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EXPERIMENTAL INVESTIGATION OF TRIBOLOGY-RELATED SURFACE TOPOGRAPHY PARAMETERS AND HARDNESS OF 16MNCR5 CASE HARDENED STEEL

Abstract. *Tribological properties are determinant in the functionality of contacting surfaces of machine elements. The wear resistance or load bearing capacity influence the lifetime of these parts. In this study tribology-related surface topography parameters (S_{sk}, S_{bi}) and the hardness of hard turned surfaces are analyzed after hardness and topography measurements. Correlation coefficients were calculated for their relationships. It was found that the cutting parameters affect the wear resistance and the hardness in the opposite direction.*
Keywords: *HV hardness; surface roughness; S_{sk}; S_{bi}; hard machining.*

1. INTRODUCTION

Case hardened steels play an important role in machined components whose surfaces are required to be wear resistant and/or have high hardness or load bearing capacity [1]. These and other characteristics are determinant in the functionality and the lifetime of the components [2]. A high number of industrial parts, e.g. gears that require hardened surfaces, are machined in the automotive industry [3, 4]. Hardened surfaces are machined conventionally by grinding; however hard turning is also a suitable technology to reach the desired roughness (mainly R_a and R_z) or equal the accuracy of a ground surface [5, 6]. At the same time, hard turning is a more productive technology because of its high material removal rate [7] and the fact that grinding burn [8] can be eliminated by its application. One of the main reasons of applying grinding, despite the advantages of hard turning, is that in certain cases ground topography [9] is needed.

A determining field of functionality of hardened surfaces is their tribological characteristics [10, 11]. Among others, wear resistance and load bearing capacity have high importance when the lifetime of a component is in the focus. The skewness (S_{sk}) provides information about the asymmetry of the surface [12, 13]. If its value is negative and decreases, the surface becomes more filled in its peak zone. This results in higher load-bearing capacity due to the increased bearing area. At the same time, such a surface is characterized by fewer peaks, which results in a relatively short wear-in phase, i.e. the surface is more wear resistant [14, 15]. Some tribological characteristics are related to the S_{sk} parameter [16], and several studies have analyzed this in detail [e.g., 17, 18]. It has to be noted that this parameter is sensitive to sharp peaks of the surface [19]. The Surface bearing index (S_{bi}) also characterizes the peak zone of a surface; however, this parameter provides the same information by a different calculation method [20, 21]. Selecting the suitable roughness or topography parameters requires complex consideration [22, 23]; for analyzing one phenomenon, it is recommended to compare a few available parameters [24, 25]. 3*D* scanning technology is recommended for measuring surface topography, because it provides more detailed information about the surface than its conventional 2*D* counterpart [26, 27], there are a number of parameters and analytic tools available to analyze the topography in more detailed way [28, 29], and the reliability of the results can also be considered higher [30].

In this study tribological-related (mainly wear resistance) 3*D* surface topography parameters (S_{sk} ; S_{bi}) and the Vickers hardness of hard turned surfaces were analyzed. The experiments were carried out at varying levels of feed rate and cutting speed, and by two CBN inserts with different geometry. Correlation relationships were calculated for the numerical results.

2. EXPERIMENTAL METHODS

The workpiece material was 16MnCr5 steel (diameter: 60 mm). Before cutting, the workpieces were case hardened: after 14 h of carburization, quenching in oil was carried out from 860 °C. In the third step, the pieces were tempered at 190 °C. In Fig. 1 the time-temperature diagram of the process is presented.

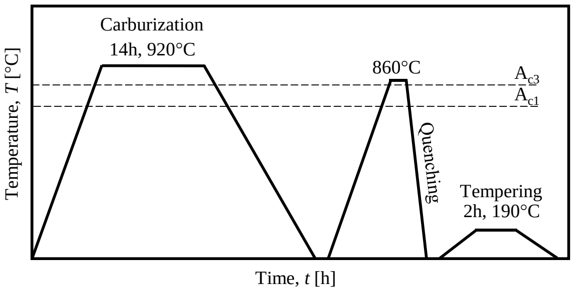


Figure 1 – Heat treatment process

In the hard turning experiment two cutting parameters were varied, the feed rate (f = 0.04; 0.12; and 0.2 mm/rev) and the cutting speed (v_c = 120; 180; and 240 m/min). The depth-of-cut was fixed (a_p = 0.2 mm). The used CNC lathe was Optiturn S600, the used tool holder was CLNR 2524 M12. Two inserts with different edge geometries were compared in the experiments: NP-CNGA 120408 TA4 and 4NC-CNGA 120408 (hereinafter inserts A and B, respectively). They differed from each other in the α angle and the *w* negative land width: α_A: 35°; α_B: 25°; w_A: 0.13 mm; w_B: 0.12 mm (Fig. 2). Nine surfaces (a total of 18 for the two inserts) were machined at all of the f and v_c data combinations.

