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COMPARATIVE STUDY OF MATERIAL REMOVAL IN HARD MACHINING OF BORE HOLES

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Preliminary notes
In the technological planning of hard machining procedures, several factors of the component have to be considered. One factor is the system of geometrical dimensions of the components. The potential procedures capable of providing the required accuracy and quality specified to the surfaces, and/or their (economical) efficiency can also be influenced by the geometrical dimensions. Beyond the generally prevailing time study, in the present paper the material removal rate and the surface rate are investigated referring to hardened internal cylindrical surfaces. These parameters are referred to the unit operation time. The values of the parameters are analysed at different bore geometries. The investigations are performed for hard machining procedures with different inserts, as well as a combined hard machining and grinding procedure, and values are given with conventional (traverse) grinding as the basis of the comparison.

Keywords: *hard machining, operation time, removal rate*

Komparativna studija skidanja materijala u strojnoj obradi tvrdih površina provrtanih rupa

Prethodno priopćenje
Kod tehnološkog planiranja postupaka u strojnoj obradi tvrdih površina potrebno je uzeti u obzir nekoliko čimbenika. Jedan je čimbenik sustav geometrijskih dimenzija elemenata. Mogući postupci za osiguranje potrebne točnosti i kvalitete površina i/ili njihova (ekonomska) učinkovitost mogu također biti pod utjecajem geometrijskih dimenzija. U radu se brzina skidanja materijala i obrade površine istražuju u odnosu na otvrdnute unutarnje cilindrične površine. Ti se parametri odnose na rad u jedinici vremena. Vrijednosti parametara se analiziraju kod različitih geometrijskih dimenzija provrta. Istraživanja se provode za postupke strojne obrade tvrdih površina s različitim umetcima kao i kombinacijom te obrade i postupka brušenja, a vrijednosti se daju uz konvencionalno (poprečno) brušenje kao osnove za usporedbu.

Ključne riječi: *strojna obrada tvrdih površina, vrijeme rada, brzina skidanja*

1 Introduction

New procedures and methods have been appearing more and more frequently in the operations of finishing of hardened surfaces machined by abrasive procedures, mainly grinding, e.g. [1, 2, 3, 4, 5]. The introduction and application of new procedures are always preceded by comparative investigations with the conventional procedures for the same problem. Accordingly several comparative investigations with their various aspects and criteria have been performed concerning the new procedures of the machining of hardened surfaces [1, 2, 6]. Their general characteristic is that conventional grinding is always the basis of the comparison, the reason for which is that grinding has been the exclusive procedure of machining hardened surfaces for long decades.

A wide range of investigations have been accomplished to settle the most important issue: are the new procedures able to produce the accuracy and quality specified for the surfaces to be machined?

In comparative investigations hard turning has been analyzed as a possible replacement for grinding, from the point of view of ensuring surface roughness [7], ensuring accuracy [8], and the surface integrity created by each of the two procedures [9, 10, 11, 12, 13].

Such studies have proved that grinding can be substituted by hard turning in several cases. But there is another task: to prove that this change can be carried out economically, or gaining the highest possible material removal values.

To prove the industrial applicability of hard turning, surface roughness and machining time were initially compared to those of grinding [1, 2, 15, 16, 17]. Later the total surface quality was investigated [3, 18, 19, 20]. It was clarified that hard turning has several advantages comparing to grinding [6, 20, 21]. However, there are cases in which the regular so-called periodic topography is not desirable from the point of view of the functionality of the components. That is why a machining solution was sought in which after hard turning the finishing step of material removal is performed by grinding [4, 5]. These solutions are defined as combined procedures.

The above detailed steps of development are easily traceable in machining disk-featured components. In producing such parts the hardest task is the machining serving the accuracy and quality requirements specified for bores.

In this study, an analysis of machining bores containing hardened surfaces is carried out to determine how productivity is influenced by the bore geometry (bore length and diameter) in different procedure versions. It is also shown how the operation time, the material removal rate and surface rate change with the different bore dimensions for grinding, hard turning and a combined procedure.

