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COMPARISON OF CUTTING TOOL GEOMETRIES BASED ON CUTTING FORCES AND ROUGHNESS OF HARD TURNED SURFACES

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Abstract. *Surface quality and energy consumption are two widely studied topics of hard machining. Due to the increasing need of companies for new, more efficient materials, tools and procedures, their manufacturers or suppliers have to deliver innovative solutions from time to time. In this study the latest development of a hard turning insert manufacturer is used in comprehensive machining experiments to show how the new tool (a wiper insert) behaves compared to its standard counterpart. Based on surface roughness and machining force measurement and analysis, this efficiency is proved by quantitative results: the wiper geometry ensures significantly better surface quality, while the energy consumption of the used machine tool is considerably lower.*

Keywords: *surface topography; cutting force; hard turning.*

1. INTRODUCTION

The high quality of machined components plays a significant role in the planning of production process, and can be achieved, among other approaches, by a comprehensively planned technological process that ensures suitable surface quality and part accuracy. To remain competitive, the latest innovation must be used in machining technology, which in the world of machining metallic materials means new machines, materials, procedures, jigs and tools. In hard turning, cutting tools are continuously being developed by their manufacturers and a wide range of applications is covered by various solutions concerning tool materials or geometries [1].

3D surface roughness analysis is a developing are of qualifying functional surfaces. The 3D topography parameters provide more information about the analyzed surface than 2D because of the number of detected points. At the same time, a wider range of reliable parameters are available [2, 3]. 3D measurement is not so efficient than the 2D one but it is widely applied by high-tech companies [4]. The 3D analysis can also provide information about the effectiveness of the applied cutting procedure [5]. Not only the innovative variants of turning and grinding [6-8] but also relative new technologies have been analyzed recently by topography studies, such as additive techniques [9, 10] or precision milling [11].

Cutting force analysis provides the basis for rough estimation about the energy consumption of a machine tool. Numerous studies have been published in precision hard machining [12, 13] and within that, hard turning topics; and the majority of them focus on the efficiency of the technology [14, 15], the surface integrity [16, 17] and part accuracy [18], the prediction of tool life or physical phenomena of the cutting process [19–21]. Many of the studies focus on the appropriate selection of technological data [22–24].

In this study the results of a machining experiment are introduced. The roughness of the machined cylindrical surfaces and the machining forces were measured and analyzed. The machining was carried out by standard insert and then by its wiper counterpart. The goal was to determine whether the wiper insert provides lower energy consumption due to the lower cutting forces and favorable surface quality due to the lower values of surface roughness. For the force measurement the cutting force (F_c), passive force (F_p) and feed force (F_f) were analyzed. For the roughness measurement the arithmetic mean height (S_a) 3D topography parameter was analyzed.

2. EXPERIMENTAL METHOD

In the machining experiment 18 external cylindrical surfaces (S1 – S18) with diameter 60 mm were hard turned by two variants (standard and wiper) of a turning insert type 4NC-CNGA 12048. The machined material was case hardened 16MnCr5 steel, the applied machine tool was a hard machining centre type EMAG VSC 400 DDS. The hard turning experiment was carried out dry. In the experiment the depth-of-cut (a_p) was fixed at 0.2 mm; the cutting speed (v_c) and the feed rate (f) were varied. The experimental plan and the applied technological data are demonstrated in Table 1.

Table 1. Experimental plan

Insert	feed rate, f [mm/rev]	cutting speed, v_c [m/min]		
		120	180	240
Standard	0.04	S1	S7	S13
	0.12	S2	S8	S14

	0.2	S3	S9	S15
Wiper	0.04	S4	S10	S16
	0.12	S5	S11	S17
	0.2	S6	S12	S18

For the force measurement, a 3-channel dynamometer, type Kistler 5011 was used. After acquisition, the data were processed by the MATLAB software.

