Decision-making in procedure selection on the basis of efficiency in machining hardened surfaces

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Abstract: Due to the rapid development of machining a component can be machined by more than one procedure when the same quality requirements can be met. In this case choosing the suitable procedure is a multi-objective optimization problem. One possible variant of the analysis is the calculation of the specific surface area or volume (Surface rate – SR; Material removal rate – MRR). If these parameters are calculated for only the machining time, a theoretical value is obtained because the actual time required for production is not considered. In this paper a comparative analysis is performed for five machining procedure versions. The cutting data with which the specified accuracy and surface quality are ensured were determined by cutting experiments. A comparative analysis is performed by machining the surfaces on the basis of these data, determining the actual times of production, comparing the results with the theoretical value. The surface is the bore of a gear wheel built into a transmission system and produced in mass production. In the paper the efficiency of material removal is analyzed in machining hardened surfaces when different machining procedures (grinding, turning) and different tools were applied. On the basis of the results a ranking was obtained for the hard machining procedures. The method can be extended to various surfaces and surface combinations.

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

1 Introduction

Nowadays the development level of machining procedures is so high that if only slight savings can be achieved by the planning of a technology or machining process, it can be considered as a significant result. This is valid particularly in large-scale or mass production. Thus, the extent of savings has a particular role, mainly in mass production of the components, because it significantly affects the production costs of the components produced over a year.

Several costing methods are known [1, 2] that differ in their objectives [3] and approaches [4, 5]. The basis of each of these methods is a certain technical parameter [6, 7]. In this paper the specific material removal rate was analyzed, which is a suitable parameter for comparing different machining procedures [8, 9].

Several researchers have published results of analysis of material removal rate. They differ in the analyzed methods and the calculation method applied for MRR. Ramana & Kumar performed steel turning experiments with the aim of constructing a regression model for the MRR parameter [10]. Tamiloli et al. applied the parameter in milling [11], while Das et al. constructed a regression model when machining aluminum alloy [12]. These authors calculated the MRR by the weight and density of the removed material. Buj-Corral et al. applied the MRR for honing and calculated its value by the volume of removed material [13]. Mohammadi et al. [14] and Tonday & Tigga [15] applied the same calculation but their experiments were performed for electrical discharge machining (EDM). Zeng & Blunt applied a special method: they calculated the MRR by the multiplication of the Preston coefficient, i.e. the contact pressure between the tool and the workpiece and the relative velocity of the tool [16]. Kumar et al. [17] and Mukherjee et al. [18] considered MRR as an input parameter in their experiments. The former aimed to find the optimum energy consumption of machining and the latter analyzed the effect of MRR on the machining time. Budak & Tekeli calculated the MRR by the conventional method for milling: they applied only cutting data in their formula [19]. Sardius et al. performed a genetic algorithm-based method optimization; the MRR was calculated only by cutting data and it was considered as the objective function of the optimization [20].

This literature review highlights that almost every machining procedure has been analyzed. However, the calculations are not extended to the consideration of all the actual time components of production in the papers. In our analysis this extension is accomplished. This method is considered useful to analyze the efficiency of material removal exactly and in a realistic manner.

In the paper the time parameters were not considered on the basis of theoretical calculations or estimations; but the material volume removed in unit time was calculated on the basis of the real time consumption. The introduced time parameters characterize not only the machining itself (cutting of the clamped workpiece) but also include additional time values connecting to production.

Machining of hardened surfaces was chosen to perform the comparative analysis. Machining of such surfaces always requires particular attention, since the wear resistance of the components and the formation of surfaces that meet requirements for quality [21] and accuracy are ensured in this finishing operation [22]. For decades this task was handled by abrasive machining, mainly by grinding. The appearance and spread of hard turning [23] widened the range of applicable procedures with its new possibilities, first of all in machining disc-featured components that contain bores [24]. In this paper five versions of available tools and procedures are analyzed from cost effectiveness point of view. In the analyses the infrastructure and professional knowledge necessary in machining are considered as given. Any lack in these areas requires the consideration of procurement and development costs when choosing among the procedures.

