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Residual Stress and Structure Analysis of Turned Duplex Steel Parts of Decanter Centrifuge

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Abstract: *První brněnská strojírna Velká Bíteš, a. s*. as an important Czech producer of decanting centrifuges is developing a new type in this product line in cooperation with the Czech Technical University in Prague. The aim is not only to increase the effectiveness of dewatering and overall reduction of energy consumption for the operation of the centrifuge, but also to improve economic efficiency by optimizing the production of technical and organizational conditions. The issue of development is dealt comprehensively from the perspective of research and technological conditions of stainless steels machining with regard to the surface integrity, in particular depth distribution of residual stresses in the surface layers after machining, as it is generally acknowledged that the machining significantly affects the state of residual stress and, thus, component life under dynamic loads. This contribution deals with results obtained by X-ray diffraction analysis of residual stress on the surfaces of selected specimens manufactured with various parameters of the cutting process coupled with further study of surface integrity characteristics such as analysis of parameters from hysteresis loop.

Keywords: decanter centrifuge, surface integrity, residual stresses

1. Introduction

One of the current trends in the ecology of cleaning wastewater and industrial sludge is to increase the relia-bility and to lower the operating costs of sewage stations whose key facilities are the decanter centrifuges. One way to ensure both is research and development in the area of a construction, especially by using new materials and progressive methods of their final machining. The reliability of machinery is directly related to research of technological parameters of machining, especially with respect to the state of residual stresses in surface layers, since it affects service life of dynamically loaded components. In the case of rotors in counter-decanting centrifuge, the maximal external load is on the surface due to centrifugal forces, ranging about 4000 rpm, which con-tributes to the high probability of grain deformation and voids creation in the surface. In order to acquire improved wear resistance and prolonged service life of rotors, duplex steels are used for their manufacturing. This innovation unfortunately brings in an issue of mechanical hardening during

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machining which is responsible for alteration of mechanical properties of the newly created surface. Mechanical hardening during turning can be accompanied by heterogeneous behaviour such as vibrations and instable chip formation [1]. Vibrations coupled with high cutting forces and high temperatures cause not only fast wear of cutting tools, but emergence of structural inhomogeneities on the machined surface as well [2]. Local inhomogeneity of both macroscopic and microscopic residual stresses or changes of phase composition are observed most frequently as a consequence of high temperatures during turning and comparatively low thermal conductivity of duplex steels [3].

Heterogeneity of macroscopic and microscopic residual stresses can be detected by Barkhausen noise (BN) analysis, yet there is no record in literature of such study in case of duplex steels. Tensile stresses in the surface increase the intensity of BN and compressive decrease. The level of BN is defined by the so called magneto-elastic parameter *mp* which is influenced by properties such as microhardness. With the aim to separate the impact of residual stresses and microhardness, other parameters of hysteresis loop, i.e. remanence *Br*, permeability μ and coercive force *Hc*, were analysed [4, 5].

2. Sample studied

Hitherto, austenitic stainless steels have been most commonly used in manufacturing of decanter centrifuges (Fig. 1) and due to the introduction of innovations into the production, the research was done on duplex austenit-ic-ferritic stainless *Cr-Ni-Mo-N* steel for casts, *EN 1.4470; GX2CrNiMoN22-5-3*. Longer service life is expected from using this material, particularly due to its higher abrasive resistance which is estimated at about 20 %. The investigated surfaces of the cylinder-shaped test specimen were machined by finish hard turning; in operation mode, the cylinders are expected to run at least for thirty thousand hours at 4000 rpm.

Fig. 1. Example of worn part of decanter centrifuge housing made of austenitic steel after 30 000 working hours (4000 rev./min).

The turning of the analysed surfaces was carried out with the aim to assess (i) the influence of tool’s feed (f = 0.1; 0.2; 0.3 mm/rev) with the constant cutting speed (c_v = 45 and 65 m/min) and constant depth of cut (a_p = 0.2 mm), (ii) the influence of cutting speed with keeping the tool's feed and depth of cut constant, on the residual stresses and other parameters of surface integrity. Two tracks with each used tool's feed parameter were at our disposal. The sequence of the machined surface with individual tool's feed for both cutting speed was chosen according to the principles of design of experiments (DOE) method and the experiments' evaluation was randomized so that the unwelcome effects were subdued. X-ray diffraction measurements and BN analysis were performed on the surfaces of all twelve tracks denoted *1 – 12*. On each track, a network of three points distant by 120° was chosen. Analysed points were measured in the direction of tool's feed *A* and in the perpendicular direction *T*.

