geometrical data of the bores of the components are summarized in Table 1. The workpieces were chosen so that in two gear wheels (B1 and B2) the bore lengths and in another two (B3 and B4) the bore diameters were nearly identical. The goal of this was that in our calculations we intended to determine how the two geometrical parameters (bore length and diameter) affect the efficiency parameters in the analyzed procedures.

Table 1. Geometrical data of the analyzed surfaces

Bore geometry [mm]	B1	B2	B3	B4
d	38	66	42	41
L	30	28	27	38

3.4. Cutting data

Experiments were carried out to determine the technological conditions and cutting data of the machining versions. These data fulfill the specified quality and accuracy requirements. From the experimental results the optimum values were determined. The technological data of the machining procedures are summarized in Tables 2-4. The non-standard notations and indices are defined at the bottom of the tables.

Table 2. Technological data of traverse grinding (TBG)

		B1	B2	B3	B4
v_c	m/s	25	29	29	25
v_w	m/min	19	19	12	21
n_w	1/min	160	90	90	160
$v_{fL,R}$	mm/min	2200	2200	2200	2200
$v_{fL,S}$	mm/min	2000	2000	2000	2000
$a_{e,R}$	mm/ds	0.02	0.01	0.01	0.03
$a_{e,S}$	mm/ds	0.001	0.001	0.001	0.0015
f_R	mm/rot	13.75	24.44	24.44	13.75
f_S	mm/rot	12.5	22.22	22.22	12.5
Z_R	mm	0.1	0.1	0.1	0.1
Z_S	mm	0.05	0.05	0.05	0.05
$n_{so,R}$	ds/min	36	38	40	28
$n_{so,S}$	ds/min	33	35	36	26
i_{so}	-	8	16	16	16

Legend: *R*: roughing; *S*: smoothing; *so*: spark-out; *ds*: double stroke; *rot*: workpiece rotation

Table 3. Technological data of hard turning (HTS, HTW)

		B1	B2	B3	B4
L'	mm	32	30	29	40
v_c	m/s	180	180	180	180

n_w	1/min	1508	868	1364	1397
$a_{p,R}$	mm	0.1	0.1	0.1	0.1
$a_{p,S}$	mm	0.05	0.05	0.05	0.05
$f_{R,SI}$	mm/rot	0.15	0.15	0.15	0.15
$f_{S,SI}$	mm/rot	0.08	0.08	0.08	0.08
$f_{R,WI}$	mm/rot	0.24	0.24	0.24	0.24
$f_{S,WI}$	mm/rot	0.12	0.12	0.12	0.12

Legend: *L'*: bore length and 2 mm approach and overrun; *SI*: standard insert; *WI*: wiper insert

Table 4. Technological data of in-feed grinding operation of the combined procedures (CPS, CPW)

		B1	B2	B3	B4
v_c	m/s	45	45	45	45
v_w	m/min	57	281	153	62
n_w	1/min	477	1355	1160	481
n_{so}	1/min	100	150	120	120
t_{so}	s	6	8	5	5
$v_{fR,R}$	mm/s	0.005	0.0033	0.005	0.005
$v_{fR,S}$	mm/s	0.0036	0.0016	0.0033	0.0016
Z_R	mm	0.04	0.04	0.04	0.04
Z_S	mm	0.01	0.01	0.01	0.01
L_o	mm	3	2	2.5	2.5
v_o	mm/min	600	600	600	600
Z_A	mm	0.27	0.27	0.27	0.27
$v_{fR,A}$	mm/s	0.108	0.108	0.108	0.108

