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# DEFORMATIONS AFTER HEAT TREATMENT AND THEIR INFLUENCE ON CUTTING PROCESS

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Preliminary notes

This paper deals with the influence of heat treatment on the deformation of parts and the following machining process. The regime of heat treatment significantly affects such aspects of material as structure, hardness and induced stress. Different process of heat treatment results in different deformation of parts and changes considering their dimensions. All these aspects are connected with the consecutive cutting operations such as grinding or hard turning, their stability, precision of produced parts, etc. Deformation of parts is also connected with the structure of material before heat treatment, placement in the furnace, regime of heat treatment and stress distribution around the parts. The results of the experimental study presented in this paper illustrate the connection between different heat treatment regimes and the following processing of parts.

***Keywords:*** *cutting process, deformation, heat treatment, residual stresses, roundness*

### Deformacije nakon toplinske obrade i njihov utjecaj na procesa rezanja

Prethodno priopćenje

Ovaj se članak bavi utjecajem toplinske obrade na deformacije dijelova i strojnom obradom koja slijedi. Režim toplinske obrade znatno utječe na takva gledišta materijala kao što je struktura, tvrdoća i inducirano naprezanje. Različit proces toplinske obrade rezultira različitim deformacijama dijelova i promjenama s obzirom na njihove dimenzije. Sva su ova gledišta povezana s uzastopnim operacijama rezanja, kao što je brušenje ili grubo tokarenje, njihovom stabilnosti, preciznosti proizvedenih dijelova, itd. Deformacija dijelova također je povezana sa strukturom materijala prije toplinske obrade, postavljanjem u peći, režimom toplinske obrade i raspodjelom naprezanja oko dijelova. Rezultati ovog eksperimentalnog istraživanja prikazani u ovom članku pokazuju povezanost između različitih režima toplinske obrade i obrade dijelova koja slijedi.

***Ključne riječi:*** *proces rezanja, deformacija, toplinska obrada, zaostala naprezanja, kružnost*

## 1 Introduction

Cutting hardened steel is a topic interest for today industrial production and scientific research. Machine parts consisting of hardened steel are high performance components which are often loaded near their physical limits. The functional behavior of machined parts is decisively influenced by the fine finishing process which represents the last step in the process chain and can as well be undertaken by cutting as grinding or turning. For this reason, fine finishing is defined as an important process and its results have to satisfy high quality requirements. The product specific issues and demands also meet effectiveness, time to market and process agility.

Development in machine tools as well as in process technology focus on cutting hardened steel and rapidly lead to a highly raised industrial relevance of hard cutting. In fact, hard cutting can seriously be regarded as an alternative for grinding operations under certain circumstances. High flexibility and the ability to manufacture complex workpiece geometry in one-set represent the main advantages of hard cutting in comparison to grinding [1]. Furthermore, the substitution of grinding process with cutting processes enables to avoid coolants and therefore can actually be regarded as interesting alternative even from the ecological point of view [1, 2].

A lot of work was carried out considering this process focused on such aspects as the experimental investigation of environmental aspect [2], surface roughness [3], analysis of chip morphology [3, 4], wear process or the progressive approach through modeling of the specific aspects [5, 6]. Some aspects of hard turning process are discussed less than others. Firsts of all, the influence of a previous operation such as heat treatment is still depreciated. Heat treatment is obviously performed as a technological operation carried out before the finishing operations. Heat treatment process does not change only the structure and other properties of parts but also significantly affects their shape, dimensions, stress state, etc. The role of finishing operation such as grinding or hard tuning is connected with precision of produced parts, surface integrity and required surface roughness. Many studies have been carried out under the stable conditions and the deformations caused by heat treatment have not been taken into consideration. Therefore this is why the present study was carried out.

## 2 Experimental conditions

Mechanical properties of roll bearing steel 100Cr6 (applied in the study) of different structure together with the regime of heat treatment are shown in Tab. 1. There were 30 rings of external diameter 49,5 mm, internal diameter 40 mm and width 8 mm prepared for each group of heat treatment process. Except for tempered martensite this study was also realized on untempered martensite of hardness 65 HRC and high tempered martensite of hardness 58 HRC (tempered at 240 °C – 2 hours). These rings were machined before heat treatment. The shape and dimension obtained after machining and after heat treatment were measured. The measured data were processed by the Q – DAS software.