2 Geometrical and technological data of the analyzed procedures

Various improvement directions are possible for machining. If, for example, a certain machining procedure is improved (e.g. a different cutting insert is applied), only the altered factors have to be included in the time and economic analyses in the comparisons. There are only a few such factors in case of a single machining procedure; therefore, the comparison is easy to perform. However, when different procedures (e.g. machining by single-point or abrasive tool) are analyzed, the comparison is more difficult because there are differences in the tool geometry and/or in the machine kinematics or structure. In these cases the area (SR) or volume (MRR) removed in unit time can be a suitable basis for comparative analyses. Due to the differences in the compared procedures the theoretical MRR value and the value that characterizes the actual production are different. The economical utility can be demonstrated on the basis of the actual time and cost consumption. To prove the validity of this approach the cutting data were determined by cutting experiments. With these data the machined surface fulfills the quality and operation requirements. After that the actual production time and efficiency were analyzed.

The machining of the chosen internal cylindrical surfaces always requires increased attention in technological planning. The machining of bores is always more difficult than, for instance, that of external cylindrical surfaces. In finishing precision machining this is more important [25] because cost effective maintenance of the strict accuracy and surface quality parameters is required in the planning of almost all machining procedures [26]. In the procedure selection technological (cutting) data were chosen for which machining fulfills the surface roughness and accuracy requirements.

Five hard machining procedure versions were compared on the basis of time consumption. In the comparison of different hard machining procedures the common characteristic of the comparison is that the basis procedure is the conventional grinding; we also chose this approach. The efficiency of material removal of the analyzed procedure versions is found and a recommendation made for the most efficient procedure.

2.1 The analyzed procedure versions

The following procedures and procedure versions were analyzed in the machining of the bore of a gear wheel.

- Traverse bore grinding (TBG)
- Hard turning with standard insert (HTS)
- Hard turning with wiper insert (HTW)
- Combined procedure with standard insert in the hard turning pass (CPS)
- Combined procedure with wiper insert in the hard turning pass (CPW)

The applied tools are summarized in Table 1.

2.2 The machined workpiece

The material of the component is core-hardened gear-wheel steel (20MnCr5). Its hardness after heat treatment is 62±2 HRD. The diameter of the bore is

d=50 mm. The bore length is L_1=30 mm, while L_2 length, which differs from the L_1 length in the approach and overrun of single-point-tools (1 mm each), is thus 32 mm. The accuracy of the machined surface is IT5, its roughness Rz=5 µm.

Table 1. Applied tools in the analyzed procedures

Procedure	Cutting tool component	
	Roughing	**Smoothing**
TBG	Corundum wheel	Corundum wheel
HTS	Standard insert	Standard insert
HTW	Wiper insert	Standard insert
CPS	Standard insert	Corundum wheel
CPW	Wiper insert	Corundum wheel

2.3 Cutting data

For the efficiency calculations cutting experiments were performed. The aim of these experiments was the determination of cutting data and technological conditions that ensure the accuracy and surface quality requirements specified in the part drawing. This is the preliminary condition of comparability of machining procedures. On the basis of the results of the experiments the optimum values were chosen and they recommended for introduction to production. These data formed the basis of efficiency calculations.

The cutting data are summarized in Tables 2-5. Further symbols in the subscripts are: R (roughing); S (smoothing); so (sparking out of the wheel); A (air grinding); o (wheel oscillation).

Table 2. Technological and geometrical data of traverse bore grinding

v_c [m/s]	30	$a_{e,S}$ [mm/ds]	0.001
v_w [m/min]	18	f_R [mm/rot]	19.64
n_w [1/min]	112	f_S [mm/rot]	17.86
$v_{fL,R}$ [mm/min]	2200	$n_{so,R}$ [ds/min]	37
$v_{fL,S}$ [mm/min]	2000	$n_{so,S}$ [ds/min]	33
$a_{e,R}$ [mm/ds]	0.02	i_{so} [ ]	8