The hard turning experiments were followed by hardness testing and roughness measurement and analysis. The roughness measurement was carried out on a 3*D* machine (Altisurf 520), equipped by an optical sensor. The resolution of the sensor in z directions was 0.012 μm. The measured area was 2 × 2 mm, with 2000 scanned points in both x and y directions. The cut-off length was 0.8 mm, and Gauss filter was applied for the preprocessing of the scanned data. The skewness (S_{sk}) is the third moment of the heights distribution of the surface; the surface bearing index (S_{bi}) is the ratio of the root-mean square deviation over the surface height at 5% bearing area. Two other parameters, the maximum height (S_z) and the arithmetical mean height (S_a), were also analyzed. They are widely applied parameters for qualification of surfaces. For the analysis of the parameters the standard ISO 25178 was applied.

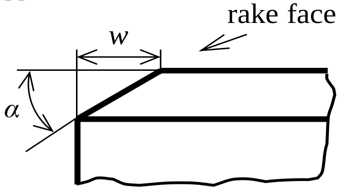


Figure 2 – Varying geometrical parameters of the applied tools

The hardness tests were carried out on a universal hardness tester (Reicherter UH250). The load was 10 kp and the dwell time was 10 s. For the measurement the standard DIN EN ISO 18265 was applied.

3. RESULTS AND DISCUSSION

As a result of the heat treatment, the thickness of the hardened layer was around 1 mm. The microstructure of this layer is basically martensitic (Fig. 3).

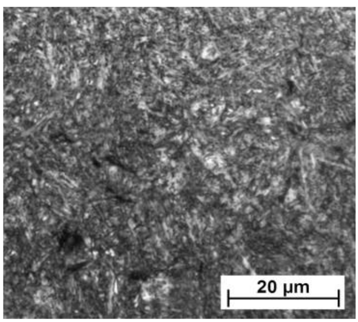


Figure 3 – Microstructure of the hardened layer (500×)

In Figs. 4 and 5 the *HV* hardness data are summarized as a function of the cutting parameters for the A and B inserts, respectively. The hardness values are between 752 and 854 in the case of insert A and between 695 and 825 in the case of insert B. The hardness values increased by the feed rate by applying bot inserts. The values increased with the cutting speed in the case of insert B. This was not observed in the case of insert A. The change in hardness results from the layer hardened during machining, which caused by the relatively high cutting forces, mainly the passive (radial) force.

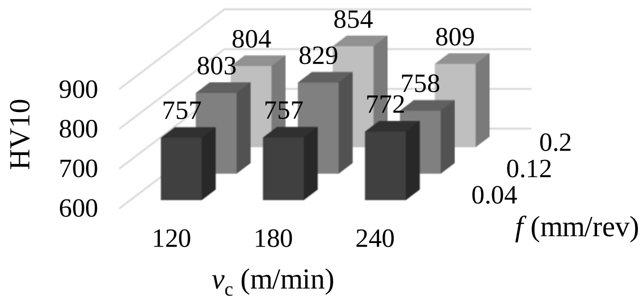


Figure 4 – Hardness data – insert A

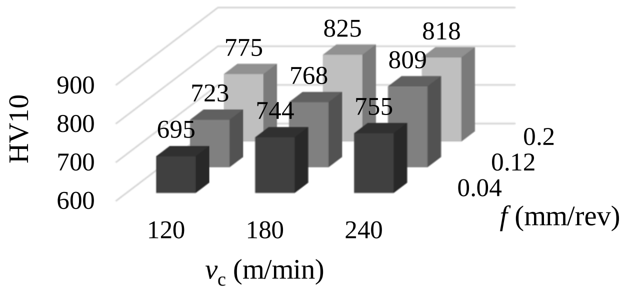


Figure 5 – Hardness data – insert B

In Fig. 6 the maximum height (S_z) values are presented as a function of the cutting speed and the feed rate. At 0.04 and 0.12 mm/rev feed rates the values are similar in the case of the two inserts. At the highest feed rate (0.2 mm), a higher deviation is observed in S_z in the case of insert B. The roughness values are not sensitive to the cutting speed; however, they increase with the feed rate. The S_z values at different feed rates are 0.10–0.21 μm lower for insert B than for insert A.