The experimental study was carried out through the measurement of dimensions of rings, their profile, stress distribution and stability of the cutting operations. Dimensions of rings were measured through the comparative method (application of an electronic linear measure TESA). Measurement of parts profiles was performed on Talyrond 73. Profiles were analyzed by software package Roform. Measurement of dimension and profile was carried out before heat treatment, after heat

**Table 1** Properties of steel 100Cr6 after heat treatment

| Parameters of heat treatment | | Microstructure | Hardness HRC | Toughness / J/cm$^2$ | | |
|---|---|---|---|---|---|---|
| Austenitization Tγ/τγ | Bainit transformation Tbt/τbt | | | –40 °C | –30 °C | 20 °C |
| Hardening for martensite 840 / 25 oil; tempering 160 °C | | Tempered martensite | 62 | 13 | 16 | 23 |
| 860/5 | 240/3 | Low bainite | 59 | 35 | 45 | 55 |

**Table 2** Experimental conditions during hard turning

| | |
|---|---|
| Cutting tool: | TiC reinforced $Al_2O_3$ ceramic inserts DNGA150408 (TiN coating), rake angle $\gamma_n = -7°$ |
| Cutting condition: | $v_c$ = 150 m/min, $f$ = 0,09 mm, $a_p$ = 0,25 mm, dry cutting |
| Machine tool: | CNC Lathe Hurco TM8 |

**Table 3** Experimental conditions during grinding

| | |
|---|---|
| Grinding wheel: | A 98 80 K9V 300×30×125 mm |
| Cutting condition: | $v_c$ = 30 m/s, $v_f$ = 5 m/min, $v_w$ = 5,9 m/min, $a_p$ = 0,025 mm (10 passes with 3 spark out passes), Ecocool MK3 (3 % concentration), Single crystal diamond dresser |
| Machine tool: | 2BuD |

treatment and also after machining. Measurement of stress distribution after heat treatment was carried through the Barkhausen noise (analysis of area of envelope curves). The principle of this method is described in the literature [7, 8, 9, 10]. Rings were mounted on the experimental shaft (Fig. 1), turned before heat treatment and mounted on the same shaft in the same position before the cutting process.

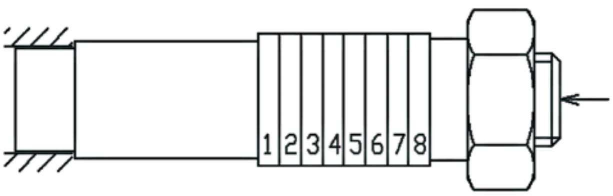



**Figure 1** Detail of parts placement

The measurement of stability during hard turning was carried out with the application of dynamometer Kistler. Measurement of stability during grinding was also carried out with the application of dynamometer Kistler 9257A adopted for measurement during cylindrical grinding. This technique was introduced by Gradišek [11]. Stability of turning operations was also carried out with the application of a commercial accelerometer (Type 4517 – frequency range from 1 Hz to 20 kHz, measuring range ± 4900 m/s$^2$ peak, reference sensitivity at 159,2 Hz ($\omega$ = 1000 1/s) by Brüel & Kjær mounted on the tool holder through the bee wax. Intensity of vibration was measured in the direction of passive component of cutting force.

## 3 Results of experiments

The results of the statistical analysis considering dimension of parts are illustrated in Fig. 2. Heat treatment process causes increase in ring diameter. This aspect is caused by structure transformation mainly of the different dimensions of martensite matrix. The degree of the martensite matrix tetragonality affects the final dimension of the parts after heat treatment. Fig. 2 illustrates that the highest average dimension increases were measured for the bainite and the untempered martensite structures. However, Figs. 2, 3 and 4 also show the lowest dispersion of measured values for the bainite structure.

The same results can be found considering roundness of measured parts illustrated in Fig. 5. It is visible that the average increase in deviation of roundness is (the difference between deviation of roundness before and after heat treatment) about 4 µm for the bainite structure, (interval ±3$\sigma$ is only 35 µm, Fig. 6) while the average increase of deviation of roundness is about 12 µm for the martensite structure, (interval ±3$\sigma$ is 65 µm, Fig. 7). This aspect must be related to the different cooling rate, different tempering stage and therefore the different process of structure transformation under the different conditions. The differences are connected with the different temperature of oil and technical salt and the following tempering process. The technical salt AISI 4030 of temperature 240 °C is used for formation of the bainite structure with the 3 hours tempering at the nearly constant temperature of the salt. This process is called isothermal tempering. The conventional hardening process is carried out with the application of oil of temperature about 25 °C with the following tempering at 160 °C (2 hours). The different cooling and tempering process lead to different states of residual stresses in the surface layers. Compressive stress is formed in the bainite structure in comparison with the martensite structures [12] (tensile stresses).

