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# EFFICIENCY OF MATERIAL REMOVAL AND MACHINING IN CUTTING

**Abstract.** *Among the methods and parameters used for analyzing the productivity of machining procedures, this paper deals with an analysis based on the efficiency (material volume removed in unit time) of material removal. The paper focuses on how this specific indicator, the material removal rate (MRR), changes when different machining procedures and production sub-phases are considered.*

**Keywords:** *MRR; hard machining; machining time.*

## 1. INTRODUCTION

The quality of a product, from its design to the end of production process – i.e. all the steps of its production – is determined and influenced by the quality and efficiency of each phase. The machining procedures are qualified as up-to-date, developed, etc. based on their efficiency. Tremendous variations have already been exploited during development, making the procedures shorter, more profitable, etc. The machined parts became more exact and their quality is improved; therefore, overall they became better and more efficient. Some examples: high-speed machining procedures; application of high feed; combined procedures; cold forming of surfaces; application of a wiper insert.

The new procedures are analyzed by comparative methods. They are applied both to the accuracy and quality of the machined parts and to the efficiency of machining or production. One of the possible analysis methods is the study of material removal efficiency, in which the volume removed in unit time, the material removal rate, is analyzed frequently.

In Table 1 the various applications are summarized by the technology used and the objective of the MRR analysis. Kumar et al., for example, analyzed the MRR by calculating the mass of the material removed in unit time [1]. Moganapriva et al. measured the material mass and density to determine the value of the MRR parameter [2]. Yadav et al. analyzed the volume of the removed material and introduced a specific indicator by the consideration of cutting time in which the tool is in direct contact with the workpiece [3]. The surface rate and the material removal rate are calculated based only on the cutting data by researchers and practitioners (e.g. tool catalogues) in [4], [5], [6]. This means that the value of the MRR parameter is calculated by the multiplication of the feed, cutting speed, and depth-of-cut.

However, if the machining incorporates more than one different pass (e.g. roughing and smoothing) or different machining procedures are intended to be compared, this parameter is difficult to specify in analyzing the removal of a certain material volume.

Furthermore, if we wish to transform this parameter into one that is suitable for comparing machining or production processes, further time components, which are needed for the production of machining of the workpieces, not only the time of direct material removal (time in which the tool and the workpiece are connected) has to be considered. Such additional time components are for example the tool's movement without any material removal (approaching, overrun), the time of preparation and finishing operations, or the time needed for workpiece changes.

Table 1 – Main applications of the material removal rate

| Technology | Effect of technological parameters on the MRR | Optimization of technological parameters | Connection between the surface roughness and MRR | Effects of tool wear and tool life on the MRR | Effect of vibration on the MRR |
|---|---|---|---|---|---|
| Milling | [7], [8], [9] | [10] | [11] | [11], [12] | |
| | Other: Connections between the cutting force and MRR [7]. Effect of material removal strategy on the MRR [13]. | | | | |
| Electro-discharged machining | [14], [15], [16] | | [17] | | [14] |
| | Other: Connection between surface integrity and MRR [18]. Effect of heat generation on MRR-re [19]. Effect of electrode rotation velocity on the MRR [20]. Effect of dielectricum on the MRR [21]. | | | | |
| Turning | [22] | [23] | [24] | [24] | |
| | Other: Connection between the MRR and machine-tool power [25] | | | | |
| LBM | [26] | [27] | [28] | | |
| Grinding | | | | | |
| | Other: Simulation of determining MRR [29]. | | | | |
| AWC | [1] | [30] | | | |
| Drilling | | [31] | | | |
| Special examples: Chemical mechanical polishing – mathematical modeling [32]. Dental grinding – Effects of technological parameters on the MRR [33]. Mechanical polishing – Effect of vibration on the MRR [34]. Tungsten chemical mechanical planarization – mathematical modeling [35]. Grinding sapphire wafers – Effect of surface roughness on the MRR [36]. | | | | | |

Because of these factors (to extend the applicability and for more exact analysis) the practical parameter of the material removal rate was introduced. Its value is calculated on the basis of the actual time consumption of machining. This specific value can express the economic efficiency of machining in a realistic manner [37], [38], [39].