Table 3. Technological and geometrical data of in-feed grinding

v_c [m/s]	45	$a_{e,R}$ [mm]	0.000857
v_w [m/min]	55	$a_{e,S1}$ [mm]	0.000566
n_w [1/min]	350	$a_{e,S2}$ [mm]	0.000274
t_{so} [s]	6	Z_N [mm]	0.035
$v_{fR,R}$ [mm/min]	0.005	Z_S [mm]	0.005
$v_{fR,S1}$ [mm/min]	0.0033	L_o [mm]	3
$v_{fR,S2}$ [mm/min]	0.0016	v_o [mm/min]	600

The bore length is L_1, the length considered in the calculations when hard turning is L_2, which also includes the approach and overrun. In the in-feed grinding operation the in-feed velocity of the wheel when air grinding is $v_{fR,A}$=0.166 mm/s.

Table 4. Technological and geometrical data of hard turning with standard insert

v_c [m/min]	180	$a_{p,S}$ [mm]	0.05
n_w [1/min]	1146	f_R [mm/rot]	0.15
$a_{p,R}$ [mm]	0.1	f_S [mm/rot]	0.08

Table 5. Technological and geometrical data of hard turning with wiper insert

v_c [m/min]	180	$a_{p,S}$ [mm]	0.05
n_w [1/min]	1146	f_R [mm/rot]	0.24
$a_{p,R}$ [mm]	0.1	f_S [mm/rot]	0.12

3 The analyzed parameters characterizing material removal

The theoretical Q_w values of material removal rate can be calculated by the cutting data. This is a theoretical value because it is calculated by the time of machining (i.e. material removal is realized by the tool). This value does not show the actual time consumption of production because a number of activities and their times are necessary to produce the components. This is the reason why the practical parameter of material removal rate is introduced in this paper, calculated as:

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L_1 \cdot Z}{60 \cdot T_x}, \quad (1)$$

where T_x can be:

- T_m: machining time
- T_b: base time
- T_p: piece time
- T_{op}: operation time

When analyzing the five hard machining procedures their machining times (base time, machining time, piece time, operation time) were compared. After this the material removal rates (MRR) were calculated by the times given from the factory and the results were evaluated in machining a disc-featured component. The different machining procedures were compared on the basis of the time consumption necessary for the machining and the practical value of the material removal rate.

The calculations of these values, considering the methods applied in the plant producing the analyzed gear wheels, are summarized in Eqs. (2)-(8). The machining times are calculated for traverse grinding, in-feed grinding and hard turning as given in Eqs. (2)-(4), respectively.

$$T_m = \frac{2 \cdot L_1}{v_{fL,R}} \cdot \frac{Z_R}{a_{e,R}} + \frac{2 \cdot L_1}{v_{fL,S}} \cdot \left(\frac{Z_S}{a_{e,S}} + i_{so} \right) \quad (2)$$

$$T_m = \frac{0.27}{v_{fR,A}} + \frac{Z_R}{v_{fR,R}} + \frac{Z_{S1}}{v_{fR,S1}} + \frac{Z_{S2}}{v_{fR,S2}} + t_{so} \quad (3)$$

$$T_m = \frac{L_2}{f \cdot n_w} \quad (4)$$

In the combined procedures the machining time is the sum of hard turning and in-feed grinding times.
The calculation of base time for the analyzed procedures is defined by Eq. (5).

$$T_b = T_m + T_{ch} \quad (5)$$

where T_{ch} contains the change times of workpiece and tool and other times. Their values are given from plant documentation.

In the case of traverse grinding the piece time is defined by Eq. (6). The multiplier 1.15 is valid if the machining time is higher than 1.5 min [16]. Calculation of the piece time in case of the other procedures is defined by Eq. (7).

$$T_p = 1.15 \cdot T_b \quad (6)$$

$$T_p = T_b + T_{suppl} \quad (7)$$

where T_{suppl} is the supplementary time.
The operation time is calculated by Eq. (8) for all of the analyzed procedures:

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

where T_{prep} is the time of preparation and completion. These values were obtained from plant documentation.

The efficiency of material removal was analyzed by the application of the practical parameter of material removal rate (Q_{wp}). Its calculation is defined by Eqs. (9)-(12) and it expresses the volume of the material to be removed by unit time defined for one of the production times (the one that is important in the current situation). The value of the parameter depends on the aim of the analysis.