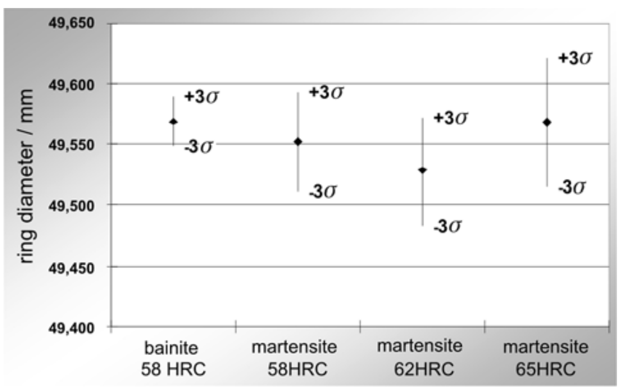



**Figure 2** Average values of dimensions and ±3$\sigma$ interval for different regimes of heat treatment

Significance of ±3$\sigma$ interval (in the scope of both parameters, dimensions and deviation of roundness) is connected with the minimum allowed working allowances for the operations after heat treatment. The operations such as grinding or hard turning have to ensure the production of parts of required precision and surface roughness. The minimum working allowances have to be higher than the ±3σ interval. Therefore higher working allowances for parts of martensite structure have to be applied in comparison with bainite structure. Higher working allowances represent the higher volume of material removal. This way grinding operations have to be carried out per more passes and so the grinding cycles will be longer for parts after conventional hardening process than that for isothermal tempering.

Turning operations are obviously carried out per one pass and the higher deformation of parts after heat treatment causes instability of cutting process. Instability of turning process affects precision of produced parts, homogeneity of surface integrity and finally intensity of tool wear. Some of these aspects are discussed in the next text.