This paper investigates how the MRR values change in the various production phases when two different types of tools are applied in machining components having different geometrical values and being machined in different batch sizes.

## 2. ANALYSIS, METHOD

The efficiency of material removal in cutting is expressed by the material volume removed or the surface area machined in unit time. Here time is defined as the duration when the cutting tool is working. This value is considered by us as a theoretical value [40] because this efficiency parameter is based only on the theoretical time of removing material from the machined part. This is not realistic in a real production process because production cannot be realized without the consideration of further time parameters. Several factors are often considering in machining: machining time, piece time, norm time, operation time, sequence time, etc. The time parameter is set based on which process phase is to be analyzed. If only the time ($t$) of the direct continuous contact of workpiece and tool is considered, the formula is:

$$t = \frac{L}{n \cdot f}; t = \frac{A}{v_c \cdot f}; t = \frac{V}{v_c \cdot f \cdot a_p}; \tag{1}$$

where $L$ is the machined length; $A$ is the machines area; $V$ is the volume of the removed material; $n$ is the revolution-per-minute of the workpiece; $f$ is the feed; $v_c$ is the cutting speed and $a_p$ is the depth-of-cut.

If this time is the basis of cutting, the specific value is only a theoretical one in the sense that it expresses only the time of material removal. This time characterizes the tool wear or tool life well but does not provide information on the efficiency of machining or production process. Here we investigate what deviations occur in the analyses if only this theoretical time is considered. This is why the theoretical material removal parameter, which is based on this cutting time, is considered as a basis (100%) in the analysis and the differences are provided in percentage values. The definitions of the most frequent parameters applied in time analysis of the material removal or production process are listed below.

Main time ($t_m$): part of the base time, it expresses the duration in which shape formation is realized on the workpiece. The main time has two parts: one is when the machining is being carried out by a workstation or machine ($t_{m,w}$) and the other when the work is done manually ($t_{m,m}$).

$$t_m = t_{m,w} + t_{m,m} \tag{2}$$

Additional time ($t_a$): part of the base time; it is needed only indirectly for the fulfillment of the specified task. This time is an accompanying component to the main time, which means that it is present in machining each workpiece. Examples for this parameter are workpiece clamping, tool approach, machine warming-up, etc.

Base time ($t_b$): sum of the main time and the additional time.

$$t_b = t_m + t_a \tag{3}$$

Supplementary time ($t_s$): time rate for servicing ($t_{serv}$) the workstation(s) and for personal needs or relaxing of workers ($t_{pn}$). The supplementary time is expressed as a proportion of operation time.

Piece time ($t_p$): sum of the base and the supplementary time.

$$t_p = t_b \left(1 + \frac{t_{serv} + t_{pn}}{100}\right) \tag{4}$$

Time of preparation and finishing tasks ($t_{prep}$): before machining it is necessary to prepare for the machining task (e.g. studying the blueprints and the technological plans; tooling the machines) and after machining some additional tasks have to be performed (e.g. doing paperwork, removing tools).

Norm time or operation time ($t_{op}$): time needed to machine one workpiece of the sequence (n: batch size)

$$t_{op} = \frac{t_{prep}}{n} + t_p \tag{5}$$

In our comparative analyses these time components are used for calculating the MRR value. Machining of four disk-type components was analyzed. Geometrical values and cutting data are summarized in Table 2.

In order to analyze the efficiency of the whole sequence, further time parameters have to be considered. In our study the preparation time was 1500s and the change time of the workpiece was 10s. Two batch sizes were analyzed: $n_1$=300 pcs and $n_2$=600 pcs.