3. Experimental techniques

3.1. X-ray diffraction technique

The measurements were performed on *Xstress 3000 G2* with CrKα radiation, the irradiated surface area was 2 mm in diameter. The diffraction line *{211} of* α-Fe phase was analysed. Values of W_A, W_T are average integral widths of *{211}* α-Fe diffraction profile corresponding to measurements of σ_A and σ_T and represent degree of plastic deformation in the given directions [6].

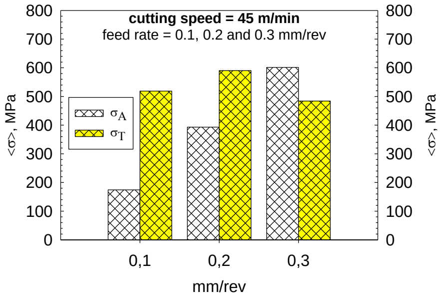
The magneto-elastic measurements were performed with *MicroScan 600-1* magnetoelastic analyser with a standard sensor. The main parameters of the applied method were: sinusoidal shape of magnetic signal, magnetic voltage 2 V, and frequency 125 Hz with band filter 70-200 kHz [7].

4. Results

A selection of results presented in this article aims at offering the readers possibility to assess the impact of tool's feed and cutting speed on residual stresses and other parameters of surface integrity. Average values, from three points on all tracks (see Tab. 1) of macroscopic residual stress and width of *{211}* α-Fe diffraction profile for applied tool's feeds at constant cutting depths are schematically depicted in Figs. 2, 3, 4 and 5. In Tab. 2 and 3, chosen values relevant for the analysis of cutting speed at constant tool's feed and depth of cut are presented. The average values of magneto-elastic parameter *mp*, remanence *Br*, permeability μ and coercive force *Hc* for chosen tool's feed and cutting speed of 45 m/min are graphically represented in Figs. 6 to 9. In Tab. 4 are noted average values related to the analysis of cutting speed at constant tool's feed and depth of cut.

Table 1. The values $\langle\sigma_A\rangle$, $\langle\sigma_T\rangle$ and width $\langle W_A\rangle$, $\langle W_T\rangle$ of diffraction line *{211}* α-Fe determined from three areas for turning trail *3*. Tool feed = 0.1 mm/rev and cutting speed = 45 m/min.

area	$\langle\sigma_A\rangle$, MPa	$\langle W_A\rangle$, deg	$\langle\sigma_T\rangle$, MPa	$\langle W_T\rangle$, deg
3.1	512±25	2,99±0,10	704±21	2,93±0,09
3.2	-59±57	3,15±0,10	447±27	3,14±0,07
3.3	-72±140	3,12±0,06	519±52	3,18±0,08



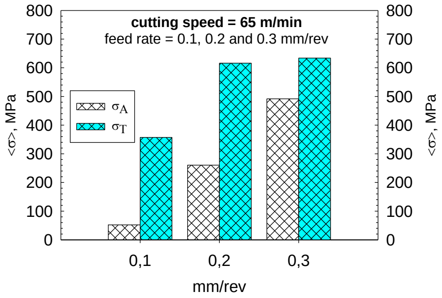
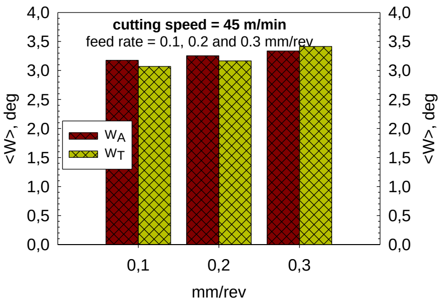


Fig. 2. The average residual stresses $<\sigma_A>$ and $<\sigma_T>$ for tools feed 0.1, 0.2 and 0.3 mm/rev. Cutting speed = 45 m/min.

Fig. 3. The average residual stresses $<\sigma_A>$ and $<\sigma_T>$ for tools feed 0.1, 0.2 and 0.3 mm/rev. Cutting speed = 65 m/min.