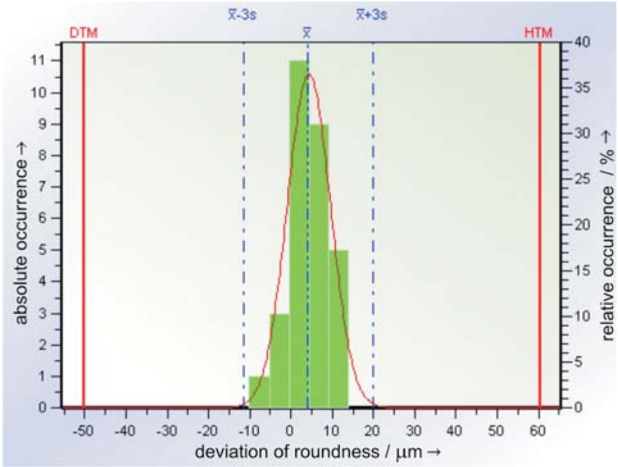



**Figure 6** Distribution of deviation of roundness occurrence - bainite 58 HRC

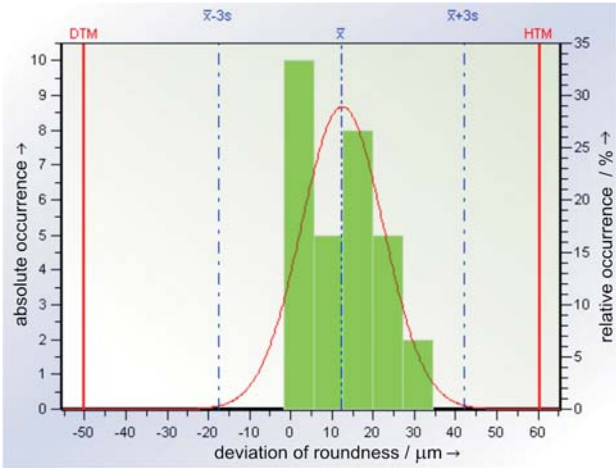



**Figure 7** Distribution of deviation of roundness occurrence - martensite 62 HRC

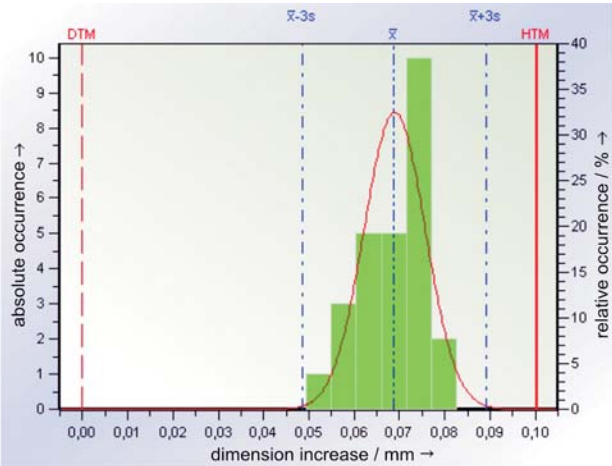



**Figure 3** Distribution of dimension occurrence of bainite 58 HRC

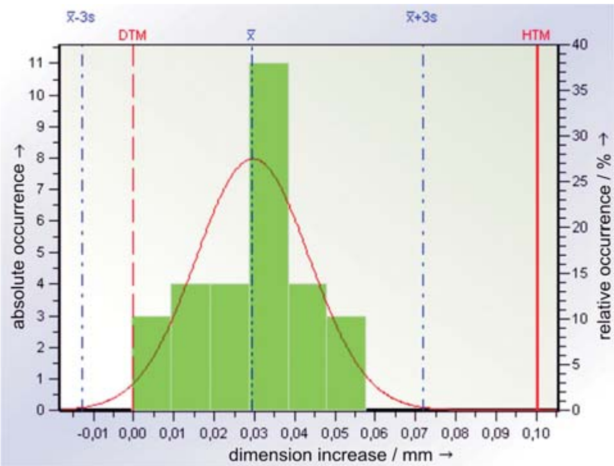



**Figure 4** Distribution of dimension occurrence of martensite 62 HRC

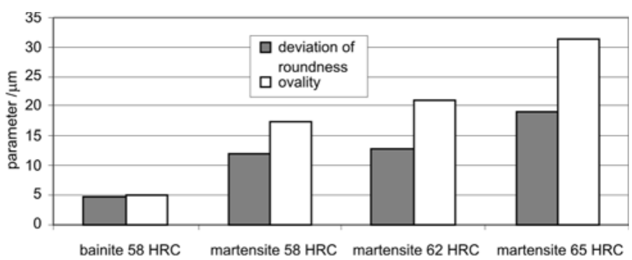
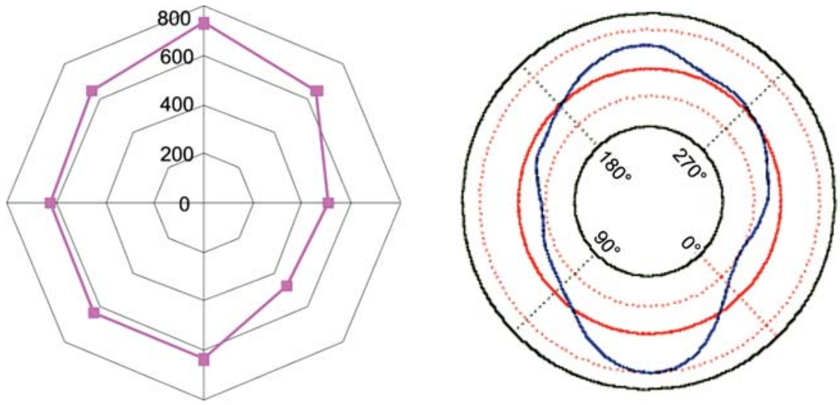



**Figure 5** Average values of deviation of roundness and ovality for the different regimes of heat treatment

The stress state of parts during the heat treatment and residual stresses induced by heat treatment itself are connected with parts deformations. However, these stresses are not the only reason for parts deformations but they also play a significant role. Residual stresses induced by heat treatment itself are only a very simple approach considering stress evaluation. The next aspect of residual stresses is associated with the stress distribution around the part (homogeneity of stress distribution). Residual stresses have to be analyzed in their complexity. The progressive method for fast and non destructive evaluation of stresses in the ferromagnetic materials is the Barkhausen noise method. Stress state is evaluated on the base of Barkhausen noise envelope curve area. The maximum (amplitude) of this envelope is connected with the hardness of structure while the area of this envelope curve is connected with residual stresses.

Stress state was evaluated around the parts at 8 points. This way the average residual stresses per each part can be evaluated and also the stress distribution of residual stresses around the part could be analyzed and compared with the profile of roundness measured after heat treatment, Fig. 8. Analysis of residual stresses shows that residual stresses vary not only in the scope of the different parts but also in the scope of the same parts. On the other hand, hardness of the structure nearly does not vary as illustrated in Fig. 9.




a) Distribution of residual stresses (area of Barkhausen noise envelopes)    b) Ring profile