Legend: *o*: oscillation; *A*: air grinding

4 Applied methodology

The efficiency of machining can be characterized most easily by the machining time (T_m). The calculation of the machining time for the five analyzed procedures is:

$$T_{m,TBG} = \frac{2 \cdot L}{v_{fL,R}} \cdot \frac{Z_R}{a_{e,R}} + \frac{2 \cdot L}{v_{fL,S}} \cdot \left(\frac{Z_S}{a_{e,S}} + i_{so}\right) \quad (1)$$

$$T_{m,HTS} = \frac{L'}{f_{R,SI} \cdot n_w} + \frac{L'}{f_{S,SI} \cdot n_w} \quad (2)$$

$$T_{m,HTW} = \frac{L'}{f_{R,WI} \cdot n_w} + \frac{L'}{f_{S,WI} \cdot n_w} \quad (3)$$

$$T_{m,CPS} = \frac{L'}{f_{R,SI} \cdot n_w} + \frac{Z_A}{v_{fR,A}} + \frac{Z_R}{v_{fR,R}} + \frac{Z_S}{v_{fR,S}} + t_{so} \quad (4)$$

$$T_{m,CPW} = \frac{L'}{f_{R,WI} \cdot n_w} + \frac{Z_A}{v_{fR,A}} + \frac{Z_R}{v_{fR,R}} + \frac{Z_S}{v_{fR,S}} + t_{so} \quad (5)$$

The further time parameters are those measured during manufacturing. To calculate the operation time (T_{op}) characterizing the manufacturing efficiency of the whole lot the change time (T_{ch}), the supplementary time (T_{suppl}) and the preparation and completion time (T_{prep}) need to be known. The sum of change time and machining time results in the base time of machining (T_b). The piece time (T_p) can be gained by the sum of the base time and supplementary time. In our calculations the piece time is calculated as 1.15 times the base time (empirical data from the plant). The operation time is the sum of the piece time and the specific value (calculated for one workpiece) of the preparation and completion time. Considering these; the calculations of the base time, piece time and operation time are:

$$T_b = T_m + T_{ch} \quad (6)$$

$$T_p = 1.15 \cdot T_b \quad (7)$$

$$T_{op} = \frac{T_{prep}}{n} + T_p \quad (8)$$

If different procedures or procedure versions are directly compared (e.g. different machine tools, application of an abrasive or single-point tool), the comparison on the basis of the cutting data is not possible in every case because, for example, the machine kinematics or the tool movements can be different. In this case the basis of comparison can be the surface machined or material volume removed within unit time (theoretical MRR). The theoretical values of material removal rate can be applied only for a single procedure. This means, for example, that this value cannot be calculated for a combined procedure containing both the hard turning and in-feed bore grinding, because the summation of the material removal parameter of the two procedures is not possible. Similarly, if the machining of more than one different surface of a single component is intended to be characterized in order to compare machining efficiency, the theoretical parameter cannot be applied for the whole machining process. To eliminate this problem we introduced the practical parameter of the material removal rate, which is calculated by the ratio of the removed material volume and the time required for the removal. The choice of this required time depends on the machining and the aim of analysis. In the study described in this paper the practical material removal rate containing the machining time (Eq.(9)) and the operation time (Eq.(10)) is analyzed (the formulas are for bore machining).

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L \cdot Z}{60 \cdot T_m} \tag{9}$$

$$Q_{wp,op} = \frac{d \cdot \pi \cdot L \cdot Z}{60 \cdot T_{op}} \tag{10}$$

To perform the efficiency calculations, beyond the technological data, further parameters connecting to production organization are needed. The operation time was calculated by considering the lot size, which was n=200. The change time (workpiece and tool change) and preparation and completion time (of the whole lot) were available in plant documents. These values are summarized in Table 5 for the analyzed procedures.

