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ANALYZING SURFACE INTEGRITY ELEMENTS OF HARD TURNED 16MNCR5 STEEL

Abstract. *Surface integrity plays a determinant role in the functional requirement of precision machined parts. In the automotive industry billions of components are manufactured by using case hardened steels. In this study some surface integrity elements, such as surface roughness or residual stress are analyzed based on systematic machining experimental plan to optimize the applied cutting parameters. Recommendations are made for these parameters based on the measurement data and some widely used functional requirements.*
Keywords: *hard turning; surface integrity; design of experiment.*

1. INTRODUCTION

Case hardened materials are widely used in precision machined industrial components where surface layers must fulfill certain functional requirements in their operating time, such as wear-resistance or high fatigue strength [1]. These components are mainly shafts of disc-shaped elements, e.g., bearings or gears. 16MnCr5 is a widely used low-carbon content steel which is applicable for case hardening. To ensure the required accuracy and surface quality, the hardened surfaces (55-65 HRC) can be machined by hard cutting or grinding [2, 3]. The applied machining procedure determines the surface topography among other surface integrity elements [4]. If a random surface is not needed, hard turning is a suitable option for machining cylindrical components [5].

Maximum height (S_z) of the surface topography is a height parameter that provides a simple piece of information about how rough a surface is. In calculating the theoretical value of the maximum height, cutting data are used [6]. The arithmetical mean height (S_a) provides the same information, but its use is more widespread in part drawings. The importance of these parameters is that they are directly or indirectly connected with several mechanical and material-related characteristics of the surface, e.g., fatigue life [7]. Another two parameters are the maximum peak height (S_p) and maximum pit height (S_v). The former is related to lubricant-retention ability and, through micro-crack propagation, with fatigue strength [8, 9]. The latter provides information about the load-bearing capacity and wear resistance of a surface. The higher-order moments of the height are skewness (S_{sk}) and kurtosis (S_{ku}). A surface that is more filled in the peak zone has negative skewness, which results in a higher load-bearing capacity and a lower extent of wear [10, 11]. A kurtosis higher than 3 indicates that fewer peaks and valleys are located on the surface [12].

The fewer peaks leads to less debris formation during operation and better wear resistance [13].

Residual stress is another determining factor of surface integrity. Due to the case hardening process, an initial residual stress can be observed in the surface layer; however, the machining procedure results generally in a higher extent of it than the initial value [14]. By hard turning, basically compressive residual stress is evolved, which is useful in cases when e.g., the risk of fatigue or corrosion is recommended to be minimized [15]. The reason for the relatively high compressive residual stress is that in hard turning the cutting tool has a negative rake angle [16] and therefore high radial-direction (passive) force arises during the material removal process.

In this paper the functionality of hardened surfaces is in focus. Based on a design of experiment, hard machining experiments and measurements have been carried out to determine the cutting parameter values that fulfill the following functionality requirements: reduction in S_a, S_z, and S_v increases the fatigue life; reduction in S_p and S_{sk} and increase in S_{ku} improves the wear resistance. At the same time, increase in the cutting and passive force components, and therefore, increase in the compressive residual stress state ($-\sigma$), results in increased fatigue strength.

The novelty and contribution of the study is that it provides information for cutting parameter selection when functionality-related surface integrity aspects (residual stress, roughness) must be considered in designing the hard turning procedure for 16MnCr5 case hardened steel in the case of external cylindrical surfaces.

2. METHODS OF THE EXPERIMENT AND MEASURMENTS

Hard turning (dry machining) experiments were carried out to analyze surface roughness, cutting force and residual stress values of the machined surfaces. The machine tool was a hard machining center: EMAG VSC 400 DDS. The applied insert was 4NC-CNGA 120408 coated CBN and the tool holder was PCLNR 2020-K12. The material was 16MnCr5 (HRC 60–63), the diameter and the length of the machined workpieces were 60 mm and 13 mm, respectively. The analyzed cutting parameter values were selected based on the recommendation of the tool manufacturer. The minimum and the maximum values of the three cutting data were varied in the experiment, which resulted in eight setups.

- Depth-of-cut (a_p): 0.05 and 0.35 mm
- Cutting speed (v_c): 120 and 240 m/min
- Feed rate (f): 0.04 and 0.2 mm/rev

The effects of the medium values of these parameters were also analyzed: a_p = 0.2 mm; v_c = 180 m/min and f = 0.12 mm/rev.