**Figure 8** Relation between distribution of residual stresses and ring profile

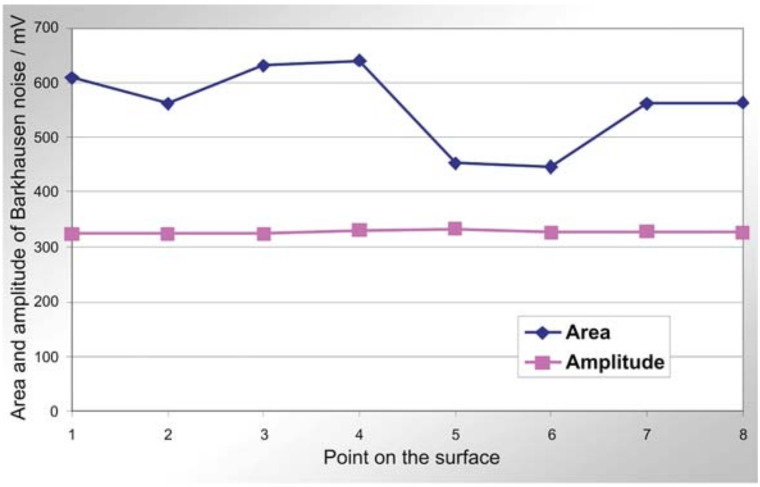



**Figure 9** Distribution of amplitude and area of Barkhausen noise around one part 8 points per 45° around the part

The average values of stresses were matched with the deviation of roundness for each part. 30 rings were analyzed for each regime of heat treatment and on the basis of these measurements the correlation between stress states (represented by average value of envelope curve area of Barkhausen noise) and deviation of roundness was calculated. The results of this analysis are illustrated in Figs. 10 and 13. It was found that the significant value of the correlation index is associated with the untempered martensite while for other heat treatment regimes the correlation indexes are low. Correlation index for the untempered martensite parts is about –0,76 (correlation with deviation of roundness) and about –0,69 (correlation with ovality). The following tempering of parts causes relaxation of residual stresses in parts and correlation index decreases (Figs. 10, 11 and 12).

The correlation between the profile of part and the distribution of stresses around the part indicates the same results as the analysis of correlation between average residual stresses and part deformation. Fig. 13 illustrates that the rings profile strongly depends on the distribution of stresses around the parts for the untempered martensite. The following tempering of parts or other regime of heat treatment leads to the decrease of this correlation. The main reason for this phenomenon can be also connected with the tempering phase and the significant stress relaxation during this phase of heat treatment.

Deformation of parts strongly affects stability of cutting process. The relative distance between a tool tip and a real surface changes in connection with the dimension and shape variation between the part and also in the scope of the same part. The real cutting depth is not stable but varies in