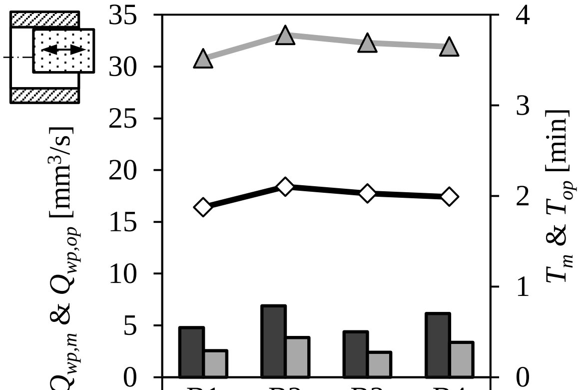
Table 5. Change and preparation times

[min]	TBG	HTS, HTW	CPS, CPW
T_{ch}	0.4	0.2	0.3
T_{prep}	180	20	40

5 Discussion

The values calculated by the detailed manner are summarized in Figures 1-5. The machining times, operation times and the practical material removal rates (based on these times) of the machining of the analyzed bores are demonstrated in Fig.1 for traditional traverse grinding. The machining time varies between 1.88 and 2.10 min. The operation times varies between 3.52 and 3.78 min. The values of the $Q_{wp,m}$ parameter calculated by the machining time are between 4.39 and 6.90 mm^3/s. On the basis of the operation time the $Q_{wp,op}$ values are between 2.41 and 3.84 mm^3/s. As mentioned above, this procedure can be considered as general to machining such surfaces; therefore, this was handled as the basis procedure (the basis of comparison).

Bore geometry	B1	B2	B3	B4
d [mm]	38	< 66	42	~ 41
L [mm]	30	~ 28	27	< 38



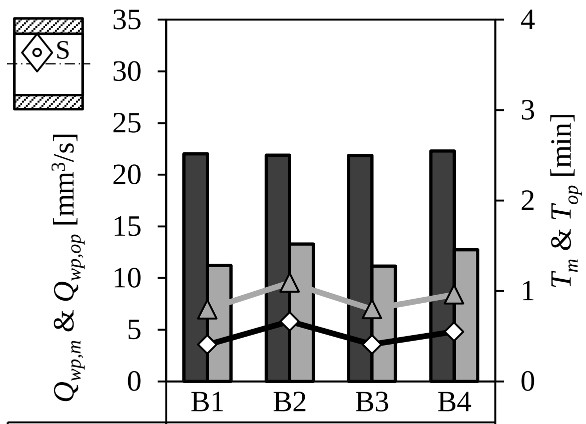
	B1	B2	B3	B4
$Q_{wp,m}$	4.77	6.90	4.39	6.15
$Q_{wp,op}$	2.55	3.84	2.41	3.35
T_m	1.88	2.10	2.03	1.99
T_{op}	3.52	3.78	3.69	3.65

Analyzed bores

Figure 1. Efficiency parameters of the TBG traverse bore grinding procedure

In the next analyzed procedure the surface is machined by single-point tools. The reason for including hard turning in the analysis is not only the accuracy and surface roughness that can obtained but also the fact that the machining can be carried out dry, in contrast to grinding, which requires a large amount of coolant and lubricant. Therefore hard turning can significantly decrease the extent of the environmental load [31]. The roughness and accuracy specifications can be reached in two passes (roughing and smoothing) by hard turning. In both passes a standard insert was used. The efficiency parameters are summarized in Fig.2. The machining time varies between 0.41 and 0.66 min. The operation times vary between 0.80 and 1.09 min. The values of the $Q_{wp,m}$ parameter calculated by the machining time are between 21.86 and 22.30 mm^3/s. On the basis of the operation time the $Q_{wp,op}$ values are between 11.15 and 13.29 mm^3/s. Compared to traverse grinding, the values of machining times vary between 20-32% and the values of operation time between 22-29%. The material removal rate calculated by the machining time and compared to traverse grinding is 4.10-fold on average and that calculated by the operation time is 4.07-fold. Thus, it can be stated that the material removal is more intense and therefore more efficient than grinding.

Bore geometry	B1	B2	B3	B4
d [mm]	38 <	66	42 ~	41
L [mm]	30 ~	28	27 <	38



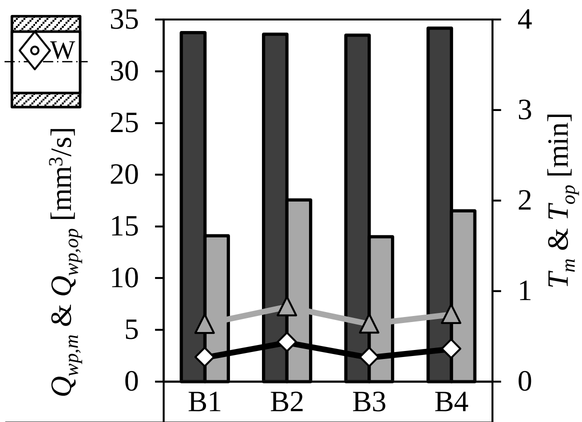
	B1	B2	B3	B4
$Q_{wp,m}$	22.01	21.91	21.86	22.30
$Q_{wp,op}$	11.22	13.29	11.15	12.73
T_m	0.41	0.66	0.41	0.55
T_{op}	0.80	1.09	0.80	0.96