2 Comparative investigations

Procedures were compared and technological data were applied that facilitate the specified values for accuracy (IT5-IT6) and surface roughness (*Rz*6) for the machined surfaces. The aim of investigations was to analyze how the machining time and the efficiency of material removal are affected by the bore diameter and bore length.

2.1 Material and geometry of workpieces

The material is case hardened gear-wheel steel (20MnCr5). Its hardness after heat treatment is 62±2 HRC. The 30 mm long bores have five different diameters (*d*: 35, 50, 65, 80, 95 mm), and the 80 mm diameter bores have five different lengths (L: 20, 25, 30, 35, 40 mm). The length L' differs from L in the value of pushing and overrun of single point tools. The extent of pushing and overrun is 1+1 mm.

2.2 Procedures and cutting conditions

Fig. 1 demonstrates the essential cutting data and the drafts of five different versions.

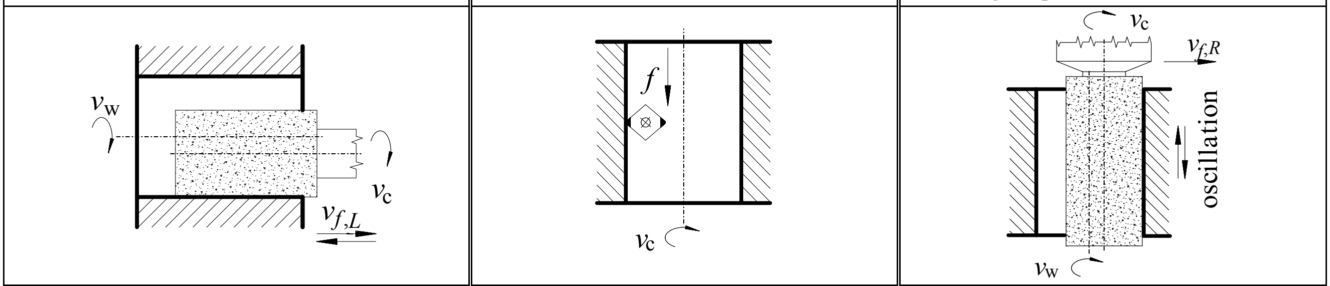
Procedure A is conventional bore grinding. It is characterized by traverse feed and discontinuous pass by double stroke.

Procedure version B is classic hard turning with a standard PCBN insert, roughing and smoothing with different inserts.

Procedure version C is hard turning with a wiper insert.

Procedure version D is a combined one: roughing with a standard insert, smoothing by high-speed infeed grinding.

Procedure version E is combined: roughing with a wiper insert, smoothing by high-speed infeed grinding.



Procedure version A				Procedure versions B and C				Grinding for procedure versions D and E			
v_c	30 m/s	v_w	18 m/min	v_c	180 m/min	$f_{(B)}$	R_{St}: 0,15 mm/rev S_{St}: 0,08 mm/rev	v_c	45 m/s	t_{sp}	6 s
$v_{f,L}$	R: 2200 mm/min S: 2000 mm/min	i_{sp}	8 strokes			$f_{(C)}$	R_W: 0,24 mm/rev S_W: 0,12 mm/rev	$v_{f,R}$	R: 0,0050 mm/s S_1: 0,0033 mm/s S_2: 0,0016 mm/s	$v_{f,R,A}$	0,108 mm/s
a_e	R: 0,02 mm/double stroke S: 0,001 mm/double stroke	Z	R: 0,10 mm S: 0,05 mm	a_p	R: 0,10 mm S: 0,05 mm	Z	R: 0,10 mm S: 0,05 mm	v_w	55 m/min	Z	R: 0,095 mm S_1: 0,010 mm S_2: 0,005 mm

Figure 1 Drafts and technological conditions of the procedure versions

2.3 Method of investigation

The comparative investigation of five different procedure versions was performed at different bore geometries. The operation time, the material removal rate and the surface rate are determined in all cases.

2.3.1 Determination of operation times

Comparative calculations were carried out for the operation time (T_{op}). For the determination the following time components were considered: machining time (T_{mach}), base time (T_{base}) and piece time (T_{piece}). The following equations demonstrate the calculations.