Table 2 – Technological data of the analysis

| **Part** | **L [mm]** | **L′ [mm]** | **D [mm]** | **$v_c$ [m/min]** | **$n_w$ [1/min]** | **L/d** |
|---|---|---|---|---|---|---|
| I | 33.8 | 35.8 | 83 | 180 | 690 | 0.41 |
| II | 27.35 | 29.35 | 48 | 180 | 1194 | 0.57 |
| III | 42.8 | 44.8 | 62 | 175 | 898 | 0.69 |
| IV | 35.1 | 37.1 | 35 | 120 | 1091 | 1.00 |
| **$f_{R,st}$** | 0.15 | **$f_{R,w}$** | 0.3 | **$a_{p,R}$ [mm]** | 0.1 | |
| **$f_{S,st}$** | 0.08 | **$f_{S,w}$** | 0.12 | **$a_{p,S}$ [mm]** | 0.05 | |

## 3. RESULTS AND DISCUSSION

The focal point of our study is that errors can be made by the process engineer if the theoretical values are considered in the efficiency analysis. For example, in the case of comparing two different procedures, the machining or production process or sub-process incorporates different elements. The time and MRR values are summarized in Table 3.

In Fig 1 the time and MRR values characterizing the efficiency of machining or production are represented. The $t_m(L)$ value is the time of actual material removal in length L and this value was considered as a basis for the analysis (100%). In the whole production process there are additional time components, that need to be determined for exact calculations. The $t_m(L')$ machining time incorporates not only the machining of the L length but also the approach and the overrun of the tool. The base time ($t_b$) incorporates the change time of the tool as additional time beyond the machining time. The value of this is fixed. The piece time ($t_p$) incorporates the supplementary time as a rate of the base time. Its value is determined based on plant practice. In the calculation of the operation time ($t_{op}$) the preparation time of the sequence was considered as a fixed value.

In case of the analyzed workpieces (different geometry and technological data) the order resulting from the calculations of the time parameters was II≻IV≻III≻I. Varying the batch size (n1 and n2) and the applied insert/feed (st/w), four technological variations can be formed: st/$n_1$; w/$n_1$; st/$n_2$ and w/$n_2$. The change of batch size does not influence the machining main time, the base time, or the piece time. By increasing the feed (i.e. applying the wiper insert) these values decrease by 38–41%. The batch size slightly influences the operation time. The order of the technological variants based on the operation time is w/$n_2$≻w/$n_1$≻st/$n_2$≻st/$n_1$.

The practical values of the material removal rate ($MRR_{wp}$) were compared to the theoretical value (Fig. 1). In contrary to the time parameters of the machining, these values decrease because in the calculation of MRR the removed material volume is divided by higher and higher time components.