After machining, the surfaces were scanned by a 3D topography measuring and analyzing equipment type ALTISURF 520. The applied sensor was a confocal chromatic one type CL2 of which resolution is 0.012 μm in z and 1 μm in x and y directions. The evaluated area of each surface was 2 × 2 mm, which resulted in 2 million detected points. The applied cut-off lengths were 0.08; 0.25; and 0.8 mm according to the specifications of ISO 25178. The raw data were processed and analyzed by the software Altimet Premium and Origin Lab.

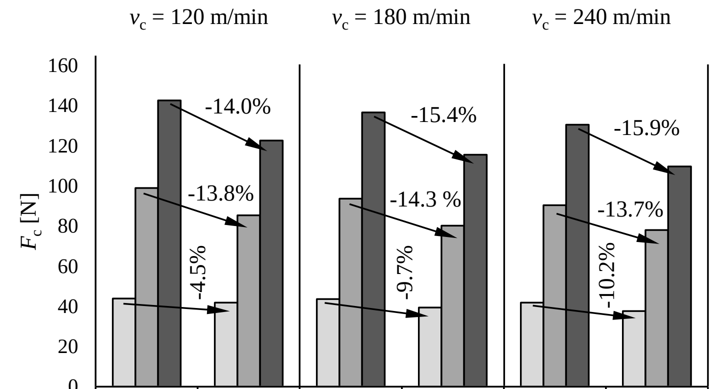
The material was case hardened before machining, the microstructure of it was martensitic with HRC hardness 60–63.

3. RESULTS OF FORCE MEASUREMENT AND SURFACE TOPOGRAPHY ANALYSIS

The three components of the machining force were analyzed separately: cutting, feed and passive force. All three of them showed significant differences when the feed rate or the tool geometry were varied. Varying the cutting speed resulted in only a slight difference in the force components. The F_c cutting force values varied between 41.9 and 142.7 N and between 37.7 and 122.7 N when the standard or wiper insert was used, respectively. The force values slightly decreased with the increase of cutting speed. The percentage difference between two consecutive cutting speed values changed by 0.3–6.4%. The F_c values increased by the increase of the feed rate. When the standard insert was used, two consecutive force component values changed by 44–126%; and when the wiper insert was used, these changes varied between 41 and 107%. This means that the F_c force component ranges were closer to each other when the machining was carried out by wiper insert.

In Fig. 1 the F_c values are demonstrated. At the applied cutting speed levels the F_c values decreased by 4.5–15.9% when the wiper insert was used compared to the results of the standard insert. The decreases were more emphasized at higher feed rates: 14–15.9%. This means that lower cutting forces can be reached with the wiper insert compared to the standard tool geometry.

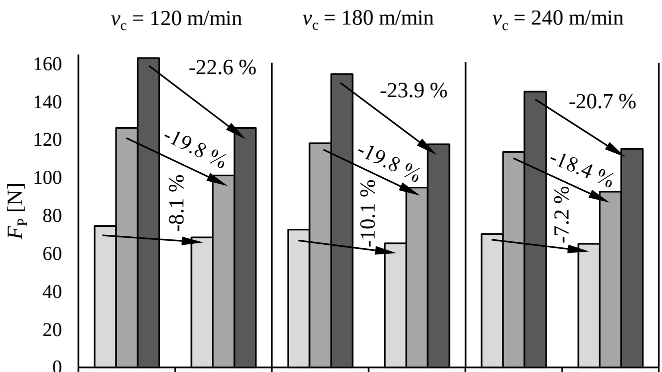
The F_p passive force values varied between 70.3 and 163.1 *N* and between 65.2 and 126.3 *N* when the standard or wiper insert was used, respectively. The force values slightly decreased with the increase of cutting speed. The percentage difference between two consecutive cutting speed values changed by 0.2–7.3%. The F_p values increased with the increase of the feed rate. When the standard insert was used, two consecutive force component values were changed by 28–69%; and when the wiper insert was used, these changes varied between 24 and 48%.