Turning operations:

$$T_{mach} = \frac{L'}{f \cdot n_w} = \frac{L+1+1}{f \cdot n_w}, \text{(min)} \tag{1}$$

$$T_{base} = T_{mach} + T_{change} + T_{other}, \text{(min)} \tag{2}$$

$(T_{change} = 0{,}2 \text{ min}; T_{other} = 0)$,

$$T_{piece} = T_{base} + T_{accessory}, \text{(min)} \tag{3}$$

$T_{accessory} = 0{,}2 \cdot T_{base}$,

because $T_{mach} \le 1{,}4$ min (given from plant)

$$T_{op} = \frac{T_{set\ up}}{n} + T_{piece}, \text{(min)} \tag{4}$$

$T_{set\ up} = 20$ min (given from plant),

$n = 200$ (lot size).

Traverse grinding:

$$T_{mach} = \frac{2L}{v_{f,L,R}} \cdot \frac{Z_R}{a_{e,R}} + \frac{2L}{v_{f,L,S}} \cdot \left(\frac{Z_S}{a_{e,S}} + i_{sp} \right), \text{(min)} \tag{5}$$

Infeed grinding (to the combined procedure):

$$T_{mach} = \frac{0{,}27}{2 \cdot v_{f,R,A}} + \frac{Z_R}{v_{f,R,R}} + \frac{Z_{S1}}{v_{f,R,S1}} + \frac{Z_{S2}}{v_{f,R,S2}} + t_{sp}, \text{(min)} \tag{6}$$

Notations not applied before in the equations: i_{sp} − double strokes of spark-out; 0,27 − radial allowance of air grinding; t_{sp} − time of spark-out.

2.3.2 Material removal parameters

The efficiency of procedures was assessed by the values of material removal rate (MRR – Q_w, mm^3/s) and surface rate (SR – A_w, mm^2/s). The theoretical values of these parameters are the removed volume of material (MRR) and machined surface area per second (SR). The calculation of the different theoretical values has been used for a long time mainly applying the different possible cutting data of a procedure. However, in the comparison of different procedures the theoretical values give only approximate results [14].

The calculated theoretical parameters refer to a single length of feed of the tool by grinding and turning. In turning some tenths of millimetres can indeed be removed by one or maybe two passes. But in grinding this is impossible. In the latter more roughing, smoothing and spark out passes (length of feed or stroke) are required. In the rate of the necessary extra time the actual values are reduced compared with the theoretical ones. This leads to the statement in [14] that the definition of practical parameters expressing the actual efficiency of material removal should be introduced, especially in different kinds of material removal methods. Accordingly the comparison of the efficiency of the different procedures was performed by the practical values of material removal rate (Q_{wp}) and surface rate (A_{wp}).

The practical value of the Q_{wp} material removal parameter is calculated by correlating the volume of the removed material to the time required for the removal.

$$Q_{wp} = \frac{d \cdot \pi \cdot L \cdot Z}{t_x \cdot 60}, \text{(mm}^3\text{/s)} \quad (7)$$

where: d − bore diameter (mm), L − bore length (mm), Z − radial allowance (mm), t_x − a certain economic time, here operation time (T_{op}).

The practical value of the A_{wp} material removal parameter is calculated by correlating the machined surface area to the time required for the removal:

$$A_{wp} = \frac{d \cdot \pi \cdot L}{t_x \cdot 60}, \text{(mm}^2\text{/s)}. \quad (8)$$

3 Operation times as a function of bore geometry

Economic efficiency of machining can be well characterized by its time consumption. We determined and compared the operation times and then analyzed the efficiency of material removal.

3.1 Operation times

The operation times were calculated by the methods given in Eq. (7) and Eq. (8).

Fig. 2 illustrates the results for version of a given geometry as an example (d=50 mm and L=30 mm). The diagram demonstrates that further procedures applied besides grinding facilitate the significant reduction of operation time, as found also in [3].

These procedures are capable of obtaining the accuracy and surface quality reachable by grinding. Similarly, the operation times were calculated for all considered cases (procedure and geometry) and thereafter the times were compared to grinding (procedure A) as the base machining.