Similar results were found in the case of the arithmetical mean height (S_a); however, no deviation can be observed in the values at the highest feed rate (Fig.7). Here, at the two lower feed rates a slight decrease can be observed when the cutting speed is increased. The S_a values at different feed rates are 0.03–0.28 µm lower for insert B than for insert A.

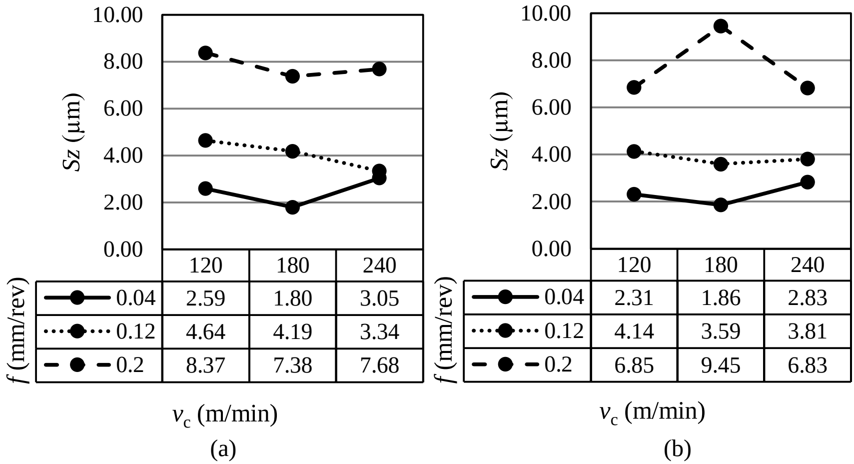


Figure 6 – Maximum height values – insert A (a); insert B (b)

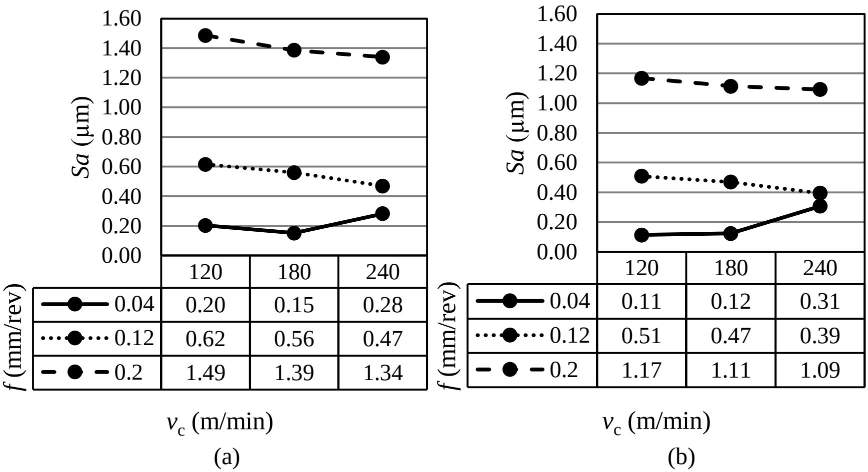


Figure 7 – Arithmetical height values – insert A (a); insert B (b)

The skewness values of the surfaces machined at the lowest feed rate show a relatively high deviation (Fig. 8). In the case of insert A S_{sk} is between -0.17 and 0.10, and in the case of insert B between -0.24 and 0.46. The negative S_{sk} values are favorable from a wear resistance point of view because the peak zone of such a surface is more filled. At the two higher feed rates the S_{sk} values are relatively close to each other, i.e., the feed rate has no significant influence on the skewness. In the case of insert B the skewness at the lowest feed rate increases with the cutting speed.