For the force measurement a Kistler dynamometer type 9257A was used (5000 sample/sec). For the 3*D* roughness measurement an Altisurf 520 machine with an optical sensor type CL2 was used. The evaluation area of the surface was 2 × 2 mm, the cut-off length was 0.08 or 0.8 mm based on the periodicity of the topography, the resolution in x and y directions was 1 μm and in z direction 0.012 μm, the measurement range in z direction was 0–300 μm. For the residual stress measurement a Stresstech type G3R *X*-ray diffractometer was used, the source was Cr *X*-ray.

3. RESULTS

In the following figures the analyzed parameter values are designated by dots. These values show quite well-separable levels for the two considered feed rates. The parameter values that belong to the minimum (0.04 mm/rev) and the maximum (0.2 mm/rev) feed rates are designated by black and gray dots, respectively.

The maximum height and arithmetical mean height of the surface should be decreased when lower fatigue strength is required from the precision machined surface. The S_z values of the surfaces machined at the 0.04 mm/rev feed rate are between 0.49 and 0.70 μm, and those machined at 0.2 mm/rev are between 4.57 and 5.51 μm. The relative deviations of these two groups are 15% and 10%, respectively (Fig. 1a). The S_a values of the surfaces machined by 0.04 mm/rev feed rate are between 0.08 and 0.10 μm, and those machined by 0.2 mm/rev are between 1.07 and 0.33 μm. The relative deviation of each group is 11% (Fig. 1b).

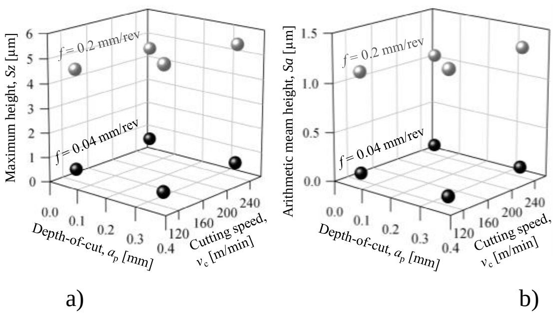
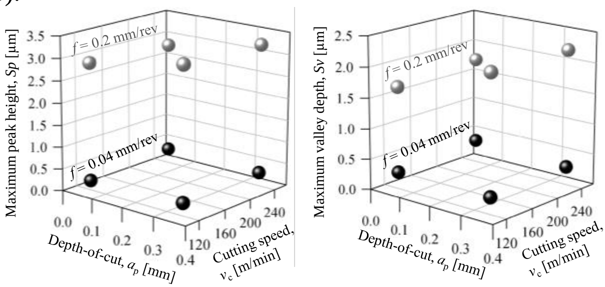


Figure 1 – The S_z (a) and S_a (b) parameter values of the machined surfaces

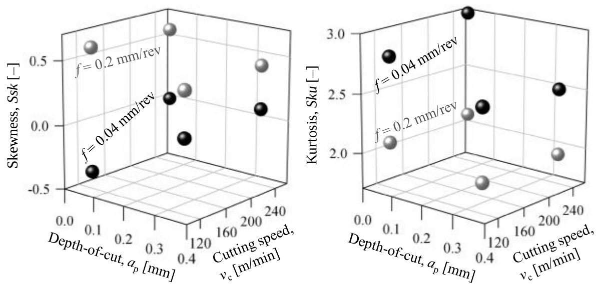
The maximum peak height (S_p) and the maximum pit height (S_v) provide information about several tribological characteristics of a surface. If the peak zone is relatively high, and includes thin peaks, they wear relatively fast, which results in debris that influences the surface. If the peak zone is low, it indicates that the surface is quite filled, i.e. the load-bearing capacity and the wear resistance of the surface is high. On the other hand, the valleys of the surface are useful from a lubricating point of view, i.e. the valleys are able to retain lubricating fluid, but they can also be the initiation places of micro-cracks. In this study the wear resistance and fatigue strength are in focus, therefore the minimization of these two parameters is the aim. The S_p values of the surfaces machined at the 0.04 mm/rev feed rate are between 0.22 and 0.33 µm, and those machined at 0.2 mm/rev are between 2.82 and 3.29 µm. The relative deviations of these two groups are 17% and 8%, respectively (Fig. 2a). The *Sv* values of the surfaces machined at 0.04 mm/rev feed rate are between 0.27 and 0.37 µm, and those machined at 0.2 mm/rev are between 1.67 and 2.23 µm. The relative deviation of each group is 15% (Fig. 2b).



a) b)

Figure 2 – The S_p (a) and S_v (b) parameter values of the machined surfaces

A surface with negative S_{sk} and relatively high S_{ku} (>3) is asymmetric, filled, and among other characteristics, wear-resistant. In the present study these requirements are fulfilled in some cutting parameter combinations.



a) b)

Figure 3 – The S_{sk} (a) and S_{ku} (b) parameter values of the machined surfaces

The S_{sk} values of the surfaces machined at the 0.04 mm/rev feed rate are between -0.37 and 0.10, and those machined at 0.2 mm/rev are between 0.43 and 0.60 (Fig. 3a). The S_{ku} values of the surfaces machined at the 0.04 mm/rev feed rate are between 2.51 and 3.01, and those machined at 0.2 mm/rev are between 1.95 and 2.12 (Fig. 3b). These results show that the lower feed rate results in favorable skewness and kurtosis values.