f [mm/rev]	Standard	Wiper	Standard	Wiper	Standard	Wiper
0.04	43.8	41.9	43.7	39.5	41.9	37.7
0.12	99.0	85.4	93.6	80.3	90.4	78.0
0.2	142.7	122.7	136.7	115.6	130.6	109.7

Figure 1. Cutting force (F_c) values of hard turning

In Fig. 2 the F_p values are demonstrated. At the applied cutting speed levels the F_p values decreased by 7.2–23.9% when the wiper insert was used compared to the results of the standard insert. The decreases were more emphasized at higher feed rates: 20.7–23.9%. This means that compared to the standard tool geometry, lower cutting forces occur when the wiper insert is used. Compared to the F_c cutting force component values; the F_p passive force values are significantly higher, which is one of the main characteristics of hard turning. The reason for this is the negative rake angle designed for hard turning inserts.



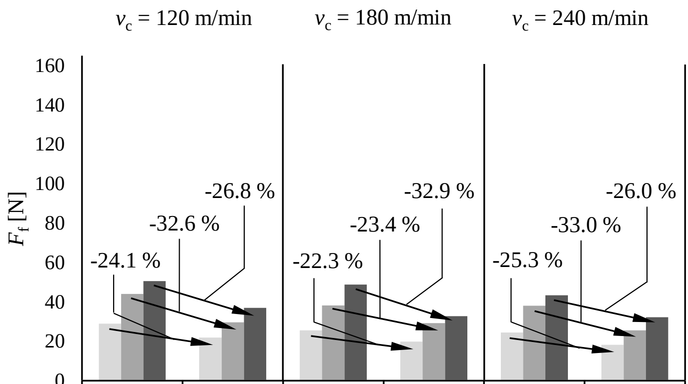
f [mm/rev]	Standard	Wiper	Standard	Wiper	Standard	Wiper
0.04	74.6	68.6	72.7	65.4	70.3	65.2
0.12	126.2	101.2	118.2	94.8	113.6	92.7
0.2	163.1	126.3	154.7	117.7	145.4	115.3

Figure 2. Passive force (F_p) values of hard turning

The F_f feed force values varied between 24.4 and 50.5 N and between 18.2 and 37.3 N when the standard or wiper insert was used, respectively. The force values slightly decreased with the increase of cutting speed. The percentage difference between two consecutive cutting speed values changed by 0.2–15.3%. The F_f values increased with the increase of the feed rate. When the standard insert was used, two consecutive force component values changed by 14–56%; and when the wiper insert was used, these changes varied between 12 and 47%.

In Fig. 3 the F_f values are demonstrated. At the applied cutting speed levels the F_f values decreased by 22.3–33% when the wiper insert was used compared to the results of the standard insert. The decreases were more emphasized at the middle feed rate (f = 0.12 mm/rev) than in the cases of the lowest and the highest cutting speed levels (120 and 240 m/min): 32.6 and 33%, respectively; and was 32.9% lower at the highest feed rate (f = 0.2 mm/rev) in the case of the 180 mm/rev cutting speed level. This also means that lower cutting forces can be achieved with the wiper insert than with the standard tool geometry. Compared to the F_c and F_p force component values; the F_f feed force values are significantly lower.

The most commonly used topography parameter, the arithmetic mean height (S_a), was analyzed to obtain information about the connection between that and the introduced force components. S_a values varied between 0.07 and 1.34 μm. Although these values resulted from an experiment where the applicability ranges of two technological parameters (v_c and f) were set, technological parameters that result in lower topography values are recommended in precision finish operations.



f [mm/rev]	Standard	Wiper	Standard	Wiper	Standard	Wiper
0.04	28.9	21.9	25.5	19.8	24.4	18.2
0.12	44.0	29.7	38.1	29.2	38.1	25.5
0.2	50.5	37.0	48.8	32.7	43.4	32.1