Table 3 – Time and material removal rate values

| Insert | Batch size [pcs] | Part | $t_m$ (L) s] | $t_m$ (L') [s] | $t_b$ [s] | $t_p$ [s] | $t_{op}$ [s] | $MRR_w$ [mm$^3$/s] | $MRR_{wp,m}$ [mm$^3$/s] | $MRR_{wp,b}$ [mm$^3$/s] | $MRR_{wp,p}$ [mm$^3$/s] | $MRR_{wp,op}$ [mm$^3$/s] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| standard | $n_1$=300 | I | 56.31 | 59.64 | 69.64 | 80.09 | 85.09 | 0.39 | 0.37 | 0.32 | 0.28 | 0.26 |
| | | II | 26.35 | 28.28 | 38.28 | 44.02 | 49.02 | 0.39 | 0.36 | 0.27 | 0.23 | 0.21 |
| | | III | 54.78 | 57.34 | 67.34 | 77.44 | 82.44 | 0.38 | 0.36 | 0.31 | 0.27 | 0.25 |
| | | IV | 36.99 | 39.09 | 49.09 | 56.46 | 61.46 | 0.26 | 0.25 | 0.20 | 0.17 | 0.16 |
| wiper | | I | 34.27 | 36.30 | 46.30 | 53.25 | 58.25 | 0.64 | 0.61 | 0.48 | 0.41 | 0.38 |
| | | II | 16.04 | 17.21 | 27.21 | 31.29 | 36.29 | 0.64 | 0.60 | 0.38 | 0.33 | 0.28 |
| | | III | 33.35 | 34.90 | 44.90 | 51.64 | 56.64 | 0.63 | 0.60 | 0.46 | 0.40 | 0.37 |
| | | IV | 22.51 | 23.80 | 33.80 | 38.87 | 43.87 | 0.43 | 0.41 | 0.29 | 0.25 | 0.22 |
| standard | $n_2$=600 | I | 56.31 | 59.64 | 69.64 | 80.09 | 82.59 | 0.39 | 0.37 | 0.32 | 0.28 | 0.27 |
| | | II | 26.35 | 28.28 | 38.28 | 44.02 | 46.52 | 0.39 | 0.36 | 0.27 | 0.23 | 0.22 |
| | | III | 54.78 | 57.34 | 67.34 | 77.44 | 79.94 | 0.38 | 0.36 | 0.31 | 0.27 | 0.26 |
| | | IV | 36.99 | 39.09 | 49.09 | 56.46 | 58.96 | 0.26 | 0.25 | 0.20 | 0.17 | 0.16 |
| wiper | | I | 34.27 | 36.30 | 46.30 | 53.25 | 55.75 | 0.64 | 0.61 | 0.48 | 0.41 | 0.40 |
| | | II | 16.04 | 17.21 | 27.21 | 31.29 | 33.79 | 0.64 | 0.60 | 0.38 | 0.33 | 0.31 |
| | | III | 33.35 | 34.90 | 44.90 | 51.64 | 54.14 | 0.63 | 0.60 | 0.46 | 0.40 | 0.38 |
| | | IV | 22.51 | 23.80 | 33.80 | 38.87 | 41.37 | 0.43 | 0.41 | 0.29 | 0.25 | 0.23 |