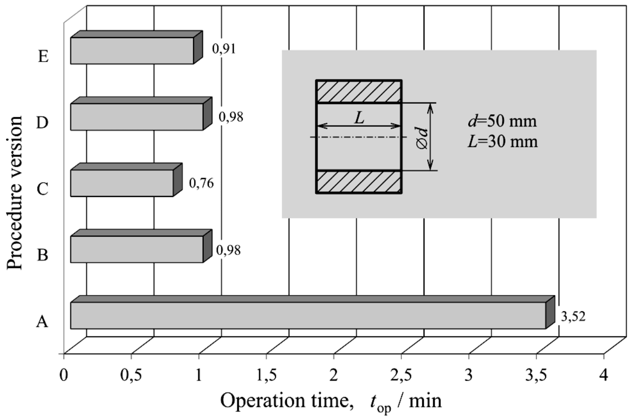


Figure 2 Operation times of the five procedure versions for d=50 mm bore diameter and L=30 mm bore length

3.2 Effect of bore length on the operation time

First we analyzed how the times of operations change when different bore lengths are machined. The rates of operation times were also calculated as follows. The operation time of grinding was considered as the basis (so the grinding represents 100 % or 1) and the operation times of the other procedures were compared to this. Fig. 3 represents the results of these calculations as a function of bore length.

The effects of bore length on the different procedure versions are:

- Since the time needed for traverse grinding (procedure A) and hard turning (procedure versions B and C) increases in about the same extent as the bore length, the relative rates of the two operation times do not change significantly.
- In the infeed grinding procedure the operation time is reduced compared to the traverse grinding procedure. Therefore the rate is reduced with the increase of the bore length (procedure versions D and E).

Since the effect of bore length differs, it is expedient to designate ranges and/or limits (bore lengths) at which the surface can be machined in the shortest time with a given procedure.

In Fig. 3 the rates of operation time are represented as a function of the L bore length for the diameter d=50 mm. Since the basis of comparison is grinding, the rate of procedure A is A/A=1. This was not recorded in the figure, because the time of conventional grinding was the largest for every combination of data.

In Fig. 3 it can be seen that hard turning better applied at smaller bore lengths, while the combined procedure is better for longer bores in the analyzed range. Considering all the procedures, the machining can be performed in the shortest operation time if hard turning with a wiper insert (C) is applied up to about 50 mm bore length and a combined procedure (E) is applied above this length.

Hereafter on the basis of Fig. 3 the limits of bore lengths (referring to any procedure) are introduced at which the change of the applied procedure is recommended in order to reach shorter time.

When the application of any procedure is possible, at L=26 mm the changeover from hard turning with standard insert (procedure version B) to E, and at L=30 mm to D is recommended. At L=52 mm the changeover from hard turning with wiper insert (procedure version C) to E and at L=79 mm to D is recommended if a more productive procedure is preferable. (In Fig. 3 at L>40 mm the limits of bore lengths are theoretical; they were determined by trend curves.)

