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A new method for analysing the efficiency of cutting inserts

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Abstract – The operational productivity and the economic efficiency of turning, drilling and milling inserts can be expressed by cutting performance. This complex definition is composed of several main and supplementary features, therefore it is not possible to characterise it by only one indicator. In the present article a new method will be introduced, being able to measure and compare the productive efficiency of turning inserts: the four most important features will be summarised in one indicator. The procedure has a low time requirement, it is built on instrumental investigations, so it does not require great financial and material expenses, it makes possible to use the tools in an optimal way, according to the four aspects, investigated by us, and to qualify the inserts in many ways. The so called complex efficiency indicator serves to measure the effectiveness of innovation, too. The procedure, developed by us, has already been used successfully in case of tools, produced by leading companies and having different functions, design and materials.

1. Introduction

Nowadays, in the area of cutting operations there are appearing new versions of mounted tools. The cutting elements, the inserts, optimised to the given task, are fixed in the tool holders, drill and milling cutter bodies by the manufacturing companies. Although the amount of operationally applicable shape variations is quite limited, the number of the chipbreakers and edge designs, usable under different circumstances, is considerably great. The operational productivity and economical efficiency of turning, drilling and milling inserts can be mostly described by the cutting performance. This term is a complex feature of the tool (its edge geometry and/or material), serving to judge and qualify its behaviour during cutting operation (wear, tool life, force effects, the shape of the developed chips etc.) and the achieved surface quality (waviness, roughness) of the machined workpiece. The *judgement* is always built on practical experiences, it provides a characterisation, describable with words, i. e. it has a quantitative character. For example, an insert is considered to be appropriate if it breaks the chip well and its wear process is low. The *qualification* is mainly built on instrumental measurements, it characterises the productive efficiency of the tested tool with the results of measurements, depending from the adjusted data combinations, i. e. in a qualitative way [1][2].

The following article is going to introduce a method for measuring and comparing the cutting performance of cutting inserts. The procedure is built on short-time examinations; therefore it does not require great material, instrumental and financial expenses. The developed method has been successfully applied in case of tools, having different tasks, constructions, cutting materials and produced by world-famous tool manufacturing companies [3][4].

2. Machinability and cutting perfomance

Among the specialists, being familiar with the technology, the pair of terms „machinability” and „cutting performance” is well-known. The first mentioned characterises the workpiece material based on three different sets of parameters. The first set of parameters provides information on the *chemical composition* of the workpiece: it refers to the percentage ratio of main and auxiliary alloy components, furthermore to the rate of the non-metallic alloys (for example, S, Ca, Se, Te etc.), having a positive influence on the machinability. The chemical composition determines the possible microstructure of the given material. It includes also undesired alloy materials, getting into the material as pollution (for example, S, O, Si). The second set of parameters refers to the *condition* of the workpiece, including the method of the production (preproduction), the (preliminary) heat treatment and structure of the material etc. To this belongs the different machinability of the cast or forged pre-production products (compared to the basic structure). The third set of parameters is formed by the *material properties* of the workpiece. These cover the mechanical, the thermo-physical and the metallographycal properties of the given grade. The first group of features includes the strength and density at low and high temperature, etc., the thermo-physical contains, for example, the specific heat, thermal conductivity and absorption properties, while the last one involves the material structure, the ratio and microhardness of hard phases, macrohardness, tendency of the self-hardening, critical temperature, etc. [5].

From the material properties of the workpiece, the listed ones have the greatest influence on the tool:

- *basic hardness* of the workpiece material (having a close correlation with the strength) has a significant influence on the cutting force and the temperature, to be developed during the machining, and it determines the mechanical and thermo-physical load of the direct environment of the tool edge.
- good ductility (appropriate elongation) has a correlation with the toughness. Some alloy materials (Cr, Mo, Ni, W) increases the toughness, while in case of other ones (Cr, Ni) it may be accompanied by the *adhesion* tendency (to sticking) and it may be a precondition to the development of built-up edge.
- hard phases of multiphase materials (for example, the presence of the primary silicon crystals with a great hardness in the hypereutectic aluminum alloys etc.) have an increased *abrasive* influence, therefore, they can cause an intensive tool wear.
- presence of some alloy materials (Cr, Ni etc.) in the workpiece causes *self-hardening* during the machining. If the allowance is detached with some cuts, then there is an increase in the hardness of the upper layers, already machined.
- thermo-physical properties of the workpiece can be influenced by alloy materials. These features determine the ratio of the (thermal) energy, developed during the machining and getting into the workpiece and chip, and also the percentage, causing tool damage.

In the last decades, a range of novel materials has appeared (ADI – Austempered Ductile Iron, CGI – Compated Graphite Iron, duplex corrosion resistant steels, heat resistant (HRSA) nickel- and cobalt-based alloys, used in gas turbine manufacturing, AMC – aluminum-based composits, AMFS – aluminum-based, syntactic composite metal foams etc.), where the economic machining causes a real challenge for tool manufacturing companies. It means that the very poor workpiece machinability should be offset by the increased cutting perfomance of applied tools.

The cutting perfomance is a measure of the efficiency of tools, having different designs, geometries and materials (including substratum and coatings, too), its main feature is the tool life (and its wear curve and wear model, describing this). Without that knowledge it is not possible to calculate, analyse or compare the manufacturing (operational) costs, the productivity (expressed, for example, in piece/hour). It requires quite great material and financial expenses to determine its value for a given task, while its validity depends to a great extent on the specific conditions of production (the composition, the condition and hardness of the workpiece, the condition of the machine etc.).