The cutting force components determine the stress state of a machined surface. Here the F_c cutting force and the F_p passive force are analyzed. The hard turned surfaces typically show high compressive residual stress, which is useful in the fatigue life of the components. The F_c values of the surfaces machined at the 0.04 mm/rev feed rate are between 34 and 79 N, and those machined at 0.2 mm/rev are between 87 and 248 N. The relative deviations of these two groups are relatively high: 43% and 52%, respectively (Fig. 4a). The F_p values of the surfaces machined at the 0.04 mm/rev feed rate are between 35 and 106 N, and those machined at 0.2 mm/rev are between 72 and 230 N. The relative deviations of these two groups are 53% and 56%, respectively (Fig. 4b). It has to be noted that the higher force results in favorable residual stress, and the reason for a higher force value is the more intense cutting parameters (e.g. higher cutting speed of depth-of-cut), which results in higher material removal efficiency. However, the material removal process characterized by the increased force requires higher energy consumption by the machine tool.

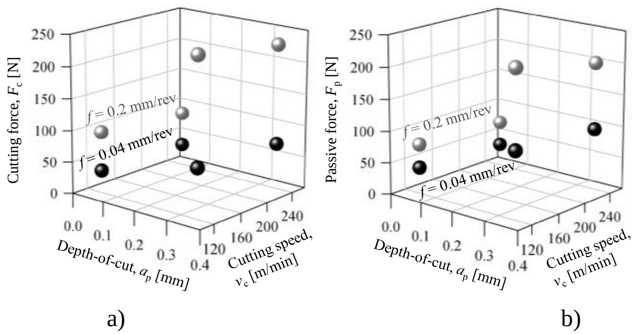


Figure 4 – The F_c (a) and F_p (b) parameter values of the machined surfaces

The two components of residual stress are the axial and tangential. They have significance in hard turning operations. To decide which component plays a determinant role in the component, the main direction of load that affects the component has to be known. In the present experiment, the axial residual stress values were favorable at the 0.04 mm/rev feed rate, and the tangential residual stress values at 0.2 mm/rev. The σ_A values of the surfaces machined at the 0.04 mm/rev feed rate are between -459 and -566 MPa, and those machined at 0.2 mm/rev are between -130 and -365 MPa. The relative deviations of these two groups are 9% and 43%, respectively (Fig. 5a). The σ_T values of the surfaces machined at the 0.04 mm/rev feed rate are between -235 and -535 MPa, and those machined at 0.2 mm/rev are between -706 and -816 MPa. The relative deviations of these two groups are 34% and 7%, respectively (Fig. 5b).

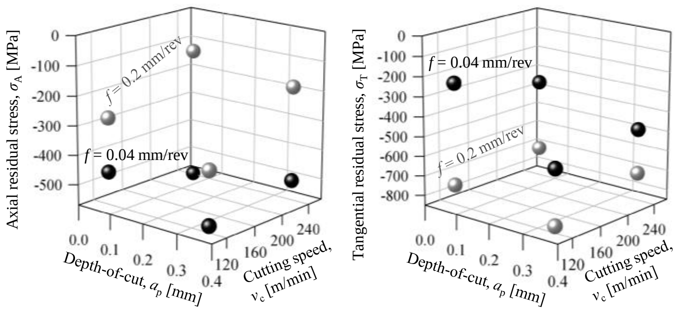


Figure 5 – The σ_A (a) and σ_T (b) parameter values of the machined surfaces

4. DISCUSSION

Not only the possible minimal (a_p = 0.05 mm; v_c = 120 m/min; f = 0.04 mm/rev) and maximal (a_p = 0.35 mm; v_c = 240 m/min; f = 0.2 mm/rev) values of the cutting parameters were set in the experiments but also the medium values (a_p = 0.2 mm; v_c = 180 m/min; f = 0.12 mm/rev). The extra data can provide information for the technologist in the data selection, because not only surface integrity-related factors but economic, efficiency or energy consumption factors should also be considered in technology planning.