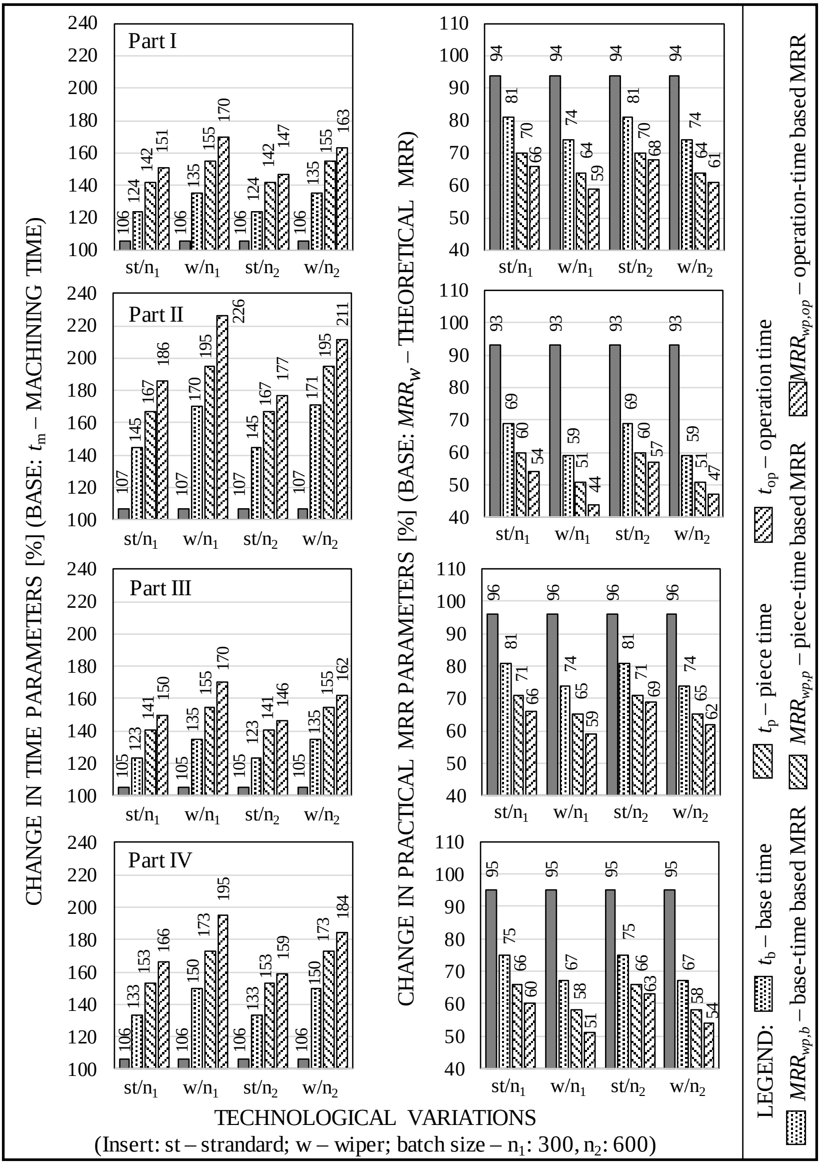


Figure 1 – Time and efficiency values for different geometrical and technological data

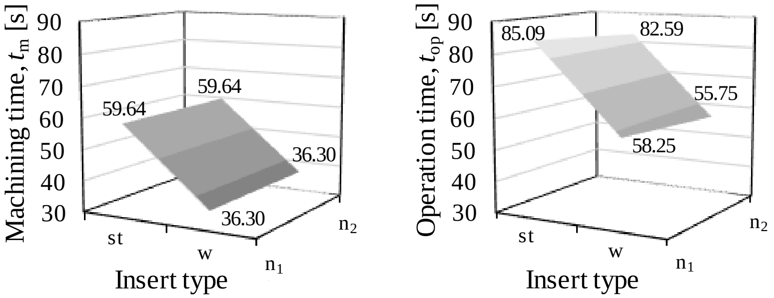


Figure 2 – Machining time and operation time as a function of the insert (applied feed) and batch size (Part: I; Borehole: L 33.8 mm, d 83 mm)

In case of the analyzed workpieces (different geometry and technological data) the order resulted from the calculations of the different material removal rate values was I≻III≻II≻IV. The order of the technological variants based on the material removal rate calculated by the operation time is w/$n_2$≻w/$n_1$≻st/$n_2$≻st/$n_1$, which is identical to the order based on the operation time.

In Figure 2 it can be observed that the increase of batch size does not influence the machining time but it decrease the operation time by 3–4%. The applied insert and therefore the increase of feed decreases the machining time by 39% and the operation time by 32%.

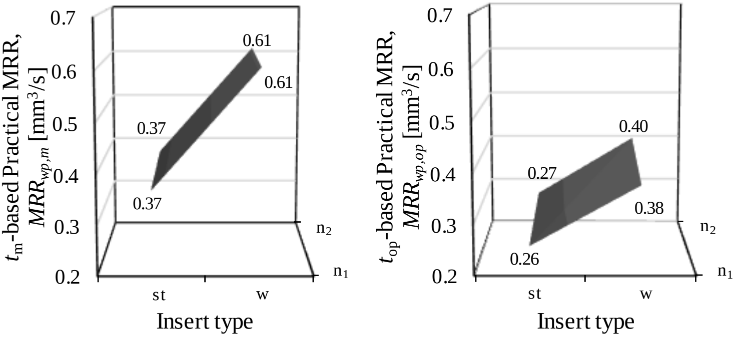


Figure 3 – The practical material removal rate based on the machining time and operation time as a function of the applied insert
(Part: I; Borehole: L 33.8 mm, d 83 mm)

The following findings were made concerning the machining time and the operation-time based practical value of material removal rate (Fig. 3): the machining-time based MRR is not influenced by the increase of batch size; the operation-time based MRR is increased by 3.7–5%. With the applied insert and thus the increase of feed, the machining-time based and operation-time based MRR are increased by 64% and 48–50%, respectively. The machining-time based MRR increased by 64% and the operation time-based increased by 55.6% in case of the parallel increase of the two influencing factors ($n_1$/st→ $n_2$/w).