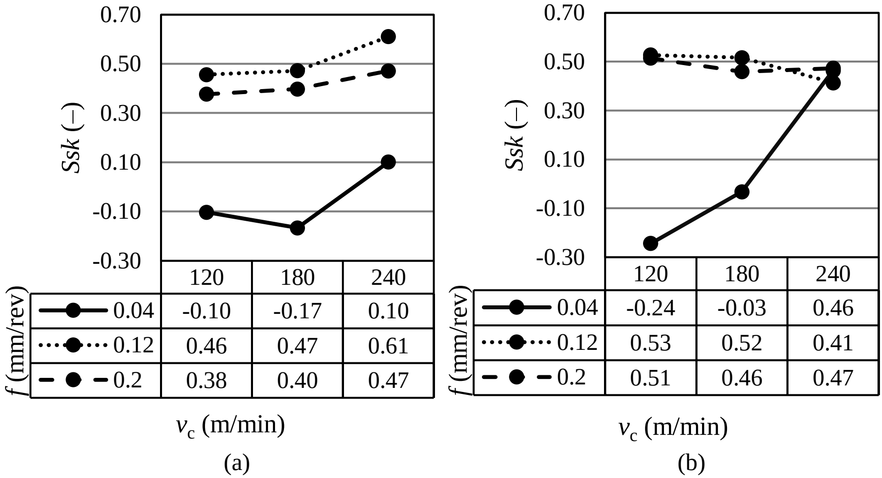
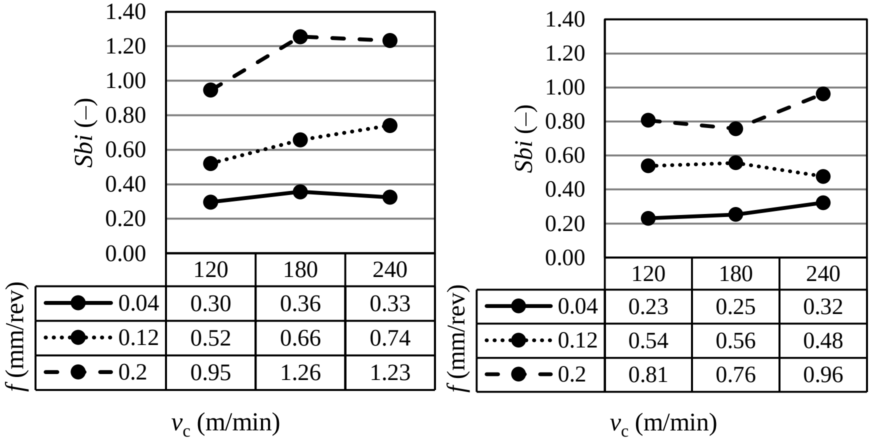


Figure 8 – Skewness values – insert A (a); insert B (b)

Concerning the S_{bi} parameter (Fig. 9), the lower value is more favorable for wear resistance. In the case of insert B the values are lower than in the case of insert A by 0.06–0.30. The skewness value does not provide sufficient information on the wear resistance at the analyzed cutting parameter values. However, the surface bearing index indicates clearer differences in the values. This demonstrates that more than one parameter is needed for obtaining more reliable information about the functionality of the surfaces.

It was found that the higher cutting forces result in a more hardened surface layer. In Fig. 10 the correlation between the S_{sk} and the hardness values is demonstrated. It was seen that both the S_{sk} and the S_{bi} values and the hardness also increase with the feed rate. In Figures 10 and 11 it can be observed that the hardness values increase with the roughness values. At the same time, the lower S_{sk} and lower S_{bi} values are favorable from a wear resistance point of view (more filled surface, larger bearing area).



(a)

f (mm/rev)	120	180	240
0.04	0.30	0.36	0.33
0.12	0.52	0.66	0.74
0.2	0.95	1.26	1.23

(b)

f (mm/rev)	120	180	240
0.04	0.23	0.25	0.32
0.12	0.54	0.56	0.48
0.2	0.81	0.76	0.96

v_c (m/min)

Figure 9 – Surface bearing index values – insert A (a); insert B (b)

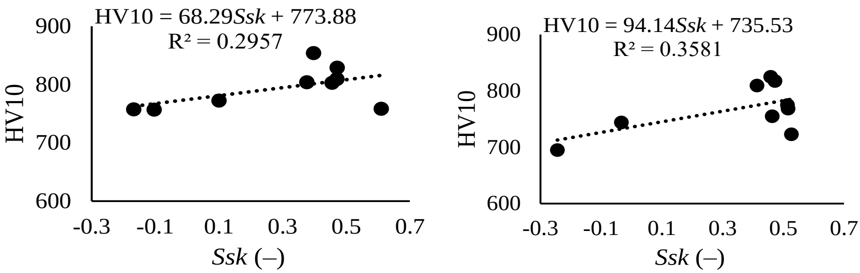


Figure 10 – Relationship between the skewness
and the hardness values – insert A (a); insert B (b)

This indicates that if the topographical parameters are favorable, the hardness value tends to be less favorable. It has to be noted, however, that the relationship between the hardness and topography values is not strong. Based on the correlation coefficients (*R*), the relationships are medium strong or weak. The correlation coefficient on the second power is the coefficient of determination. These values can be seen in the figures. The values between 0.2 and 0.4 indicate a weak relationship and between 0.4 and 0.7 a medium-strength relationship. The former is valid for the S_{sk} values (Fig. 10) and the latter for the S_{bi} values (Fig. 11).