The *supplementary features* of cutting performance include several factors: material flow velocity (with other words, the material removal rate), cutting temperature, cutting force components and power requirement, the shape and size of the chips, the microgeometry (wavieness, roughness) and the layer properties of the machined surface. Some of the listed properties can only be measured with complicated instruments (for example, the temperature in case of dry-machining) or the measurement can cause damage in the produced workpiece (for example, the material structure, the change in the microhardness, the distribution of the residual stress etc.).

3. Examination of the efficiency of cutting inserts

In the indicator, developed to qualify cutting inserts, research and practical experiences of two decades have been summarised. The quintessence of the developed method is to determine the cutting performance of a single insert with four selected supplementary features. Important factors will be considered that first can be easily calculated and observed, and, second, they can be quite easily measured. An advantage of this procedure is that the test of the tool occurs with material-, instrument- and cost-friendly way, i. e. with short-time use. This requires only nine different setups and it means turning a length of just 150-200 mm.

The cutting performance is a complex definition and it is impossible to express it with a single indicator. If we asked a practicing specialist what are the characteristics of fine working tools than his reply probably would be the following: „productive and easy chip detachment, furthermore, favourable, foreseeable surface roughness, resulting from the low cutting force and favourably broken chips".

Accordingly, the selected supplementary features are: the material removal rate (MMR), the chip shape, the active cutting force and the Rz parameter of surface roughness. The specific feature of this method is that all the four factors are described with a single indicator and in this figure the most important requirements, concerning the tool, are summarised.

In case of any setting, the formula of efficiency indicator, describing the cutting performance of a turning insert, is the following:

$$H = \frac{1000 \cdot V' \cdot g}{F_a \cdot Rz} = \frac{1000 \cdot a \cdot f \cdot v_c \cdot g}{F_a \cdot Rz} \left[\frac{\text{mm}^3}{\text{min} \cdot N \cdot \mu m} \right] \qquad (1) \ ,$$

where there are: MMR (V´, mm^3/min), the figure, referring to the chip shape (g), the active cutting force (F_a , N) and the achieved surface roughness (Rz, µm). The formula (1) suggests that the greater material flow rate and more favourable chip shape is, the better the efficiency is. On the other hand, the smaller power requirement of the chip detachment and break is, and the smaller roughness on the machined surface is, the more favourable the use of the insert is.

The selection of the four „critical" features (beside their simple measurability and exact determination) can be explained by the following considerations.

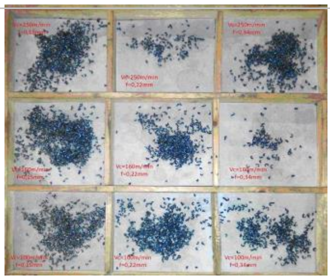
1. ***Material removal rate*** refers to the productivity of the cutting process. In case of turning operation it is the product of depth of cut, the feed and the cutting speed, and – after substitution – it has the unit of measurement: cm^3/min. By reason of the scale of „H" indicator it is recommended to use the unit mm^3/min in formula (1).

   During the tests, the depth of cut has a constant value, while – according to the function of tested insert – the feed rate and cutting speed values were varied on three-three levels (i. e. altogether 9 settings).

   The cutting perfomance features can be really shown when there is a several-fold increase in the intensity of the chip detachment during the tests. During the tests the tool wear should not affect the results of the measurements, therefore all the three technological data have to be adjusted to the workpiece material (cutting speed), and to the chip breaking range of the insert (depth of cut and feed).

2. ***Favourable chip shape*** decisively affects the process-sure operation of machines with limited superivision (CNC-lathe centres, multitasking machines etc.), but it has an effect on the aesthetic appearance of machined products, too. The rebound movement of chip to the machined surface may cause faulty products, as the chip may cause damage on other clearly visible surfaces or on the coated surface.

   The chip samples, detached during the tests, will be arranged in a chart form (in a so-called „chip chart") and after that the value of „g", reffering to the chip shape, can be determined. It is a mark (is a whole number) and its value may be between g= 1...5. The most favourably broken chips were awarded the mark „5", while the dangerously tangled, flowing chips receive the mark „1". We would like to note that this classification matrix – to our knowledge – was applied first in Hungary by the authors [6][7][8].



Efficiency: 89%	f=0,15 mm	f=0,22 mm	f=0,34 mm
v_c=250m/min	4	5	5
v_c=160m/min	4	4	5
v_c=100m/min	4	5	4

Figure 1 Chip chart and marks of the detached chips
Insert: CNMG120408 MP3 WPP20S
Machining conditions: C50 unalloyed steel (HB220±5); a=2 mm; dry machining

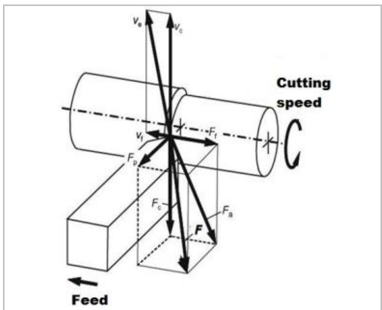
The ***Figure 1*** shows the chip chart of an insert (together with the evalution, „mark”). In the heading of the table the general chipbreaking efficiency is shown, it is a number, exactly the percent ratio of the sums of the marks, awarded to the inserts, and the sum of the maximum available marks (in this case it is 9x5 = 45).