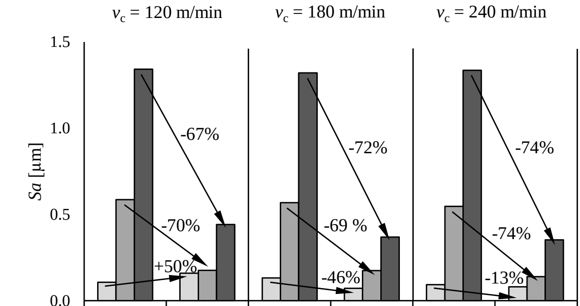
Figure 3. Feed force (F_f) values of hard turning

In many of the cases the S_a values decreased slightly with the increase of cutting speed; however, this technological parameter cannot be the basis of S_a minimization. At the same time, the S_a values decreased significantly with the decrease of feed rate. When the feed rate decreased from the highest (0.2 mm/rev) to the lowest (0.04 mm/rev) value, the S_a values decreased by 90–93% and by 64–81% when the standard or wiper insert were used, respectively.

In Fig. 4 the S_a values are given. In most of the cases the S_a values decreased when the wiper insert was applied. At the 0.2 mm/rev feed rate this decrease was between 67 and 74% and at 1.12 mm/rev between 69 and 74%. At the lowest feed rate (0.04 mm/rev) the decrease was between 13 and 46% for the two higher cutting speeds; however, at the lowest (120 m/min) a 50% decrease was obtained for the S_a value.

In Figs. 5 and 6 the connections between the S_a topography values and the force components are demonstrated. When the standard insert was used, the S_a values formed well-separated areas based on the feed rates. At the same time, similar areas can be observed for the different force components. It can be stated that the lowest

S_a values can be reached at 0.04 mm/rev feed rate and at this level, all the force components are minimal (Fig. 5).



f [mm/rev]	Standard	Wiper	Standard	Wiper	Standard	Wiper
0.04	0.106	0.160	0.132	0.071	0.093	0.081
0.12	0.586	0.176	0.568	0.175	0.546	0.140
0.2	1.342	0.441	1.321	0.369	1.336	0.352

Figure 4. Arithmetic mean height (*Sa*) values of hard turned surfaces

When the wiper insert was used, such clear areas cannot be designated (Fig. 6). The S_a values can be separated clearly only at the highest feed rate, but the F_p and F_c values are nearly identical at this level. The most easily separable area for the force components is that belonging to the lowest feed rate; however, in this case the S_a values form an overlapping set with values belonging to the middle feed rate. This means that the technological parameter-based planning strategy is not as obvious as when using the standard insert. Similar results were found by Nagy [25].

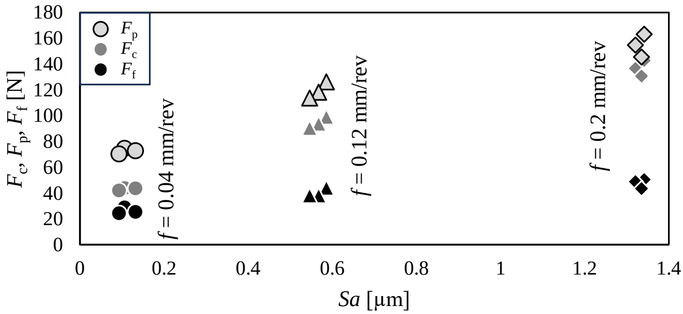


Figure 5. Connections between the S_a values and the force components when standard insert was applied

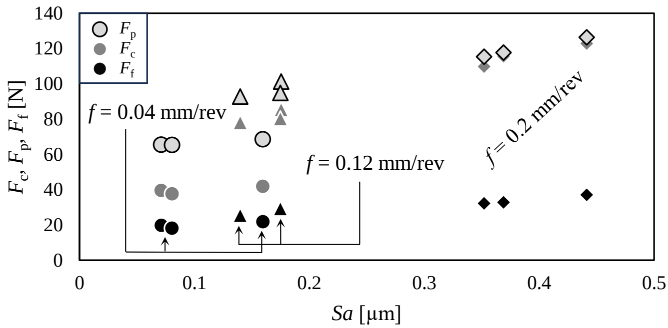


Figure 6. Connections between the S_a values and the force components when wiper insert was applied