Analyzed bores

Figure 2. Efficiency parameters of the HTS hard turning procedure

In the next procedure roughing and smoothing were carried out with the application of two different inserts. In the roughing pass another insert (wiper) was used, therefore a higher feed rate could be applied. The efficiency parameters of the machining are demonstrated in Fig.3. The machining time varies between 0.27 and 0.43 min. The operation times vary between 0.64 and 0.83 min. The values of the $Q_{wp,m}$ parameter calculated by the machining time are between 33.75 and 34.19 mm^3/s. On the basis of the operation time the $Q_{wp,op}$ values are between 14.10 and 17.55 mm^3/s. Compared to traverse grinding the values of machining times vary between 13-21% and the values of operation time between 17-22%. The material removal rate calculated by the machining time and compared to traverse grinding is 6.28-fold on average and that calculated by the operation time is 5.21-fold.

Bore geometry	B1	B2	B3	B4
d [mm]	38 <	66	42 ~	41
L [mm]	30 ~	28	27 <	38



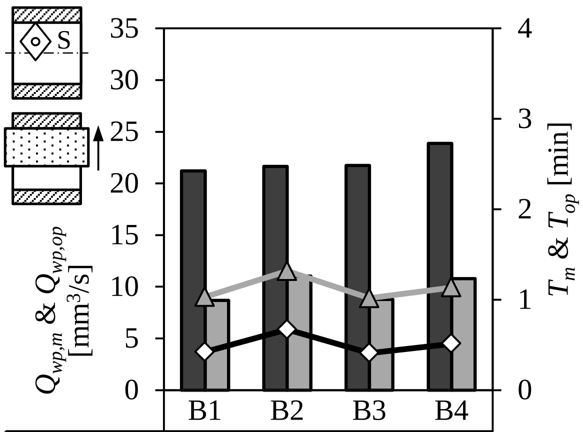
	B1	B2	B3	B4
$Q_{wp,m}$	33.75	33.60	33.51	34.19
$Q_{wp,op}$	14.10	17.55	14.01	16.50
T_m	0.27	0.43	0.27	0.36
T_{op}	0.64	0.83	0.64	0.74

Analyzed bores

Figure 3. Efficiency parameters of the HTW hard turning procedure

Since the applied procedures were analyzed as finishing procedures, not only the roughness and accuracy values were considered but also the fulfillment of operating requirements of the machined surface. In case of gear-wheel bores this means that the topography formed by hard turning is not always correct because of its periodic feature. In this case the last step has to be an abrasive procedure to ensure random topography. Traditionally this meant two machine tools (a lathe and a grinding machine) but today machine tools are available that allow the two procedures to be carried out in one clamping. This is called a combined procedure and with it the advantages of the two procedures can be utilized. The efficiency parameters of the combined procedure, where the roughing pass was carried out by a standard insert, are demonstrated in Fig.4. The machining time varies between 0.42 and 0.67 min. The operation times vary between 1.03 and 1.32 min. The values of the $Q_{wp,m}$ parameter calculated by the machining time are between 21.23 and 23.88 mm^3/s. On the basis of the operation time the $Q_{wp,op}$ values are between 8.69 and 11.03 mm^3/s. Compared to traverse grinding the values of machining times vary between 20-32% and the values of operation time between 28-35%. The material removal rate calculated by the machining time and compared to traverse grinding is 4.10-fold on average and that calculated by the operation time is 3.28-fold.