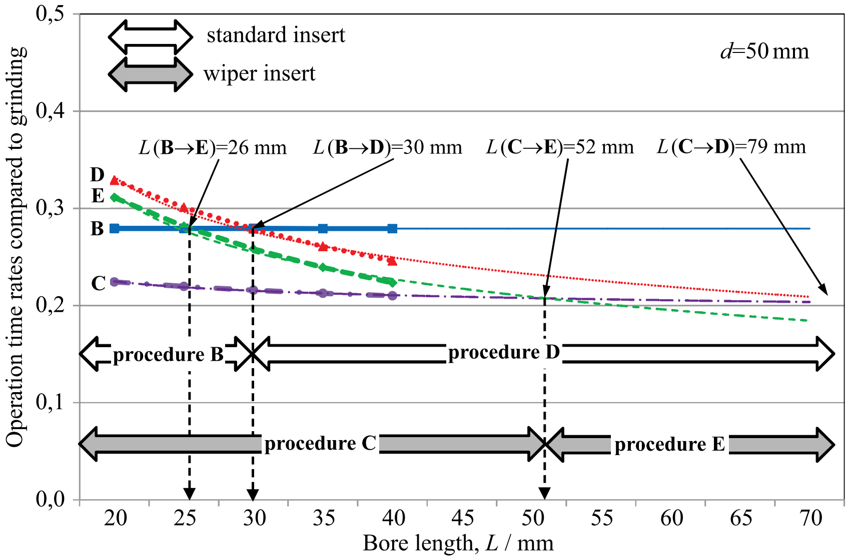


Figure 3 Limits of bore length on the basis of operation time changes

3.3 Effect of bore diameter on the operation time

In Fig. 4 the rates of operation time are represented as a function of the bore diameter at L=30 mm bore length. The effects of bore diameter on different procedure versions are:

- The operation time of the traverse grinding is independent of the bore diameter (it depends only on the bore length).
- The operation time increases linearly in the other procedure versions. The increment is larger in procedure versions B and C than in D and E.

In Fig. 4 the limits referring to bore diameter are given. At this point it is recommended to change the procedure in order to reach shorter operation time.

To minimize the operation time it is recommended to apply the combined procedure instead of hard turning with standard insert above d=50 mm and instead of hard turning with wiper insert above d=75 mm. The shortest operation time is obtained by the application of a wiper insert in all cases. (In Fig. 4 at d>95 mm the limits of bore diameters are theoretical; they were determined by trend curves.)

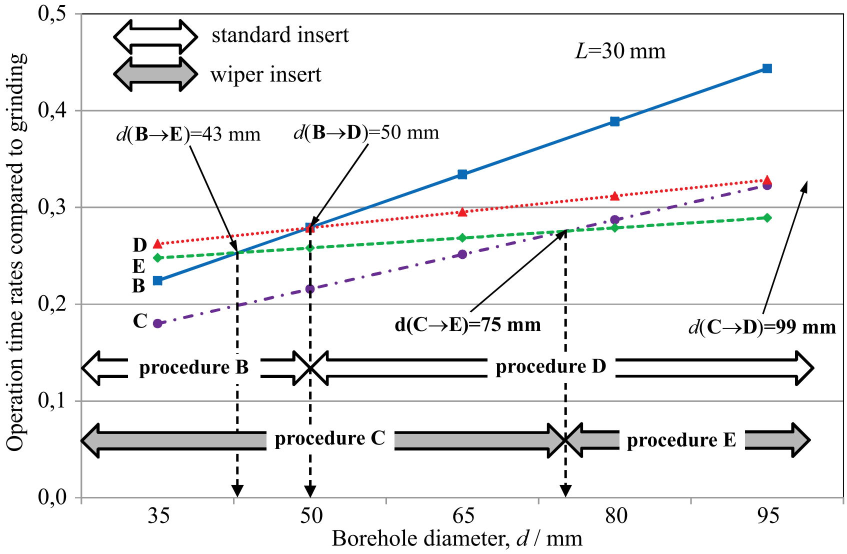


Figure 4 Limits of borehole diameter on the basis of operation time changes

4 MRR and SR as a function of bore geometry

The investigations of MRR and SR and the comparison of the efficiency of the different procedures were performed with the use of the practical values of the material removal rate (Q_{wp}) and surface rate (A_{wp}).

4.1 The effect of bore length on material removal rate and surface rate

The results of calculations are represented in Figs. 5 and 6 at five bore lengths (d=50 mm). It can be seen that the A_{wp} (Fig. 5) and Q_{wp} (Fig. 6) show the lowest value for grinding at every diameter. This demonstrates the quite poor material removal rate and surface rate of the abrasive procedure.