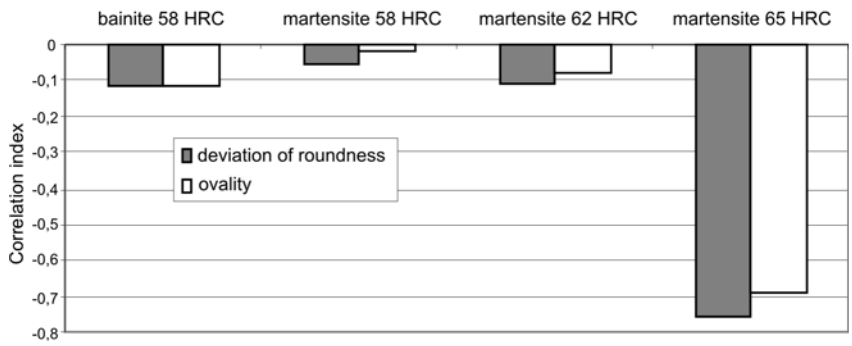



**Figure 10** Correlation indexes between area of Barkhausen noise and deviation of roundness/ovality

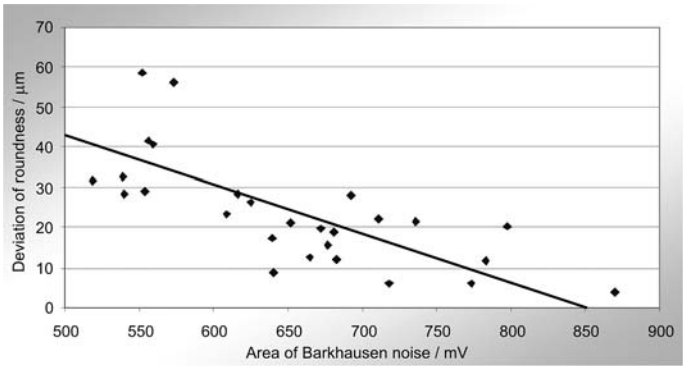



**Figure 11** Relation between ovality and area of Barkhausen noise - martensite 65 HRC

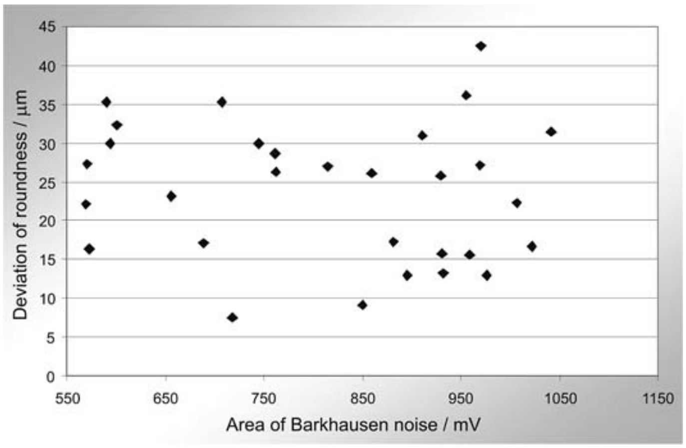



**Figure 12** Relation between ovality and area of Barkhausen noise - martensite 62HRC

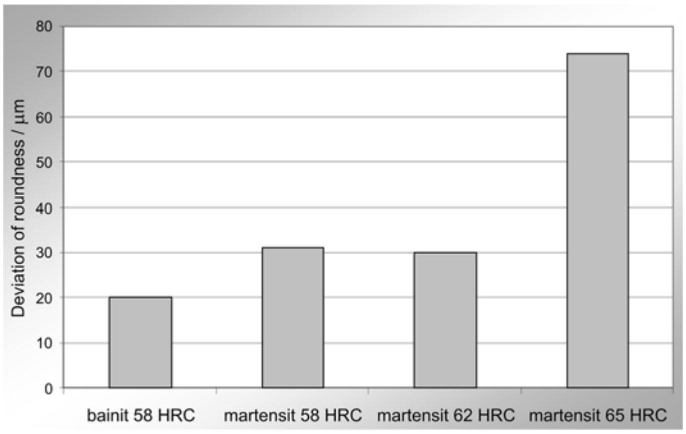



**Figure 13** Correlation between distribution of stress and deviation of roundness/ovality

connection with the relative position of a cutting insert tip and the real surface of a part. This way the real cutting process is not stable but quasi stable. The dynamic character of cutting process becomes more intensive with increase of the parts deformation and the increasing interval $\pm 3\sigma$. The dynamic character of cutting process can be detected through the application of either dynamometers or accelerometers. Fig. 14 illustrates the different intensity of vibration during hard turning of martensite and bainite parts (applied rings represent the average value of ovality typical for each group of the heat treatment regime). Fig. 14 illustrates a more stable character of cutting process during turning bainite ring than that for martensite ring (RMS value of $F_p$ for martensite is 41 N, for bainite 27 N, RMS of acceleration for martensite is 130 m/s$^2$ while 90 m/s$^2$ was measured for bainite ring).

The previous studies indicated that the instability of hard turning significantly affects the intensity of tool wear

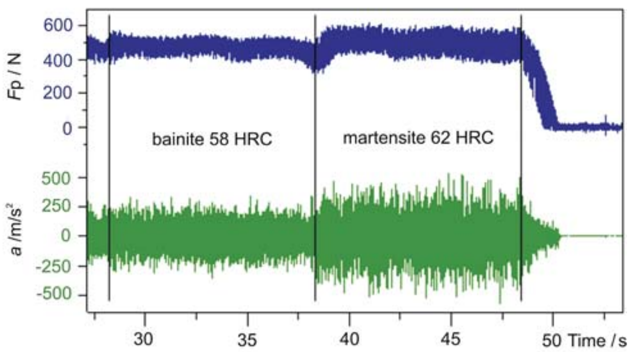



**Figure 14** Record of $F_p$ and acceleration during turning

[14]. The experimental studies obviously do not reflect the aspects of part deformation after heat treatment and the turning process is usually carried under the stable conditions. These conditions do not reflect the real hard

turning process in the real practice conditions. The specific study of the real hard turning conditions investigated that the tool life of ceramic cutting inserts in the real cutting conditions can be from 15 to 40 % lower than the tool life of the same tool under the stable cutting process (when the deformations after heat treatment were removed before the tests) [14].

The different character of grinding process is connected with the different strategy. While turning process is performed as one pass, grinding operations are performed through the consecutive passes. While cutting depth 0,25 mm represents only a single pass of tool through the part, the grinding operation can be carried out as consecutive 10 passes of cutting depth 0,025 mm with the following spark out cycle. Instability of grinding operations is connected with irrupted contact between the grinding wheel and the ground part. When the full contact is reached the deformation caused by the previous operation is removed. Therefore the low deformation of parts can result in a decreasing number of passes and so in the shortening of cycle time of grinding operation. This situation is illustrated in Fig. 15 and Fig. 16. While the cycle time associated with the interrupted contact is about 6,2 seconds during grinding the bainite ring, this cycle time is about 9 seconds when grinding the martensite structure. Moreover, grinding forces are higher during grinding martensite parts in comparison with the bainite parts. Mechanical load, especially its dynamic character during cutting operation significantly affects the precision of produced parts and the homogeneity of surface integrity. Fig. 17 illustrates a typical profile obtained for different cutting operations and different structures. It can be easily viewed that the grinding operations (which are not carried as one pass) lead to production of parts of lower deviation of roundness (on the other hand this comparison strongly depends on precision and toughness of applied machines, cutting conditions and