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L_1 \cdot Z}{60 \cdot T_m} \quad (9)$$

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L_1 \cdot Z}{60 \cdot T_b} \quad (10)$$

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L_1 \cdot Z}{60 \cdot T_p} \quad (11)$$

$$Q_{wp,m} = \frac{d \cdot \pi \cdot L_1 \cdot Z}{60 \cdot T_{op}} \quad (12)$$

In our calculations the value of allowance is Z=0.15 mm.

4 Discussion

Analyzing the results of the four normative times calculated with the given formulas, it can be stated that compared to grinding, which is considered as the basis and applied widely, the time consumptions of the other procedures are significantly lower: one-third to one-fourth of times for grinding.

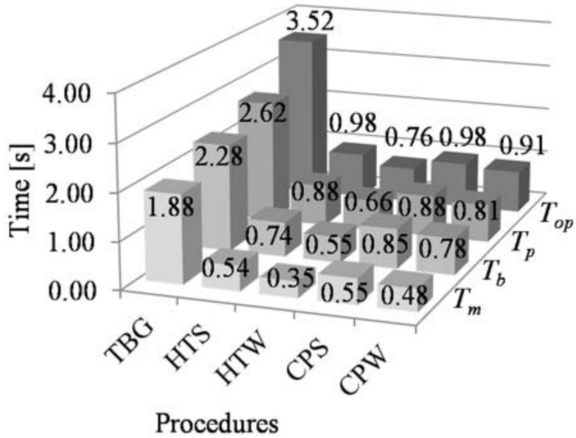

Figure 1. Time parameters of the analyzed procedures

In Fig.1 it can be seen that grinding requires 1.88 minutes of machining time, while in hard turning and in the hard turning operation element of the combined procedure where a standard insert is applied these values are 1.54 and 1.55, respectively. This highlights that the time consumption of the combined procedure (where the surface can be machined in one clamping, in one machine tool by different tools – single-point or abrasive tool) shows essentially no increase compared to hard turning [27]. Machining with a wiper insert takes a shorter time, but it has to be noted that the difference in the machining times of hard turning and the combined procedure is 37%. This rate is similar in case of the other analyzed times. These findings show that by choosing the technological data properly, a ground topography can be formed by the combined procedure without the time consumption increasing at all or much, compared to the machining of hard turned surface. The reason for this is that when exploiting the advantages of hard turning (high material removal efficiency, proper accuracy) in the combined procedure, only a minimum allowance is ground in order to form random topography.

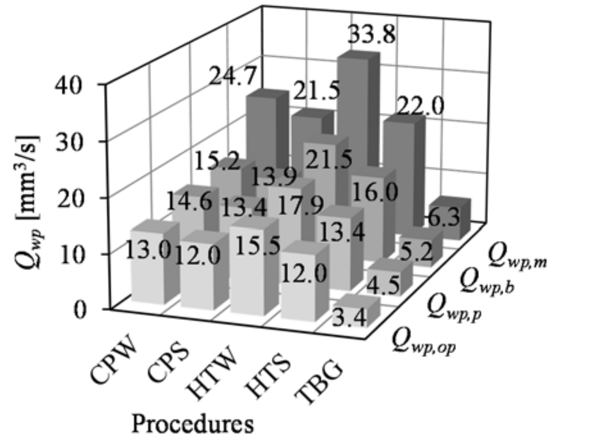

Figure 2. Practical material removal rate parameters of the analyzed procedures

Analyzing the procedures on the basis of the material volume removed in unit time (Fig.2), it can be seen that the application of the wiper insert in hard turning or in the combined procedure results in the highest Q_{wp} value.