The most favorable (best) S_z, S_a, S_p and S_v values were obtained by setting all three cutting parameters at their minimum values (min). The least favorable (worst) values of these parameters were obtained at minimum cutting speed and maximum (max) depth-of-cut and feed rate values (Figs. 6 and 7). The medium value is 43% and the most favorable is 9% of the least favorable value of S_z. These values in the case of S_a are 43% and 6%, respectively. The medium value is 44% and the most favorable is the 7% of the least favorable value of S_p. These values in the case of S_v are 43% and 12%, respectively. When minimization of these roughness parameters is aimed for, it is recommended to choose the minimum values of the cutting data.

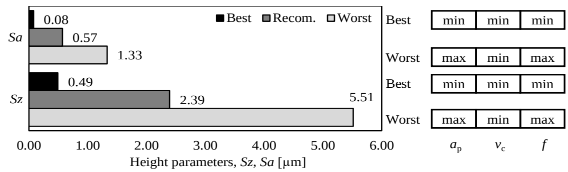


Figure 6 – The best and the worst S_z and S_a values
and their cutting parameter combinations

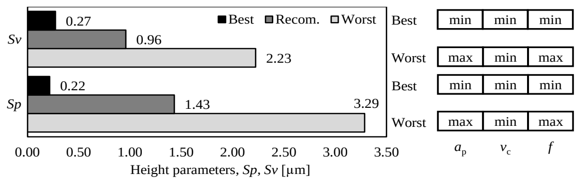


Figure 7 – The best and the worst S_p and S_v values
and their cutting parameter combinations

The most favorable value of the S_{sk} parameter was obtained at the minimum levels of all the three cutting parameters (Fig 8).

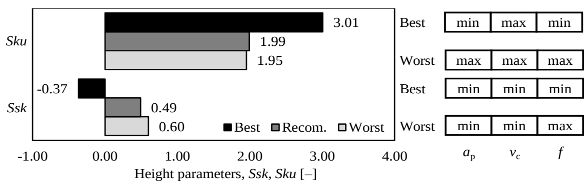


Figure 8 – The best and the worst S_{sk} and S_{ku} values
and their cutting parameter combinations

The relatively low cutting speed and feed rate supports the cutting edge (with negative rake angle) in burnishing the surface. The medium and the less favorable values are relatively close to each other, but the peak zones of the connecting surfaces are less filled, which results in poorer tribological characteristics. The most favorable value of the S_{ku} parameter was obtained at the minimum levels of the depth-of-cut and feed rate and the maximum level of the cutting speed (Fig 8). The other two S_{ku} values are close to each other and result in relatively poor tribological characteristics.

In Fig. 9 the F_c and F_p force components are demonstrated. The most favorable values were obtained at minimum depth-of-cut and feed rate and maximum cutting speed, if minimization (e.g. energy efficiency) is specified. The medium value of the F_c is 38%, the most favorable value is 14% of the least favorable one. The medium value of the F_p is 51%, the most favorable value is 15% of the least favorable one. However, if the high values are considered favorable (residual stress, and therefore fatigue strength improvement), the recommended cutting data values are the opposite: depth-of-cut and feed rate at maximum and cutting speed at minimum level.

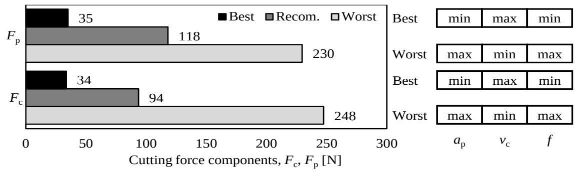


Figure 9 – The best and the worst F_c and F_p values and their cutting parameter combinations

Concerning the residual stress values (Fig. 10), their high negative values are favorable when fatigue strength and wear must be minimized. For the σ_T tangential residual stress, the most favorable value was obtained when the depth-of-cut and the feed rate were set to their maximum values, while the cutting speed was minimal. The highest values of the cutting force components F_c and F_p were obtained at this cutting parameter combination. The most favorable value for the σ_A axial residual stress was obtained when the F_c and F_p values were the lowest. The corresponding cutting parameter combination is the minimal depth-of-cut and feed rate and maximum cutting speed. It was observed that the lower feed rate whose direction is axial supports the higher compressive residual stress. The reason for that is that the tool moves more slowly and spends more time in one place, meanwhile loading the surface. In the case of the tangential residual stress, the same is observed in the perpendicular direction: the tangential direction cutting speed is relatively low, which increases the tangential residual stress value. The medium value of the axial residual stress is 2.3 times and the most favorable is 4.4 times better than the least favorable. The medium value of the axial residual stress is 2.5 times and the most favorable is 3.5 times better than the least favorable.