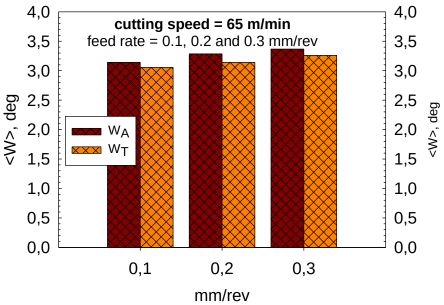
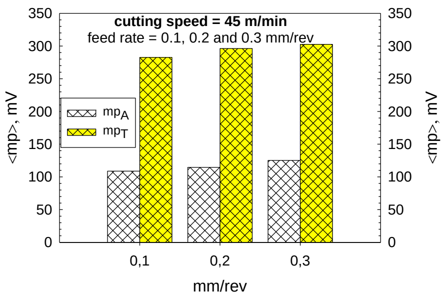


Fig. 4. The average width of the *{211}* *α*-Fe $<W_A>$ and $<W_T>$ for the tools feed 0.1, 0.2 and 0.3 mm/rev. Cutting speed = 45mm/min.

Fig. 5. The average width of the *{211}* *α*-Fe $<W_A>$ and $<W_T>$ for the tools feed 0.1, 0.2 and 0.3 mm/rev. Cutting speed = 65mm/min.



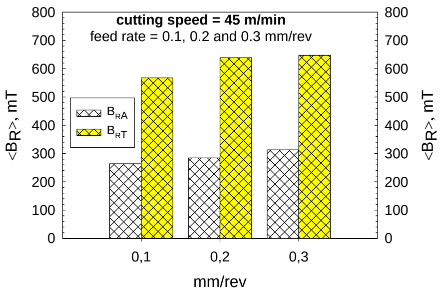


Fig. 6. The resulting values for magnetoelastic parameter $<mp_A>$ and $<mp_T>$ for the tool feed 0.1, 0.2 and 0.3 m/rev and cutting speed 45 m/min.

Fig. 7. The resulting remanence values $<Br_A>$ and $<Br_T>$ for the tool feed 0.1, 0.2 and 0.3 mm/rev and cutting speed 45 m/min.

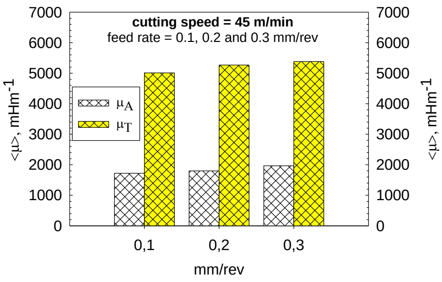


Fig. 8. The resulting permeability $<\mu_A>$ and $<\mu_T>$ for the tool feed 0.1, 0.2 and 0.3 mm/rev and cutting speed 45 m/min.

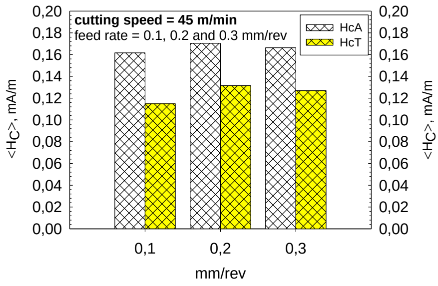


Fig. 9. The resulting coercive force $<H_{cA}>$ and $<H_{cT}>$ for the tool feed 0.1, 0.2 and 0.3 mm/rev and cutting speed 45 m/min.

Table 2. The resulting values $<\sigma_A>$, $<\sigma_T>$ and width $<W_A>$, $<W_T>$ of diffraction line *{211}* α-Fe for tool feed 0.1 mm/rev. Cutting speed = 45 and 65 m/min.

cutting speed, m/min	$<\sigma_A>$, MPa	$<W_A>$, deg	$<\sigma_T>$, MPa	$<W_T>$, deg
45	174	3.18	519	3.07
65	52	3.14	357	3.06

Table 3. The resulting values $<\sigma_A>$, $<\sigma_T>$ and width $<W_A>$, $<W_T>$ of diffraction line {211} α-Fe for tool feed 0.3 mm/rev. Cutting speed = 45 and 65 m/min.