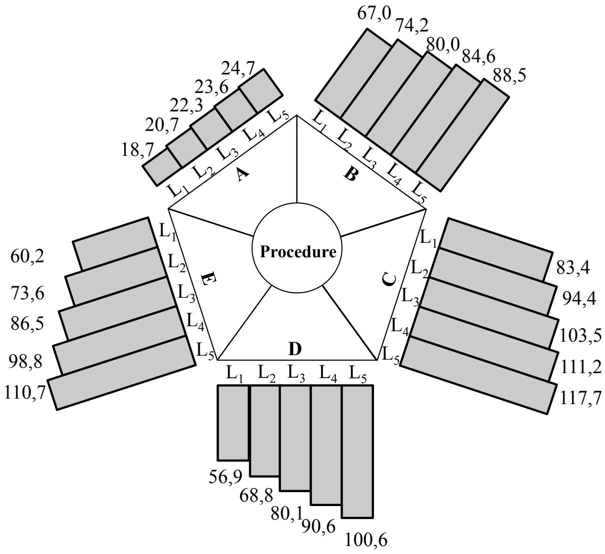


Figure 5 Effect of bore diameter on SR at d=50 constant bore diameter

At the smallest bore length hard turning gives the most favourable value referring to A_{wp} (B: 67; C: 83,4). These values are 3,6 times and 4,5 times higher than in grinding (Fig. 5). At the largest investigated bore length the rank of A_{wp} values is C, E, D and B. The rates of these to grinding are 4,8; 4,5; 4,1 and 3,6, respectively. The values of removable volume per second (Q_{wp}) in one operation at small bore length are larger than 10 in procedure versions B and C, while at larger bore lengths the procedure versions C (17,7) and E (16,6) are favourable.

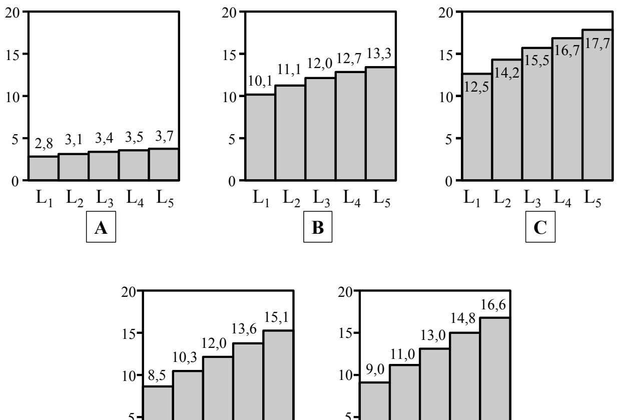


Figure 6 Effect of bore diameter on MRR at d=50 constant bore diameter

The A_{wp} and Q_{wp} rates of the procedures compared with grinding are equal, for the allowance can be removed in one pass in the cutting task. The values are represented in Fig. 7. It can be noticed that while in the combined procedures the effect of the increase of bore length on the rates (D/A: 3,0...4,1; E/A: 3,2...4,5) can be judged significant, in the other procedures it is practically constant (B/A: 3,6; C/A: 4,6…4,8).

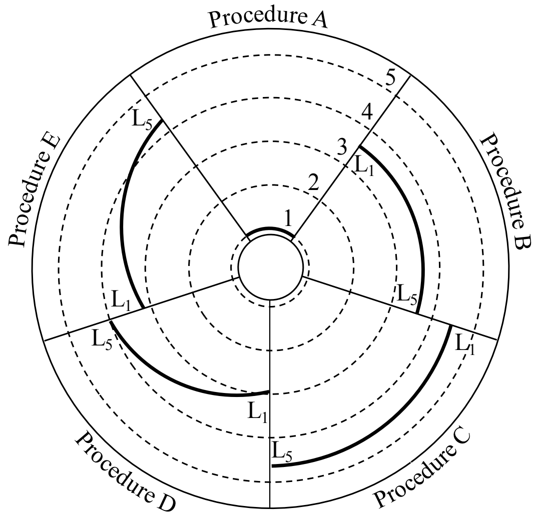


Figure 7 Rates of material removal parameters of the investigated procedures compared to grinding (Procedure A) at different bore lengths ($L_1…L_5$)

4.2 The effect of bore diameter on the material removal rate and surface rate

As can also be seen in Figs. 8 and 9, by machining of any surface in the operation necessary for the machining the material removal rates of grinding are the lowest. Increasing the diameter from 35 mm to 95 mm, the values of A_{wp} of the single procedures are 2,72 times (A), 1,37 times (B), 1,51 times (C), 2,16 times (D) and 2,33 times (E) higher.