3. ***The active force*** is the summarised value of two force components, determined by instrument measurement. Although the force measuring equipment is able to register 3 force components, the method, introduced earlier, is built on the simultaneous registration of cutting (F_c) and feed (F_f) force components. The passive force is important from the point of view of the workpiece accuracy, therefore it will not be considered in case of our method. The active force (F_a) is the vector resultant of F_c and F_f forces therefore

$$F_a = \sqrt{F_c^{\,2} + F_f^{\,2}} \qquad (2).$$

The cutting force determines – beside its effects, carried out on the tool – the necessary power requirement. The feed force depends – in case of tools, having the same lead angle values, and inserts, having the same corner radius value – mainly on the tool edge design (edge rounding off, edge preparation etc.) and on the design of the chipbreaker.

This F_a force component is able to characterise the chipbreaking ability: the greater the F_f force component is, the greater the plus force is, being necessary to cut (break) the detached chips into pieces of sufficient size. Therefore the qualification of inserts happens based on the active F_a force and important conclusions can be drawn from the ratio of F_f and F_c.



Two-factor force models
(a=constant ; v_c=100…200 m/min)

$$F_c \cong 3185 \cdot f^{0,79} \cdot v_c^{-0,03} \text{ [N]}$$

deviation : ±20 N ; R^2>0,95

$$F_f \cong 1200 \cdot f^{0,41} \cdot v_c^{-0,07} \text{ [N]}$$

deviation: ±15 N ; R^2>0,95

Figure 2 The cutting force components and their models
Machining conditions: Ko36 stainless steel (HB170±5); a=2 mm; dry machining

On **Figure 2** the force components and the two-factor model of force components of an insert, having PP chipbreaking geometry and modern coating, and produced by a well-known company, are summarised and shown. As it can be seen well the feed rate has a determining effect on the development of both force components, while the cutting speed does not affect significantly the forces, developing during the machining.

4. The fourth feature is the ***surface finish*** producing capability of the tool, it clearly belongs to the qualitative requirements. This term means that the tools are able to produce surfaces, having nearly the same roughness parameters, under determined circumstances, *almost* independently

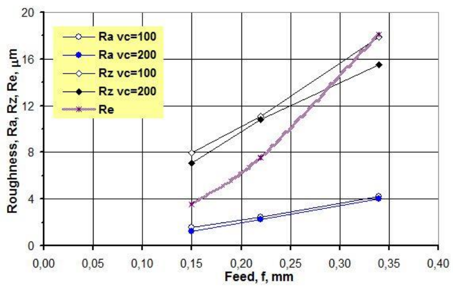
from their measured (or detected) wear condition in a way, where it can be calculated/predicted planned in advance [2].

The roughness of the turned surfaces can be characterised with different measures. On **Figure 3** the development of the roughness (and R_e theoretical roughness) is shown in function of feed rate in case of different settings.

Although the use of the average roughness (Ra) is quite widespread in the practice in Hungary, in this case the unevenness height (Rz) was used to compare the different inserts. This can be explained by the fact that in the supplier segment almost only Rz parameter is applied, and the Rz shows an *acceptable agreement* with Re theoretical roughness in case of some feed rate ranges. In case if we know the value of corner radius (r_ε , mm), then the lastly mentioned can be calculated [2] with the following formula (Bauer-formula, 1937):

$$R_e \approx 125 \cdot \frac{f^2}{r_\varepsilon} \; [\mu m] \qquad (3).$$

As it can be seen well on Figure 3, the theoretical roughness follows the development of Rz value in the range of $0{,}25 \leq$ f, mm $\leq 0{,}35$ mm; at the same time, the „popular" average roughness shows a moderate change in the same range. We note that in case of the tested insert the general rule Rz=(5…6)×Ra prevails, it means that the approach $Rz \cong 4 \cdot Ra$, commonly used in the technical practice, is not correct. The denial of this myth can be found in [9][10].



Two-factor Rz model:

(a=constant; v_c=100…200 m/min)

$$Rz \approx 103 \cdot f^{0,99} \cdot v_c^{-0,15} \; [\mu m]$$

Deviation: ±0,34 µm; R^2>0,99

Figure 3 The roughness parameters of the machined surface
Insert: CNMG120408 MR WP15CT
Machining conditions: C50 unalloyed steel (HB220±5); a=2 mm; dry machining

With the following example it will be presented how to substitute the factors, mentioned earlier, into the (1) relationship. In the **Table 1** the efficiency indicators of an inserts, having the marking EM/YBN and produced by a well-known company, are presented.

Table 1. The efficiency indicators of insert EM/YBN

Efficiency of the cutting insert (H)									
v_c	a	f	V'	F_c	F_f	F_a	Rz	g	H
100	1,5	0,1	15	405	253	478	4,98	3	18,9
100	1,5	0,15	22,5	539	330	632	4,33	4	32,9
100	1,5	0,25	37,5	870	300	920	5,67	4	28,7
160	1,5	0,1	24	382	230	446	5,61	3	28,8
160	1,5	0,15	36	518	300	599	5,67	4	*42,4*
160	1,5	0,25	60	826	423	928	8,98	4	28,8
200	1,5	0,1	30	355	220	418	4,68	2	30,7
200	1,5	0,15	45	498	282	572	5,53	4	**56,9**
200	1,5	0,25	75	762	357	841	8,41	4	*42,4*
Machining conditions: dry machining **Insert:** CNMG120408 EM YBN253 **Workpiece:** C50 unalloyed steel (HB 220±5)									