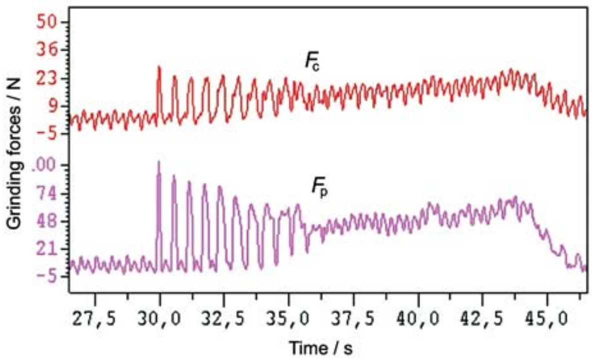



**Figure 15** Record of grinding forces during grinding bainite ring (58 HRC)

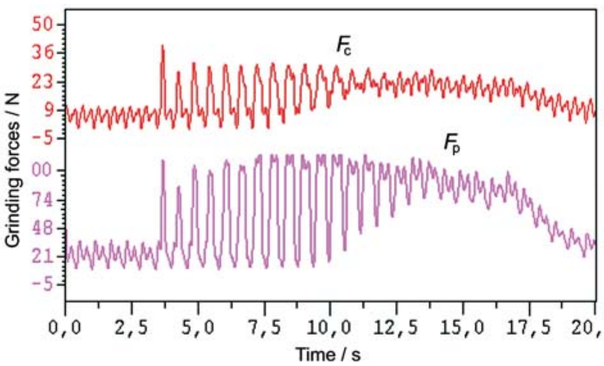
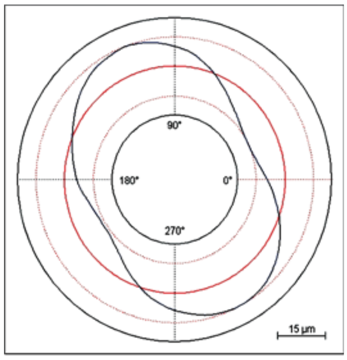
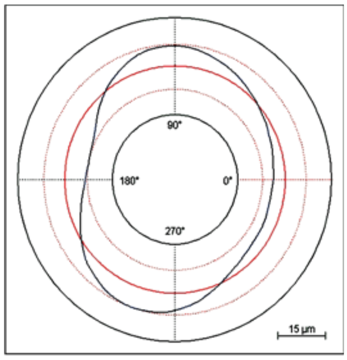


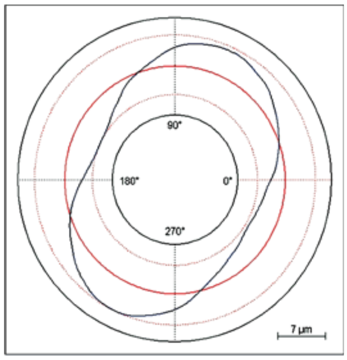

**Figure 16** Record of grinding forces during grinding martensite ring (62HRC)



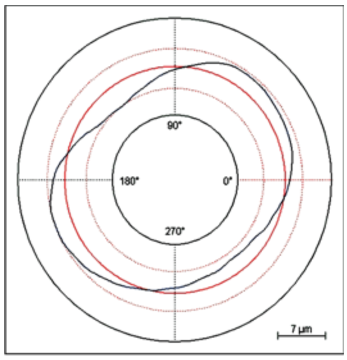

a) martensite 62 HRC, $\Delta z$ = 18 µm, turned




b) bainite 58 HRC, $\Delta z$ = 13 µm, turned




c) martensite 62 HRC, $\Delta z$ = 8,6 µm, ground

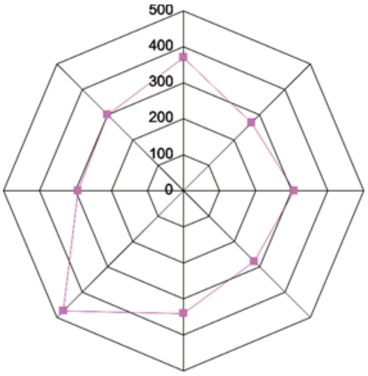



d) bainite 58 HRC, $\Delta z$ = 5,7 µm, ground

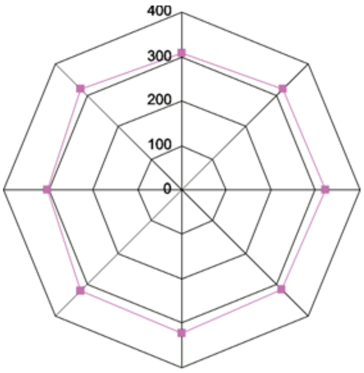
**Figure 17** Profile of rings after machining ($\Delta z$ – deviation of roundness)

other aspects). Moreover, the lower deviation of roundness can be reached for the bainite structures because of lower cutting forces and the more stable cutting process.