The effect of change in batch size on the operation time and the material removal rate was analyzed generally. The data of Part II were considered (Fig. 4). It was found that with the increase of batch size, the operation time converges to the piece time and the operation time-based MRR converges to the $MRR_{wp,p}$ calculated based on the piece time. On the basis of Fig. 4 a certain batch size can be determined if the practical value of the material removal rate is designated as a proportion of the $MRR_{wp,p}$. In the figure the batch size values used as examples are connected to the rates 0.85; 0.9 and 0.95. The intersections show the values of batch sizes ($n_{0.85}$=185; $n_{0.9}$=300; $n_{0.95}$=650).

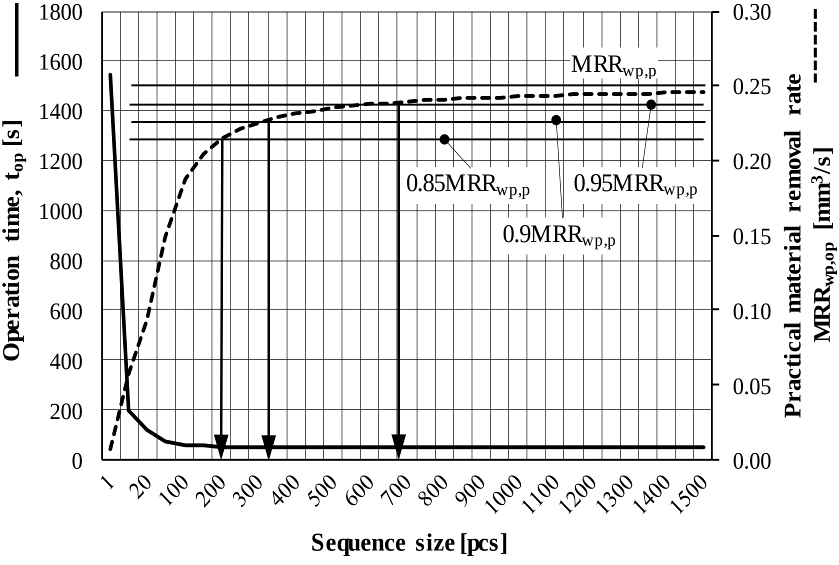
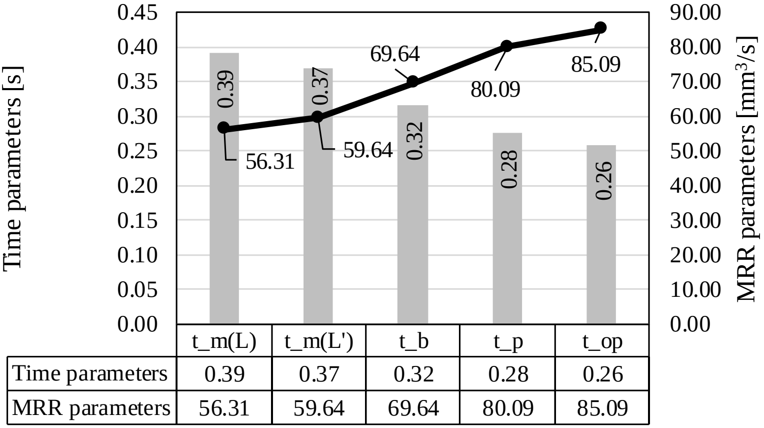