Bore geometry	B1	B2	B3	B4
d [mm]	38 < 66		42 ~ 41	
L [mm]	30 ~ 28		27 < 38	



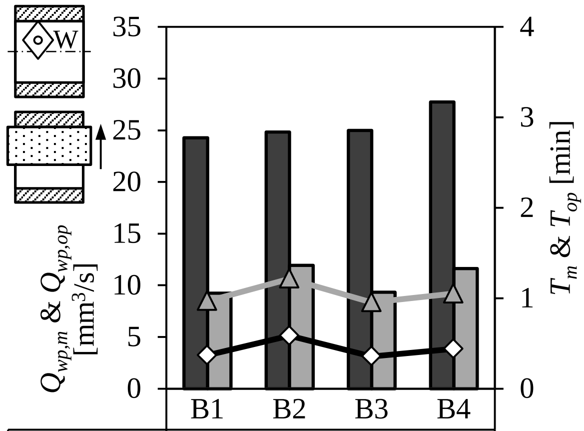
	B1	B2	B3	B4
$Q_{wp,m}$	21.23	21.64	21.74	23.88
$Q_{wp,op}$	8.69	11.03	8.77	10.79
T_m	0.42	0.67	0.41	0.51
T_{op}	1.03	1.32	1.02	1.13

Analyzed bores

Figure 4. Efficiency parameters of the combined procedure CPS

In the next analyzed version the insert was changed to a wiper insert in the combined procedure, because the roughing pass of the combined procedure is hard turning. The efficiency parameters of the procedure are given in Fig.5. The machining time varies between 0.36 and 0.58 min. The operation times vary between 0.95 and 0.22 min. The values of the $Q_{wp,m}$ parameter calculated by the machining time are between 24.28 and 27.76 mm^3/s. On the basis of the operation time the $Q_{wp,op}$ values are between 9.24 and 11.93 mm^3/s. Compared to traverse grinding the values of machining times vary between 18-28% and the values of operation time between 26-32%. The material removal rate calculated by the machining time and compared to traverse grinding is 4.72-fold on average and that calculated by the operation time is 3.52-fold.

Bore geometry	B1	B2	B3	B4
d [mm]	38 < 66		42 ~ 41	
L [mm]	30 ~ 28		27 < 38	



	B1	B2	B3	B4
$Q_{wp,m}$	24.28	24.84	24.99	27.76
$Q_{wp,op}$	9.24	11.93	9.33	11.63
T_m	0.37	0.58	0.36	0.44
T_{op}	0.97	1.22	0.95	1.05

Analyzed bores

Figure 5. Efficiency parameters of the combined procedure CPW

On the basis of time parameters and material removal rates the a ranking can be identified for the procedures:

HTW≻CPW≻HTS≻CPS≻TBG

In the analysis of the effects of geometrical parameters it was found that the recommended order of the procedures is the same at most of the geometrical values. In the case of relatively long bore holes (Bore B4) the hard turning carried out by standard insert proved to be less efficient than the combined procedure carried out by standard insert.

6 Conclusions

In this paper five precision machining procedures were analyzed for machining internal cylindrical surfaces on the basis of the efficiency of material removal. The analyses were carried out for four gear-wheels that incorporate different bore geometrical values and are produced in large scale. The technological data of the procedures with which the accuracy and roughness specifications can be reached with the machining of the analyzed surfaces were previously determined. Among the chosen procedures some were also analyzed which can form random topography. The range of possibly used procedures was widened by this. The the MRR of the five procedures were analyzed applying the so- called practical parameter of MRR instead of its theoretical parameter. This allowed the consideration of the actual times spent and the introduction of the efficiency calculated on the basis of the whole manufacturing process. The rank of the analyzed procedures was determined: 1. hard turning with a wiper insert in the roughing pass and a standard insert in the smoothing pass (HTW); 2. a combined procedure with a wiper insert in the roughing pass; 3. hard turning with a standard insert in both the roughing and smoothing passes; 4. a combined procedure with a standard insert in the roughing pass; 5. traverse bore grinding. Out of the two geometrical parameters (bore lengths and diameter) the effect of bore length is determinant: a change in bore length can cause rank reversal. One future research direction is the extension of the analysis to components that contain more than one surface or surface combination. We expect to find that a ranking can be obtained even when the number of procedures, the surfaces and the surface/procedure combinations is increased.

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