The stability of cutting process does not affect only the profile of a machined part, its deviation of roundness, ovality, etc., but also significantly affects the homogeneity of surface integrity. Fig. 18 illustrates the distribution of residual stresses (measured through the Barkhausen noise) around the parts after turning. The variable cutting depth during turning operation causes the variable mechanical and thermal load of machined surface in different positions.




a) martensite 62 HRC




b) bainite 58 HRC

**Figure 18** Distribution of residual stresses after turning (area of Barkhausen noise envelopes)

Mechanical and thermal load affect the formation of residual stresses under the machined surface. The different conditions for stress formation lead to non homogeneity of the surface integrity after machining.

## 4 Conclusions

The results of measurements indicate the strong influence of heat treatment on the following technology process:

- the highest average dimension increases were reached for the bainite and the untempered martensite structures,
- the lowest $\pm 3\sigma$ intervals of measured values were reached for the bainite structure,
- $\pm 3\sigma$ intervals are connected with the minimum working allowances for the following cutting operations,
- part deformations during heat treatment influence the stability of cutting process and homogeneity of surface integrity,
- tempering of parts causes relaxation of stresses in the surfaces,
- correlation between the stress state distribution and the part profile decreases during the tempering stage of heat treatment,
- while hardness of surfaces is relatively homogenous around the parts non homogeneity of the stresses is much higher.

This study compares the different regimes of heat treatment and their influence on the following cutting process. It should be noticed that the comparison between hard turning and grinding process is difficult because of many factors influencing the final results considering cycle times, surface integrity, precision of parts, economy aspects, etc [15]. These difficulties are connected with the variety of cutting conditions which can be used for both methods, variety of tools, cutting strategies, shapes of parts, applied machines, etc. Therefore each study like this has to be analyzed in the scope of specific applied conditions.

## Acknowledgement

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## 5 References

[1] Tonshoff, H. K.; Arendt, C.; Mor, R. B. Cutting of Hardened Steel // CIRP Annals 49/2/200, 547 – 564.

[2] Heo, S. J. Environmentally Conscious Hard Turning of Cemented Carbide Materials on the basis of Micro-cutting in SEM: stressing four kinds of cemented carbides with PCD tools. // Journal of Mechanical Science and Technology, 22 (2008), 1383-1390.

[3] Khidhir, B. A.; Mohamed, B. Study of Cutting Speed on Surface Roughness and Chip Formation when Machining Nickel-based Alloy. // Journal of Mechanical Science and Technology, 24, 5(2010), 1053-1059.

[4] Kountanya, R.; Al-Zkeri, I.; Altan, T. Effect of Tool Edge Geometry and Cutting Conditions on Experimental and Simulated Chip Morphology in Orthogonal Hard Turning of 100Cr6 Steel. // Journal of Materials Processing Technology, 209, 11(2009), 5068-5076.

[5] Oliveira, A.; Diniz, A.; Ursolino, D. Hard turning in continuous and interrupted cut with PCBN and whisker-reinforced cutting tools. // Journal of Materials Processing Technology, 209, 12-13(2009), 5262-5270.

[6] Chou. Y. K.; Song, H. Thermal Modelling for White Layer Predictions in Finish Hard Turning. // International Journal of Machine Tools and Manufacture, 45, 4-5(2005), 481-495.

[7] Neslušan, M.; Turek, S.; Brychta, J.; Čep, R.; Tabaček, M. Experimental Methods in Cutting Process. EDIS Žilina, 2007, 349 pages, ISBN 978 – 80 – 8070 – 811 – 8.

[8] Karpuchewski, B. Introduction to Micromagnetic Techniques. // ICBM1 report Hanover, 2002.

[9] Abuku, S.; Cullity, R. D. A Magnetic Method for the Determination of residual Stress. // Exp. Mech. 11,1971.

[10] Theiner, W. A.; Willems, H. H. Determination of Microstructural Parameters. // Symposium on Nondestructive Methods for Material Property Determination, April 6-8, 1983 Hesrhey, Pennsylvania.

[11] Govekar, E. et al. A New Method for Chatter Detection in Grinding. // CIRP 48/1( 1999), 29 – 33.

[12] Šípek, M. Study of deformation after heat treatment of roll bearing steel. // DP 2008, Faculty of Mechanical Engineering, University of Žilina.

[13] Schumann, H. Metallographie. Deutscher Verlag fúr Grundstoffindustrie, Leipzig, 1989.

[14] Tabaček, M. Turning steel 100Cr6 of bainite structure. // DDP 2007,

[15] Tonshoff, H. K. - Wobker, H. - Brandt, D. Hard Turning – Substitute for Grinding Operations. // Eurometalworking, Udine, September 28-30, 1994, p. 60/1-60/8.

[16] Čep, Robert; Neslušan, Miroslav; Barišić Branimir. Chip Formation Analysis During Hard Turning. Strojarstvo, 50, 6(2008), pp. 337 – 345. ISSN 0562 – 1887.

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