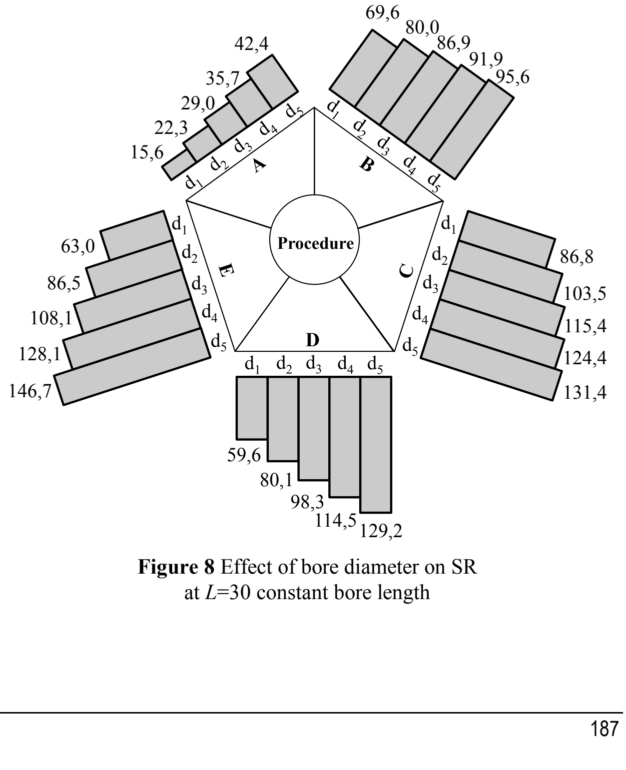


Figure 8 Effect of bore diameter on SR at L=30 constant bore length

From our analysis of hard turning it can be stated referring to both applications (separated operation or as part of the combined procedure) that the material removal is more efficient when using a wiper insert. In the MMR analysis, within the analysed range of diameters the maximum of the material volume removed per second in one operation at the smallest diameter was 13,0 mm^3 (Procedure C), while at the largest diameter 22,0 mm^3 was obtained (Procedure E) (Fig. 9).

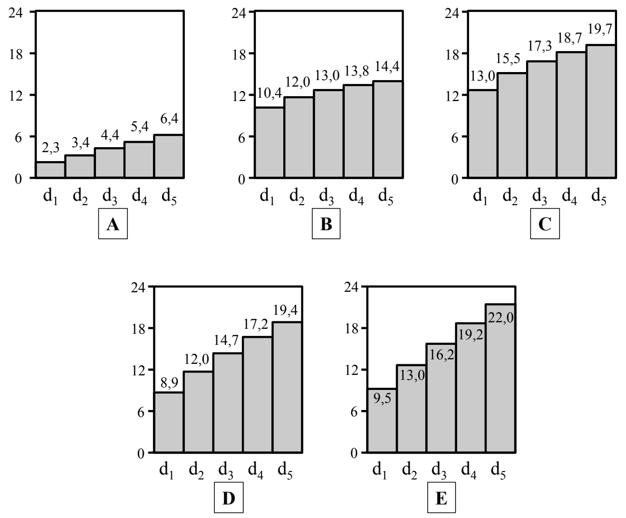


Figure 9 Effect of bore diameter on MRR at *L*=30 mm constant bore length

The rates of material removal parameters are represented in Fig. 10. As the bore diameter increases the precedence of the other procedures over grinding is reduced but remains significant. From another aspect: as the bore diameter decreases, the efficiency of material removal of every procedure increases significantly compared to grinding (B/A: 4,46…2,26, C/A: 5,56…3,10; D/A: 3,82…3,04, E/A: 4,04…3,46). At the smallest diameter the smallest increment of the rate of material removal parameters is 3,82 (D/A), while the largest increment is 5,56 (C/A). At the largest diameter the smallest increment is 2,26 (B/A), while the largest increment is 3,46 (E/A).