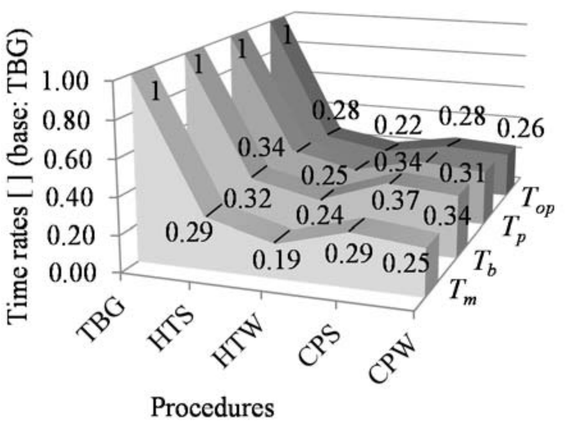

Figure 3. Rates of time parameters, basis: TBG

These results highlight that the realization of the same surface roughness values with a wiper insert allows higher feed to be applied. The specific material volume is lower when a standard insert is used in the cutting. However, these values are more than three-fold of the removable material volume by grinding. In summary, it was found that a ground topography can be formed not only by grinding but also by the combined procedures (CPS and CPW). In this case the removed material volume is 2.7-3.9 times higher.

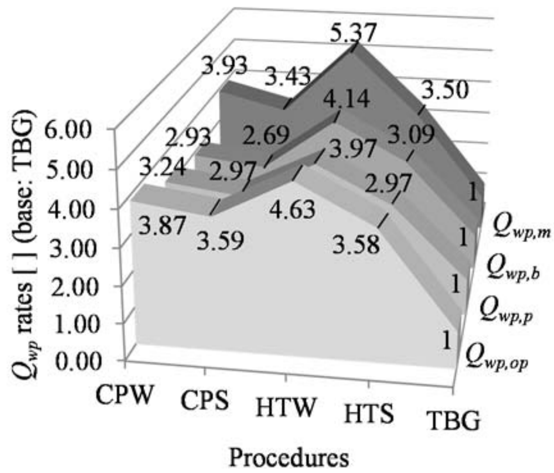

Figure 4. Rates of Q_{wp} values, basis: TBG

When comparing hard machining procedures an important assessment factor for plants is the operation time and indicators including operation time. The operation times compared to that of traverse bore grinding (TBG) can be characterized by the following rates:

- Hard turning version with standard insert (HTS): 28%;
- Hard turning version with wiper insert (HTW): 22%;
- Combined procedure version with standard insert (CPS): 28%;
- Combined procedure version with wiper insert (CPW): 26%.

The material removal rates of the analyzed procedures compared to the material removal rate (calculated with the operation time) of traverse bore grinding (TBG) can be characterized by the following rates:

- Hard turning version with standard insert (HTS): 358%;
- Hard turning version with wiper insert (HTW): 463%;
- Combined procedure version with standard insert (CPS): 359%;
- Combined procedure version with wiper insert (CPW): 387%

5 Conclusions

In the investigations five precision hard machining procedures were compared on the basis of the time parameters (machining time, piece time, base time, operation time) of the machining and the practical parameter of material removal rate when machining internal cylindrical surfaces. The machining procedures can be compared if they fulfill the same requirements of the component (surface roughness, accuracy, quality of the component). In this case it is recommended to analyze whether it is worth replacing the previously used. Time analysis and calculation of the material removal rate (MRR) is a suitable method of gaining data for this decision. Analysis of MRR is particularly recommended when comparing significantly different procedures such as those using abrasive or single-point tools or with the combination of these. On the basis of our calculations a clear ranking could be determined between the analyzed procedures. Both the time analysis and the calculation of MRR highlighted that the productivity of hard turning is the best. However, if the running requirements of the component require ground topography, it is worthwhile to replace conventional grinding with the combined procedure. Of the examined combined procedure versions, 1. CPW (wiper insert in the hard turning operation element) ranks above 2. CPS (standard insert in the hard turning operation element). One future research direction is the extension of analysis to components that contain more than one surface or surface combination. We expect to find that the ranking can be performed even when the number of procedures, the surfaces and the surface/procedure combinations is increased.

Acknowledgement:
This research was supported by the project no. EFOP-3.6.2-16-2017-00007, titled 'Aspects on the development of intelligent, sustainable and inclusive society: social, technological, innovation networks in employment and digital economy'. The project has been supported by the European Union, co-financed by the European Social Fund and the budget of Hungary.

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