Apart from the not perfectly clear technological data-based area designation, it can also be stated that the use of the wiper insert leads to significantly lower machining forces and the technological parameter values that result in the lowest force values also provide the lowest S_a values. This means that high-quality surfaces can be machined using low machining forces, i.e. energy consumption is reduced.

4. CONCLUSIONS

In the introduced machining experiments, where two variants of a cutting insert (standard and wiper) were compared, the technological parameter values v_c and f were varied in the ranges recommended by the tool manufacturer. The following findings were obtained. The lowest cutting force (F_c), passive force (F_p) and feed force (F_f) values were obtained at the highest cutting speed (240 m/min) and the lowest feed rate (0.04 mm/rev) when the depth-of-cut was fixed. The lowest *Sa* topography values (lower than 0.1 µm) were obtained at the lowest feed rate and at 180 and 240 m/min cutting speeds. These results are valid in the analyzed technological data ranges.

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ПОРІВНЯННЯ ГЕОМЕТРІЇ РІЖУЧОГО ІНСТРУМЕНТУ НА ОСНОВІ СИЛ РІЗАННЯ І ШОРСТКОСТІ ТОЧЕНИХ ПОВЕРХОНЬ

Анотація. *У токарній обробці загартованих сталей ріжучі інструменти постійно розробляються їх виробниками, і широкий спектр застосування охоплюється різними рішеннями, що стосуються інструментальних матеріалів або геометрії. У цьому дослідженні представлені результати експерименту з механічної обробки. Вимірювали та аналізували шорсткість оброблюваних циліндричних поверхонь та зусилля обробки. Механічна обробка здійснювалася стандартною вставкою, а потім її аналогом після доводки. Мета полягала в тому, щоб визначити, чи забезпечує вставка після доводки менше енергоспоживання за рахунок менших сил різання та сприятливу якість поверхні за рахунок нижчих значень шорсткості поверхні. Для вимірювання сили були проаналізовані сила різання (F_c), пасивна сила (F_p) і сила подачі (F_f). Для вимірювання шорсткості було проаналізовано параметр 3D топографії середнього арифметичного значення висоти (S_a). Для вимірювання сили використовувався 3-х канальний динамометр типу Kistler 5011. Після отримання, дані були оброблені програмним забезпеченням Matlab. Після механічної обробки поверхні були відскановані за допомогою 3D обладнання для вимірювання та аналізу топографії типу Altisurf 520. Застосований сенсор був конфокальним хроматичним типу CL2, роздільна здатність якого становить 0,012 мкм у z та 1 мкм у напрямках x та y. Оцінена площа кожної поверхні становила 2 × 2 мм, що призвело до 2 млн виявлених точок. Застосована довжина зрізу становила 0,08; 0.25; і 0,8 мм згідно зі специфікаціями ISO 25178. Необроблені дані були оброблені та проаналізовані програмним забезпеченням Altimet Premium та Origin Lab. Матеріал перед механічною обробкою був загартований, мікроструктура його була мартенситною з твердістю HRC 60–63. Були отримані наступні результати. Найнижчі значення сили різання (F_c), пасивної сили (F_p) і сили подачі (F_f) були отримані при найбільшій швидкості різання (240 м/хв) і найнижчій швидкості подачі (0,04 мм/об) при фіксованій глибині різання. Найнижчі значення топографії S_a (нижче 0,1 мкм) були отримані при найменшій швидкості подачі і при швидкостях різання 180 і 240 м/хв. Ці результати справедливі в аналізованих діапазонах технологічних даних.*

Ключові слова: *рельєф поверхні; сила різання; жорстке токарне оброблення.*