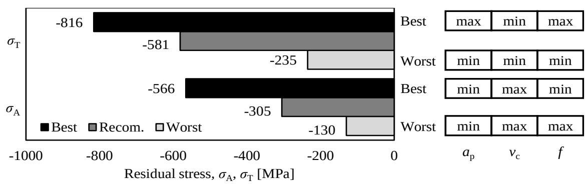


Figure 10 –The best and the worst σ_A and σ_T values
and their cutting parameter combinations

5. SUMMARY AND CONCLUSIONS

In this paper well-known surface roughness parameters (S_z, S_a, S_p, S_v, S_{sk} and S_{ku}), two cutting force components (F_c and F_p) and two residual stress components (σ_A and σ_T) were analyzed. They are determinant indicators for some surface integrity characteristics, such as wear resistance, fatigue strength or load-bearing capacity. Depending on the function of the surfaces of machine components or other (e.g., economic) purposes, these parameters can be minimized or maximized. This study focused on how this optimization can be carried out by varying the cutting parameter values. The following findings were made.

- To minimize the parameter values of maximum height (S_z), arithmetical mean height (S_a), maximum peak height (S_p), maximum pit height (S_v) and skewness (S_{sk}), it is recommended to set the depth-of-cut (a_p), cutting speed (v_c) and feed rate (f) to their minimum values.
- To maximize the kurtosis (S_{ku}) parameter value, maximum v_c and minimum a_p and f are recommended.
- The F_c (cutting speed direction) and F_p (depth-of-cut direction) cutting force components reach their maximum values at maximum a_p and f levels.
- The highest compressive axial residual stress can be reached at minimum a_p and f and maximum v_c. The highest compressive tangential residual stress can be reached at maximum a_p and f and minimum v_c.

These findings are valid for hard turning by the applied CBN insert (4NC-CNGA 120408) in the investiaged cutting parameter ranges (a_p = 0.05–0.35 mm; v_c = 120–240 m/min; f = 0.04–0.2 mm/rev), and for the applied material (16MnCr5). The limitation of the study is that only the maximum and minimum cutting parameter values were considered. The experiments are recommended to be extended to other insert geometries and material grades.

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АНАЛІЗ ЦІЛІСНОСТІ ПОВЕРХНІ ЕЛЕМЕНТІВ ЗІ СТАЛІ 16MNCR5 ПІСЛЯ ТОЧІННЯ

Анотація. *Цілісність поверхні відіграє вирішальну роль у функціональних вимогах до деталей, оброблених на верстаті. В автомобільній промисловості мільярди компонентів виготовляються з використанням загартованої сталі. У цьому дослідженні деякі елементи цілісності поверхні, такі як шорсткість поверхні або залишкові напруження, аналізуються на основі експериментального плану систематичної обробки для оптимізації застосовуваних параметрів різання. Для цих параметрів розроблені рекомендації на основі даних вимірювань і деяких широко використовуваних функціональних вимог. У цій статті були проаналізовані добре відомі параметри шорсткості поверхні (S_z, S_a, S_p, S_v, S_{sk} і S_{ku}), два компоненти сили різання (F_c і F_p) і два компоненти залишкових напружень (σ_A і σ_T). Вони є визначальними показниками для деяких характеристик цілісності поверхні, таких як зносостійкість, втомна міцність або несуча здатність. Залежно від функції поверхонь деталей машини або інших (наприклад, економічних) цілей ці параметри можна мінімізувати або максимізувати. Це дослідження були зосереджені на тому, як цю оптимізацію можна здійснити шляхом зміни значень параметрів різання. Були зроблені такі висновки. Для мінімізації значень параметрів максимальної висоти (S_z), середньої арифметичної висоти (S_a), максимальної висоти піку (S_p), максимальної висоти ями (S_v) і перекосу (S_{sk}), рекомендується встановити глибину різання (a_p), швидкість різання (v_c) і швидкість подачі (f) до їх мінімальних значень. Для максимізації значення параметра ексцесу (S_{ku}) рекомендується максимальна v_c і мінімальні a_p і f. Компоненти сили різання F_c (напрямок швидкості різання) і F_p (напрямок глибини різання) досягають своїх максимальних значень на максимальних рівнях a_p і f. Найвищі осьові залишкові напруження стиску можуть бути досягнуті при мінімумах a_p і f і максимумі v_c. Найвище тангенціальне залишкове напруження стиску може бути досягнуто при максимальних a_p і f і мінімальних v_c.*

Ключові слова: *жорстке точіння; цілісність поверхні; план експерименту.*