Analysing the data, gained from the nine different settings (v_c = 100…200 m/min ; f = 0,1...0,25 mm) and in case of constant (a=1,5 mm) depth of cut, the following conclusions can be drawn:

- in case of combination of the feed and cutting speed values, the insert has a greatly varying efficiency (H_{1-9} = 18…56). The simultaneous increase of both cutting speed and feed values has a clearly favourable effect on the machining productivity and on the tool efficiency, too. In case of this combination of chipbreaker/material, the fivefold increase of the material removal was followed only by a moderate increase in the efficiency;
- using the insert under the most favourable conditions, the value of its efficiency nearly *tripled*, compared with the lowest value (H_8 = 56,9). It is mainly due to the reason that the material removal, already mentioned, increases, at the same time, the chip shape and the roughness, achieved during the process, have a very favourable values;
- as it can be seen well, the insert efficiency is extremely good in case of feed value of f = 0,15 mm (almost independently from the settled cutting speed value).

Based on the method, introduced earlier, it is easy to select the best efficiency of application and the settings, enabling the favourable results (see the coloured columns). With these, the optimal conditions of application can be selected for any insert. With this method it is possible (moreover, from the aspect of the operational practice it is desirable) to qualify the inserts in a form of tests (carried out under the ***same*** conditions), in a versatile and objective way (taking four factors into consideration at the same time), to compare them (or to discover the differences between same insert types).

4. The complex efficiency of cutting inserts

It is not usually to compare inserts, having different functions (finishing, semi-finishing and roughing), material grades, edge constructions (ISO or wiper) and chipbreaking geometries. The method, proposed in the present article, makes it possible to realistically compare them with introducing a new term, the so-called complex efficiency.

The basis of the complex comparison of tools, intended for different fields of use, is the behaviour of the tested inserts: this will be determined based on the analysed cutting data (v_c, a, f, V') and based on the measured and calculated features (F_a, Rz, g, H). The complex efficiency (H_K) of any insert builds on H_1 … H_9 values, determined for individual settings: it expresses the efficiency of the given insert geometry and/or edge construction in percentage, taking the examined four features into consideration. Its value represents the average cutting perfomance of an insert, with reference to all settings, it means it is a complex, percentage indicator. When evaluating the inserts, the main statistical features (average, deviation, variance ratio) will be used, at the same time, the ***percentages*** of some measured/calculated values will be considered.

The complex efficiency can be calculated with the following formula:

$$H_K = 100 \cdot \frac{V_{\%}{}' \cdot g_{\%}}{F_{a\%} \cdot Rz_{\%}} \; [\%] \qquad (4).$$

The interpretation and the calculation method of this formula will be introduced with a specific example.

Table 2. The complex efficiency of an insert, having a shortened edge

Value	v_c	a	f	V'	F_c	F_f	F_a	Rz	g	H
Average	128,3	1,5	0,17	32,1	634	339	721	9,0	3,7	18,2
Deviation	26,1	0	0,07	14,5	196	42	192	2,2	0,5	5,1
Var,%	20,3	0	39,7	45,2	31	12	27	24,6	13,6	28,2
In %				**100**	**100**	**53,5**	**114**	**206**	**73**	
Complex efficiency			**Insert: TT9080/09 PC**				**H_K = 31,2%**			
Machining conditions: dry machining **Insert:** CNMG090408 PC TT9080 **Workpiece:** Ko36 austenistic stainless steel (HB 170±5)										

In the **Table 2** the turning results of a hard-to-machine, austenitic corrosion-resistant steel will be summarised, in case of a fixed depth of cut a = 1,5 mm, (limit values: v_c = 100...160 m/min; f = 0,1 … 0,25 mm). The data, shown in Table 2, have been calculated with formula (4). From the results, the following conclusions can be drawn:

- if the range of the test settings is the same, the average of the material flow ($V'_{\%}$) will agree, too, in the evaluation it means 100 percent. However, it there is any change in the test conditions (for example, the comparison of semi-finishing and roughing chipbreaking geometries) then this change has to be mentioned, $V'_{\%} = 100 \times V'_{new\%}/V'_{base\%}$ [%];
- the percentage ratio of the active force ($F_{a\%}$) can be calculated in the following way: the average active force (F_{aave}), measured during the tests, will be compared to the average cutting force (F_{cave}), it means: $F_{a\%}=100\times F_{aave}/F_{cave}$ [%]. Accordingly, the $F_{a\%}$ is always greather than 100%, and, the greater the ratio of the feed force is, the greater this deviation is. We note that this proportion depends crucially on the tool holder construction (PCLNR or PSSNR) and on the corner radius of the insert (r_ε). The average ratio of F_f/F_c is a subsidiary, but very useful information, in this case it was 53,5%. In the present case of corrosion-resistant steels this value is in the range of 48-62% (in case of PCLNR tool holder, corner radius is 0,8 mm, without edge preparation, depending on the chipbreaker construction);
- the percentage value ($Rz_{\%}$) of the surface finish producing capability compares the measured and theoretical roughness values. The average of the measured unevenness height was compared with the average theoretical roughness, its value was calculated with formula (3) for the average feed. With the percentage data, indicated in the table, it is expressed that the measured values are approx. 2 times greater than the theoretical roughness values. It is common in case of corrosion-resistant steels ($Rz_{measured}/Rz_{calculated} \approx$ 200...250%) as at low cutting speed and feed values there is a development of built-up edge. Some types of corrosion-resistant steels, having a „sticky" (tensile) character, result in an undetachable material layer (so-called „Spanzipfeltheorie"), and its appearance requires rather to apply the Brammertz roughness model [11]. The tested austenitic steel is extraordinary inclined to self-hardening. The initial wear phase of the coating is not able to prevent the developing material adhesion on the rake face, close to the tool nose, and it makes the roughness even worse;
- the percentage value of chip shape ($g_{\%}$) expresses the average chipbreaking efficiency of an insert (see Figure 1). The chipbreaking efficiency of inserts, tested till now, varied in the range of 40-90%. It has been confirmed by other tests that the applied PC chipbreaking geometry has an outstanding performance in case of turning corrosion-resistant steels [12][13];
- the value of complex efficiency (i.e. 31,2%), calculated according to formula (3), is - in our experience - markedly acceptable in case of hard-to-machine materials [10][13].