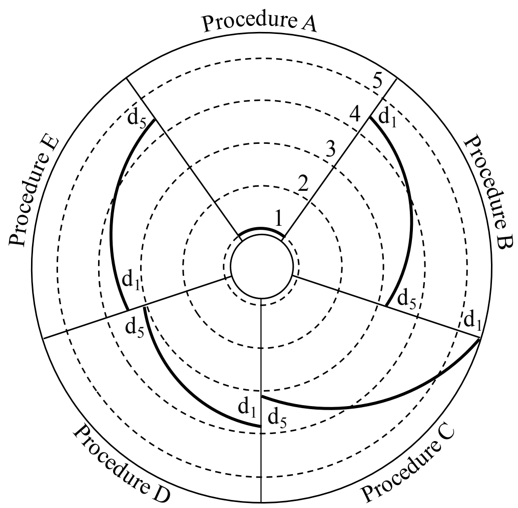


Figure 10 Rates of material removal parameters of the investigated procedures compared to grinding (Procedure A) at different bore diameters ($d_1…d_5$)

5 Conclusion

Based on our findings it can be stated that the efficiency of material removal is influenced by the bore geometry. The extent of the effect differs for the different hard machining procedures.

In the analyzed range of bore lengths and bore diameters, on the basis of the surface rate and material removal rate, hard turning and the combined procedure are procedures which have significantly larger efficiency compared to grinding.

The effect of the increase of bore length on the rates of material removal parameters in the combined procedures can be judged significant compared to values for grinding, while it is actually unchanged in the other procedures.

Reducing the bore diameter leads to a significant increase in the efficiency of material removal of every procedure compared to grinding.

Whether hard turning is investigated either as a separated operation or as the part of the combined procedure, our results show that the application of wiper inserts results in more efficient material removal.

When planning hard machining technology, a precise analysis is recommended to gain information about the efficiency of the available procedures.

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Glossary

Nomenclature	Unit	Explanation
d	mm	bore diameter
L	mm	bore length
L'	mm	length of bore length and overrun
v_c	m/s	cutting speed of grinding
v_c	m/min	cutting speed of turning
v_w	m/min	workpiece speed
n_w	rev/min	revolution number of the workpiece
n	piece	lot size
$v_{f,L}$	mm/min	speed of traverse grinding
$v_{f,L,R}$	mm/min	speed of traverse grinding in roughing
$v_{f,L,S}$	mm/min	speed of traverse grinding in smoothing
$v_{f,R}$	mm/s	speed of infeed grinding
$v_{f,R,R}$	mm/s	speed of infeed grinding in roughing
$v_{f,R,S}$	mm/s	speed of infeed grinding in smoothing
$v_{f,R,A}$	mm/s	speed of infeed grinding in air
f	mm/rev	feed
$f_{(B)} - R_{St}$	mm/rev	feed of rough turning with a standard insert (procedure versions B and D)
$f_{(B)} - S_{St}$	mm/rev	feed of smooth turning with a standard insert (procedure version B)
$f_{(C)} - R_W$	mm/rev	feed of rough turning with a wiper insert (procedure versions C and E)
$f_{(C)} - S_W$	mm/rev	feed of smooth turning with a wiper insert (procedure version C)
a_e	mm/double stroke	depth of cut of traverse grinding
$a_{e,R}$	mm/double stroke	depth of cut of traverse grinding in roughing
$a_{e,S}$	mm/double stroke	depth of cut of traverse grinding in smoothing
a_p	mm	depth of cut
$a_{p,R}$	mm	depth of cut in roughing
$a_{p,S}$	mm	depth of cut in smoothing
i_{sp}	double stroke	stroke number of spark-out
t_{sp}	s	time of spark-out
Z	mm	radial allowance
Z_R	mm	radial allowance in roughing
Z_S	mm	radial allowance in smoothing
T_{op}	min	operation time
T_{mach}	min	machining time
T_{base}	min	base time
T_{piece}	min	piece time
T_{change}	min	changing time
T_{other}	min	other time
$T_{accessory}$	min	accessory time
$T_{set\ up}$	min	set up time