Figure 4 – The operation time and the operation-time based material removal rate as a function of batch size
(Part: II; Borehole: L 27.35 mm, d 48 mm)



| | t_m(L) | t_m(L') | t_b | t_p | t_op |
|---|---|---|---|---|---|
| Time parameters | 0.39 | 0.37 | 0.32 | 0.28 | 0.26 |
| MRR parameters | 56.31 | 59.64 | 69.64 | 80.09 | 85.09 |

Figure 5 – The analyzed MRR and time parameters in case of the st/n$_1$ parameter combination (Part: I; Borehole: L 33.8 mm, d 83mm)

If the batch size is given, then based on Fig. 4 the practical value of MRR and its rate to MRR$_{wp,w}$ connected to the batch size can be determined in order to facilitate decision-making.

In Fig. 5 the analyzed time and MRR efficiency parameters are demonstrated for a chosen workpiece. The time parameters are ordered by their increase and meanwhile the practical material removal rate parameters (connected to the different time parameters) show a decrease. Thus, the higher the number of time components of the production process considered, the more the efficiency of material removal decreases.

## 4. CONCLUSION, SUMMARY

In this paper some parameters expressing the efficiency of material removal were introduced when machining certain workpieces. It was also shown how these parameters change if more realistic time components of machining are considered in the calculations. The chosen efficiency parameter, which can be applied to any process phase, is a specific indicator which incorporates the efficiency of allowance removal and the time consumption required by the technological conditions. Since the production process incorporates numerous steps (and so different time components), the first step of the efficiency analysis has to be the decision of what process phase or what procedure the practical value of MRR is intended to be applied for, and whether we need to analyze efficiency or apply it for a comparative analysis. The deviations in the analyzed parameters from the theoretical value demonstrated for different geometries. The results proved that it is not enough to analyze the theoretical MRR values, because this can result in a distorted conclusion.

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# ЕФЕКТИВНІСТЬ ВИДАЛЕННЯ МАТЕРІАЛУ ПРИ МЕХАНІЧНІЙ ОБРОБЦІ РІЗАННЯМ

**Анотація.** *Ефективність видалення матеріалу при різанні виражається обсягом матеріалу, що видаляється або площею поверхні, обробленої в одиницю часу. Час визначається як тривалість роботи ріжучого інструменту. Це значення розглядається як теоретичне, оскільки цей параметр ефективності заснований тільки на теоретичному часі видалення матеріалу з оброблюваної деталі. Це нереально у виробничому процесі, тому що виробництво не може бути реалізоване без урахування додаткових часових параметрів. Одним з можливих методів аналізу є вивчення ефективності видалення матеріалу, при якому аналізується обсяг, видалений в одиницю часу (MRR). У цій статті досліджуються зміни MRR на різних етапах виробництва, при використанні двох різних типів інструментів, застосовуваних у різних видах обробки, які мають різні геометричні параметри і при обробці різних розмірів партій деталей. При обробці певних деталей були введені деякі параметри, що виражають ефективність видалення матеріалу. Також було показано, як змінюються ці параметри, якщо в розрахунках враховуються більш реалістичні компоненти терміну обробки. Вибраний параметр ефективності, який може бути застосований до будь-якої фази процесу, є спеціальним індикатором, який включає в себе ефективність видалення припуску і витрати часу, необхідні за технологічними умовами. Оскільки виробничий процес включає в себе численні етапи (і, отже, різні часові компоненти), першим етапом аналізу ефективності має бути рішення про те, для якої фази процесу або для якої процедури повинна застосовуватися практична цінність MRR, і чи потрібно нам проаналізувати ефективність або застосувати її для порівняльного аналізу. Відхилення аналізованих параметрів від теоретичного значення продемонстровані для різних геометрій інструментів. Результати довели, що недостатньо проаналізувати теоретичні значення MRR, тому що це може призвести до викривленого висновку.*

**Ключові слова:** *MRR; жорстка обробка; час обробки.*