With introduction of the term „complex efficiency" and with the formula (4) it became possible to compare the efficiency of tool materials and /or chipbreakers, formed on inserts, having the same shape, but modified sizes, to analyse the tools, having different edge constructions (for example, ISO or wiper) and to qualify the innovation effectiveness of certain insert developments. The experiences of the tests, carried out till now, have been summarised in **Table 3**.

Table 3. Evaluation of the complex efficiency

Conditions: Insert/workpiece material		Complex efficiency, H_K, %			
		poor	proper	good	very good
ISO	unalloyed steel	≤20	≤40	≤60	≈80
	stainless steel	≤18	≤36	≤50	≈65
wiper	unalloyed steel	≤40	≤80	≤120	≈160
	stainless steel	≤35	≤70	≤100	≈130

The complex efficiency of inserts can be divided into four categories according to the material grade of workpieces and the edge constructions of inserts. The outstanding performance of the wiper edge construction can be explained mainly by the lower active force and with the very low roughness values.

5. The weigthed efficiency of cutting inserts

The requirements for the inserts are obviously different in case of different machining conditions or tasks, like roughing, semi-finishing and finishing. International surveys have been published in this topic (for example, the CIRP-study, published in the eighties), however, to our knowledge there was not carried out such an assessment about the situation in Hungary in the second decade of the 21st century. Due to this reason, a questionnaire has been sent out to tool sales companies and some manufacturing companies to collect their opinions: what ratios are represented by the four supplementary features - selected *systematically* and considered to be the *most important* - during the turning operation, according to their experiences.

Three companies, having a close partnership with our Faculty, summarised and sent us their practical experiences, while the representation of tool manufacturing companies was the following: 4 companies from Sandvik Group, 2 from IMC Group, 1 from Kennametal Group. The ten replies, received from the companies, have been averaged. The weighted numbers of requirements for the inserts, calculated from the data of questionnaires, are shown in **Table 4**.

Table 4. Weighting of the requirements for the inserts

Supplementary features	The weighted numbers of machining conditions			Weighting ratios
	Roughing	Semi-finishing	Finishing	
Removal rate	**0,4**	**0,3**	0,15	λ_1
Chip shape	0,3	**0,3**	**0,35**	λ_2
Force effects	0,2	**0,25**	0,1	λ_3
Roughness	0,1	0,15	**0,4**	λ_4
Sum total	1,0	1,0	1,0	

On **Figure 4** it is expressively shown what kind of priority principles are necessary to select and to apply the appropriate insert. The data, gained from the questionnaires, have confirmed our expectations as regards the material removal rate, the developing force effects and the produced surface roughness. Only the chipbreaking requirement had the same weight in case of all the three machining ranges. It is understandable in case if the machines, used during the turning proccess, are able to operate under conditions of production with poor monitoring (with other words, „unmanned machining"). Comparing the data from the Table (1) and Figure (4), it is clearly seen that in case of roughing there is one, in case of finishing there are two, while in case of semi-finishing there are three features, having the greatest weight and playing a determining role.

It means that the complex efficiency of inserts, involved in the test series, has to be modified with weight numbers, expressing the usability based on the tool distribution trends and the operational practical experiences.

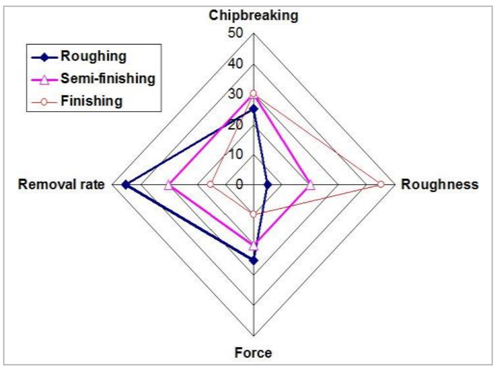


Figure 4 The percentage weight ratios of supplementary features

The individual measurement results and the chipbreaking behaviour of inserts can be gained with consideration of Table (1) and with the correction of formula (4). Concerning the suitability of inserts, the formula, to calculate the *complex efficiency*, *corrected by weight numbers* and expressing the demands of the users, is the following:

$$H_{SK} = \frac{1000 \cdot (1+\lambda_1) \cdot V'}{(1-\lambda_3) \cdot F_a} \cdot \frac{(1+\lambda_2) \cdot g}{(1-\lambda_4) \cdot Rz} \; [\%] \qquad (5).$$

The interpretation of the published formula and the calculation method will be introduced with a help of an example. In **Table 5** the results of semi-finishing turning operations are shown, carried out on C60 structural steel grade, with wiper edge insert (limit values: v_c=100…250 m/min; f=0,15…0,34 mm).