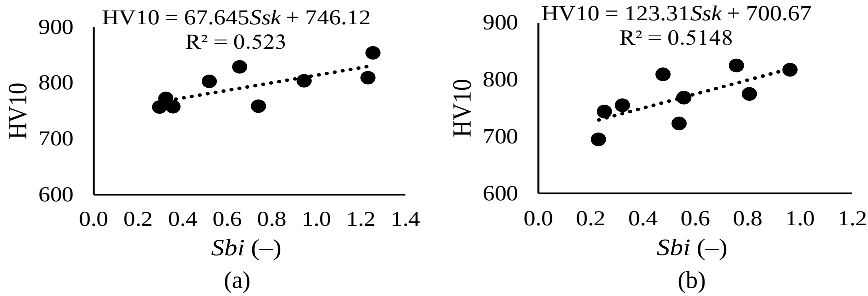


Figure 11 – Relationship between the surface bearing index and the hardness values – insert A (a); insert B (b)

5. SUMMARY

Hard turned surfaces were analyzed from a wear resistance and load bearing capacity point of view. The S_z, S_a, S_{sk} and S_{bi} topography parameters and the HV10 hardness values were analyzed and compared to each other. The following was found.

- The S_z, S_a, S_{bi} and HV10 parameters increase by the feed rate. This is valid for the S_{sk} parameter in the case of insert A (NP-CNGA 120408 TA4; α = 35°).
- The S_z, S_a, S_{bi} and HV10 values are lower in the case of insert B (4NC-CNGA 120408; α = 25°).
- The relationship between the hardness values and the S_{sk} values is weak, while the S_{bi} values have a medium-strong relationship with the hardness values. When the topography parameters improve, less favorable values are obtained for the hardness values.

The above findings are valid in the analyzed ranges of the hard turning parameters (a_p = 0.2 mm; v_c = 120–240 m/min; f = 0.04–0.2 mm/rev).

The analysis can be extended to the analysis of more depth-of-cut levels, more tools and more surface integrity or tribology related properties.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ТОПОГРАФІЇ ПОВЕРХНІ ТА ТВЕРДОСТІ ЦЕМЕНТОВАНОЇ СТАЛІ 16MNCR5, НА ОСНОВІ ТРИБОЛОГІЇ

Анотація. *Трибологічні властивості є визначальними у функціональності контактних поверхонь елементів машин. Зносостійкість або несуча здатність впливають на термін служби цих деталей. У цьому дослідженні були проаналізовані параметри тривимірної топографії поверхні (S_{sk}; S_{bi}), пов'язані з трибологією (головним чином зносостійкість) і твердість за Віккерсом жорстко точених загартованих поверхонь. Експерименти проводилися на різних рівнях подачі та швидкості різання, а також на двох пластинах КНБ з різною геометрією. Для чисельних результатів розраховано кореляційні зв'язки. В експерименті з жорстким токарним обробленням змінювалися два параметри різання: швидкість подачі (f = 0,04; 0,12; 0,2 мм/об) і швидкість різання (v_c = 120; 180; 240 м/хв). Глибина різання була фіксованою (a_p = 0,2 мм). Випробування на твердість проводили на універсальному твердомірі (Reicherter UH250). Навантаження становило 10 кПа, а час перебування 10 с. Для вимірювання застосовувався стандарт DIN EN ISO 18265. Тверді точені поверхні аналізували з точки зору зносостійкості та несучої здатності. Параметри топографії S_z, S_a, S_{sk} і S_{bi} і значення твердості HV10 були проаналізовані та порівняні один з одним. Параметри S_z, S_a, S_{bi} і HV10 збільшуються з ростом швидкості подачі. Це справедливо для параметра S_{sk} у випадку вставки A (NP-CNGA 120408 TA4; α = 35°). Значення S_z, S_a, S_{bi} та HV10 нижчі у випадку вставки B (4NC-CNGA 120408; α = 25°). Зв'язок між значеннями твердості та значеннями S_{sk} слабкий, тоді як значення S_{bi} мають середньо-сильний зв'язок зі значеннями твердості. Коли параметри рельєфу покращуються, отримують менш сприятливі значення значень твердості. Наведені вище висновки справедливі в проаналізованих діапазонах параметрів жорсткого точіння (a_p = 0,2 мм; v_c = 120–240 м/хв; f = 0,04–0,2 мм/об). Аналіз можна розширити до аналізу більшої кількості рівнів глибини різання, більшої кількості інструментів і більшої цілісності поверхні або властивостей, пов'язаних з трибологією.*

Ключові слова: *твердість HV; шорсткість поверхні; S_{sk}; S_{bi}; жорстка механічна обробка.*