Based on the weighted, complex efficiency indicators the following conclusions can be drawn:

- as a result of weighting, the average indicators have changed only slightly, in case of some of them there is an increase (material flow, chipbreaking efficiency), while in case of others, there is a decrease (force effects, roughness). It can be considered that in the category of semi-finishing, the *weighting* has *not* basically *changed* the percentage ratios, created by the complex efficiency indicators. The reason for this is that three from the considered four supplementary features had *almost* the **same** weight;
- the efficiency of inserts, having a wiper edge construction, means a special category, as it has already been introduced [14][15]. It is contributed by the fact that all tested features are extremely favourable, in particular, the surface finish producing capability and chipbreaking efficiency are outstanding. We note that similar experiences have been gained in case of tools with this (wiper) edge design, produced by other companies: the weighted complex efficiency is nearly two times greater, compared to the ISO edge tools;

Table 5. The weighted complex efficiency indicator of a tested insert

Evaluation	v_c	f	V_s'	F_c	F_f	F_{as}	Rz_s	g_s	H_s
Average	170	0,24	78,5	1065	591	914	3,8	5,1	150,9
Deviation	65,4	0,08	42,1	301	116	238	1,4	1,0	118,6
Var, %	38,5	35,2	53,7	28	20	26	36,5	20,1	78,6
in %			**100**	**100**	**55,5**	**85,9**	**43,2**	**101,1**	
Correction factors	λ_1	***0,3***	λ_2	***0,3***	λ_3	***-0,25***	λ_4	***-0,15***	**2,651**
Corrected complex efficiency		**Insert type: NF chip breaking geometry**							**H_{SK}=273%**
Machining conditions: dry machining **Insert:** CNMG090408 NF (wiper) WPP20S **Workpiece:** C60 unalloyed structural steel grade (HB 215±5)									

- In this connection we note that based on our measurement results the passive force component is extraordinary great in case of wiper insert; due to this reason, the characteristic features of the edge desing have to be considered! For the purposes of productivity, the longitudinal turning of components, having a small ratio of cutting length/diameter, carried out on lathes with a great stiffness, could be a favourable solution. In case of machining surfaces with tapering and other profile (for example, torus) shapes, the favourable decrease in roughness does not occur; on the other hand, the accuracy, achieved during the machining, develops unfavourable, due to the wiper edge geometry [14][15].

In order to increase the reliability of all results, it is recommended to select the inserts, to be tested, by thorough examinations (carried out with microscope) and to test only inserts of appropriate (well pressed) condition, intact coatings and correct edges.

6. Long-term efficiency of cutting inserts

The long-term efficiency of inserts is closely related to the deterioration of the tool (or with other words, the degradation of cutting performance of the tool): by this term is understood the sum of *unfavourable* influences, expressly resulting from the tool wear or – maybe even indirectly – they can play a role in it. As a result of the wear, there is a clear increase in the cutting temperature, in the force, torque and power demand, in the vibration tendency and noise impact, and there is a change in the roughness and/or in the waviness, too [16]. It is obviously, a tool life, belonging to an appropriately determined wear criterion, can be considered as the main feature for the purposes of the workpiece machinability and the cutting performance of the tool.

It would be a self-evident thought that the time, spent in machining, had to be considered when calculating the efficiency, based on the formula (2) and containing four selected features. To monitor the wear process of a tool from the beginning till the end, would make the examinations very time-consuming (and cost-intensive) as it would be necessary to collect chip samples, to measure the values of force components and the development of the Rz roughness parameter at the same times of individual wear measurements. Although the constancy of the cutting data (a, f, v_c) and material removal rate (V') can be ensured during the lifetime measurements, the other three features (chip shape, force components and the Rz roughness values) change to a great extent during the wear period of tool.

The modification of the chip shape is illustratively shown on **Figure 5**. The change, created by crater wear, may cause even 3-class difference in the value of „g" as the crater, developing gradually on the rake face, impairs the initially favourable chipbreaking efficiency. In the first phase of the persistent wear process, there are developing chips, having C and G shape and divided into small pieces, later - depending from the place, width and depth of the crater - there are cylindrical, spiral chips, having a length of 40-90 mm, even later, there are unmanageable, dangerously coiled, flowing chips. When achieving the wear criterion, there are again well manageable chips, having a C shape and/or chips, coiled up like a snake and spreading dangerously.

The influence of the tool wear on the cutting force components is well-known. The change in the F_c cutting force, resulting from the wear, means an increase of 25-30 percent in the force formula of Kienzle and Victor [2]. This experience has been confirmed by our measurements, too (see Table 6). An even greater change (i. e. increase) is shown in case of feed and passive force components (F_f and F_p), thus it is understandable that the condition monitoring systems are based, among others, on the change of these two force components (or their ratio).

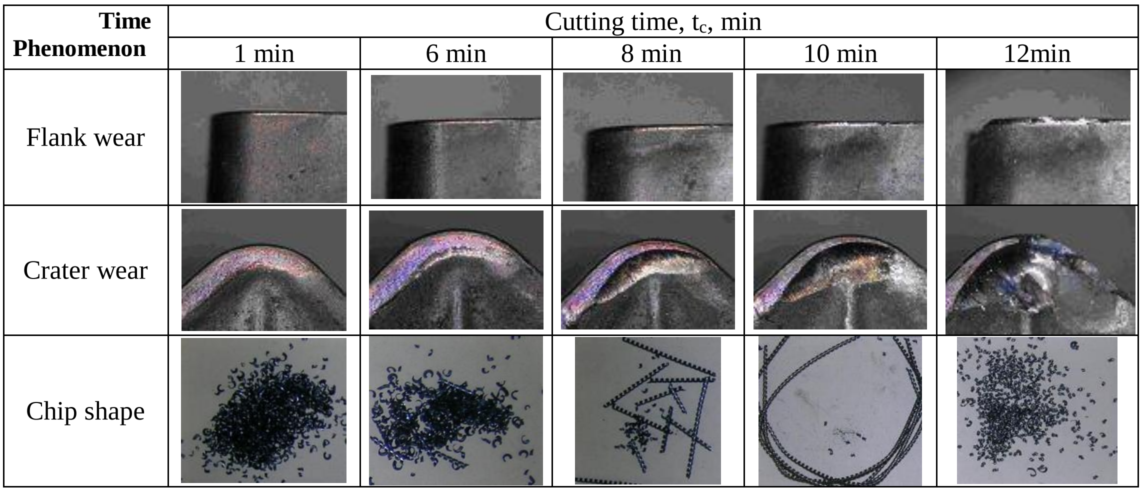


Figure 5 The change in chip shape due to the tool wear
Insert: CNMG120408 PM K10+TiAlN-mono (PVD); Workpiece: C60 unalloyed steel (HB220±5);
Machining conditions: a=1,5 mm; f=0,25 mm; v_c=200 m/min; dry machining

The roughness data of machined surface are also in relation to the wear condition of the tool. On **Figure 6** the change of the roughness features (Ra, Rz) is shown in function of the cutting time in case of a hard-to-machine, austenitic, corrosion-resistant steel. As it can be seen well on the diagram, in the phase of uniform wear (t_c = 2...6 min) the value of Rz suddenly doubles, after that - in function of the current condition and ironing effect of the edge - there is a sharp fall in the value of unevenness height.

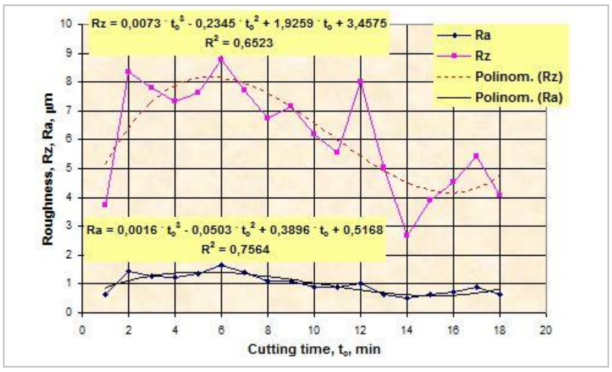


Figure 6 The change in roughness of machined surface in function of time [10][17]
Insert: CNMG120408 MT TT5100; Workpiece: Ko36 stainless steel (HB170±5)
Machining conditions: a=1 mm; f=0,1 mm; v_c=160 m/min; dry machining

Towards to the end of the tool life (t_c > 4 min), there is again an increase in both measured roughness features. The change of the surface finish producing capability, shown on the mentioned figure, is not allowed, for example, in case of series production of components, having a small diameter and length measurement or in case of production conditions, when the specified quality has to be ensured.

The protective effect of PVD-coatings of different materials, structural compositions, thicknesses and nano-hardnesses, has been examined by long-term (lasting) test series. In the **Table 6** the results of wear test of a single-layer coating are summarised.

Table 6. The effect of tool wear on the efficiency of insert

Long-term efficiency of inserts							
Wear data		Force values, N			Roughness	Chip	Efficiency
Time, min	VB, mm	F_c	F_f	F_a	Rz, µm	g	H
1	0,08	840	361	914	8	4	41,0
2	0,09	830	390	917	9	4	36,3
4	0,1	830	407	924	10	4	32,5
6	0,11	835	434	941	11	3	21,7
8	0,12	725	355	807	13	1	7,1
10	0,14	820	426	924	12	1	6,8
12	0,2	1100	605	1255	5	4	47,8

Machining conditions: dry machining
a=1,5 mm; f=0,25 mm; v_c=200 m/min; V'=75 cm^3/min
Insert: CNMG0120408 PM K10 + single-layer of TiAlN (PVD)
Workpiece: C60 steel (HB 225±5)

As long as the wear criterion (VB_{meg} = 0,2 mm) has not been achieved, there was a 3-class difference in the classification of chip shape, the active force (F_a, N) increased by approx. 25 percent, the feed force (F_f) grew nearly by 70 percent, while Rz, the unevenness height, changed rhapsodically (almost following the development, shown on Figure 6). In function of the cutting time, the efficiency first decreased gradually, then - unexpected - fell to a third. In the last phase of the wear process, the efficiency indicator (H) increased to such a great extent that it exceeded largely the value, measured at the starting phase. This can be explained by the fact that the Rz roughness of the machined (turned) surface reduced (due to the ironing effect of the tool edge) to a small proportion, the classification of chip shape has became better by three marks. The wear measurement results and the efficiency indicators of multilayer coating, having the same material, are summarised in **Figure 7**.

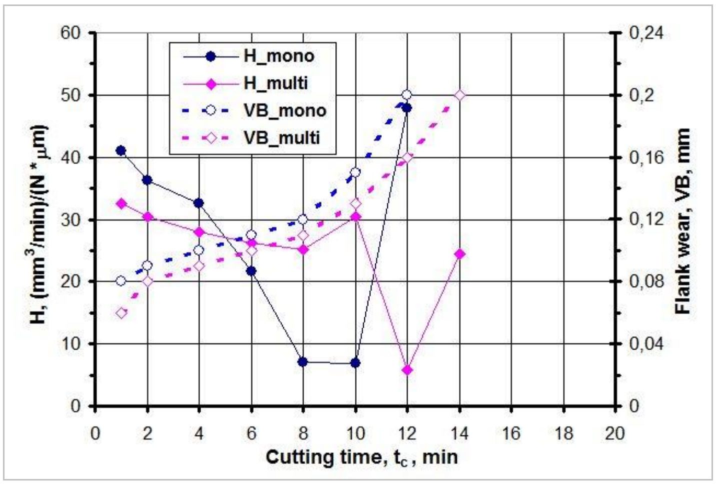


Figure 7 Wear and insert efficiency in function of the time, in case of different coatings
Insert: CNMG0120408 PM K10; Coating: TiAlN single-layer and TiAlN multilayer coating (PVD)
Machining conditions: C60 steel (HB225±5); a=1,5 mm; f=0,25 mm; v_c=200 m/min; dry machining

The wear curve of TiAlN single-layer coating can be described by the formula

$$VB(t_c) = t_c \cdot EXP\left(4{,}7 - 0{,}46 \cdot t_c + 0{,}03 \cdot t_c^2\right) \ [\text{mm}] \quad (6)$$

$$s = \pm 0{,}007 \ ; \quad R^2 = 0{,}972$$

while the TiAlN multilayer-coating by the following:

$$VB(t_c) = t_c \cdot EXP\left(4{,}3 - 0{,}33 \cdot t_c + 0{,}02 \cdot t_c^2\right) \ [\text{mm}] \quad (7)$$

$$s = \pm 0{,}01 \ ; \quad R^2 = 0{,}945$$

Comparing the equations (6) and (7), it can be seen that the greater number of layers - reducing the wear on the flank land - improves the insert efficiency and increases the tool life by 20 percent. In function of the cutting time, the efficiency has a dynamic decreasing tendency throughout the process in case of single-layer coating, and it has a favourable value only shortly before the failure. At the same time, in case of multilayer coating, the efficiency first decreases slightly, then it starts to increase and at the next wear measurement there is a drastical reduction. In the final phase of the wear process, according to the formula (1) we have again a great value. This can be explained by the fact that the increasing value of developing force effects can be compensated by the edge, ironing the surface (leaving a very low roughness values behind) and by the very favourable (snake/spiral-like) chip shape.

Our opinion has been confirmed by the results of durable tests that it is not recommended to apply the efficiency, calculated by the formula (1) to describe the long-term productive efficiency of inserts, due to the following reasons:

- the wear period of the tool has an inconsistent effect on the most important four supplementary features. With other words, the value of „H" indicator has a sudden and drastic reduction close to the inflexion points of wear curves (t_c = 8...10 min);
- the flank wear, used as criterion in case of lifetime measurement, has a clear effect only on the developing force effects from the supplementary features (in case of tools, having a great lead angle value, it affects mainly the F_f component), it has an indirect effect on the developing roughness, while it has no influence on the chipbreaking effiviency;

- the wear on the front of the insert (mainly the crater wear formation) has a hectic effect on the chip development;
- the actual condition and real shape of the tool edge, depending from the wear status, may make the roughness measurement on the workpiece unsure. An instabile cutting procces, the current shape of tool edge, having been copied and/or the ironing effect at the same time, may lead to fluctuations, shown on Figure 7.

Due to the reasons, mentioned above, it is not recommended to make any connection between the efficiency, as interpreted by us and calculated according to formula (1), and the long-term productive efficiency of inserts. It does not offer an appropriate solution to average the efficiency values, belonging to the dates of wear measurements or even to weight these values.

7. Result and discussion

In the present article a new qualification method has been introduced, it can be beneficially applied when determining the cutting ability of inserts. The method is able to compare inserts, having a different shapes, edge constructions, sizes, chipbreakers, material grades and coatings, in an objective way; furthermore, it makes possible to make efficiency rank orders and to measure the of success the innovations, too. It defines three important efficiency elements which enable to select the optimal data settings, using the formula (1) and, defining the complex efficiency (see the formula (4)), there is only a single percentage ratio to describe the tested insert. The applicability, modified with weighted numbers based on the manufacturing trends and operational practical statistics, can be calculated with formula (5). With the weighted complex efficiency it is possible to compare inserts, having different functions, in an objective way.

The advantage of the elaborated method is that it is based on four, simple features (to be exact: the material removal rate, chip shape, active force and surface roughness): these can be easily calculated, evaluated and measured; furthermore, this process is sufficiently cost-effective as it needs a low time-, material and financial expense.

The disadvantage is that it is possible to make only short-time tests with this. It is well-known that the main feature of the cutting performance of an insert is the long-term productive efficiency, with other words, the wear behaviour and the edge durability of the tool. The connection between the wear process development (see formulas (6) and (7)) and the efficiency is rather accidental. The example, introduced in the present article, illustrates that the efficiency, calculated from four main parameters of the supplementary features, should not be confused with the productive efficiency of inserts.

Three world-leading tool manufacturing company groups provided us with inserts to these tests; the usability and the adequacy of method has already been confirmed by test results, carried out on 85 different inserts. In the future we are going to test newly developed inserts with the method, described earlier: these inserts, to be launched on the market, can almost revolutionise the turning operation.

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