cutting speed, m/min	$<\sigma_A>$, MPa	$<W_A>$, deg	$<\sigma_T>$, MPa	$<W_T>$, deg
45	601	3.34	484	3.41
65	492	3.37	634	3.26

Table 4. Resulting values $<mp_A>$, $<mp_T>$, mV and $<Br_A>$, $<Br_T>$, mT also $<\mu_A>$, $<\mu_T>$, mHm^{-1} and $<H_{cA}>$, $<H_{cT}>$, mA/m for the tool feed 0.2mm/rev and cutting speed 45and 65 m/min.

v_c	$<mp_A>$	$<mp_T>$	$<Br_A>$	$<Br_T>$	$<\mu_A>$	$<\mu_T>$	$<H_{cA}>$	$<H_{cT}>$
45	125	303	313	647	1967	5381	0.167	0.127
65	98	250	236	595	1366	4131	0.171	0.144

5. Discussion

The state of residual stress after turning is the result of joint occurrence of the following processes [8].

• Plastic deformation takes place in the cutting zone during the chip formation. This elasto-plastic deformation reaches also beneath the machined surface. Considering the fact that the tool cutting edge is not ideally sharp and part of the set cutting depth is not sliced off, the material of the machined layer is squeezed. This holds true also in the case of this study when the feed of 0.1 mm/rev is small. Residual stress creation and/or redistribution can be explained by the phenomenon when the density of a metal decreases and the specific volume increases during plastic deformation [10]. When the specific volume raises in the surface layer, compressive residual stresses will be generated.

- When ductile and plastic metals and alloys are machined, the ratio of tensile strength R_m to yield strength $R_{p0.2}$ is larger than 1.25 (for the material studied in this contribution, this ratio amounts approx. 1.60), and continuous chip is formed with the joint between the chip and the work-piece uninterrupted. The grains of the basic material are deformed due to bond with the chip; the grains close to the surface are deformed approximately in the same direction as the chip. However, reorientation of the surface grains does frequently occur and the grains are elongated in the direction perpendicular to the surface and compressed parallel to it. Consequently, the surface layer strives to adopt smaller area and since the layer beneath the surface ones stay virtually unaffected, tensile residual stresses are generated.

- When deformation-related processes during contact between the cylinder made from plastic material and elasto-plastic plane are simulated, compressive residual stresses arise in case of large load of tool edge and tensile the load is smaller. This is in accordance with the obtained results when the higher tool's feed and, correspondingly, higher load of tool edge lead to higher tensile residual stresses and the diffraction profile analysis reveal bigger degree of plastic deformation as seen in Figs. 2, 3, 4 and 5. The effect of higher load of tool edge at increasing tool's feed is caused by fast mechanical hardening of austenite in duplex steels .

- Existence of higher temperatures in surface layer leads to generation of tensile residual stresses.

6. Conclusions

6.1. X-ray diffraction analysis of residual stresses

Despite the inhomogeneous character of the analysed *{211} α-Fe* diffraction line, which is due to the presence of preferred orientation, the performed X-ray diffraction measurements of residual stresses allow us to make following conclusions.

The effect of inhomogeneities

- During the surface mapping, favourable compressive residual stresses in the direction of tool's feed *A* were found in several points, but only for the smallest tool's feed of 0.1 mm/rev, see Tab. 1. This observation is in line with already published studies dealing with residual stresses after turning [5].

- With one single exception, the residual stresses are in absolute values always lower in the direction of tool's feed *A*, i.e. $|\sigma_T| > |\sigma_A|$. This is caused by mechanical interaction of tool's edge with the work-piece when elongation of surface layers occurs due to the main cutting movement of work-piece rotation (the direction of σ_T).

Effect of tool´s feed

• With increasing tool´s feed, the residual stress values and diffraction profile width increases in both analysed directions. For the cutting speed of 65 m/min, bigger gradient is observed as seen in Fig. 3. The only exception is σ_T when f = 0.3 mm/rev and v_c = 45 m/min, but that correlates with the values of diffraction profile widths measured in this direction, see Fig. 4.

• Effect of tool´s feed change is more pronounced in the axial direction.

• The so called homogenisation of residual stresses, or levelling off σ_A and σ_T, takes place with increasing tool´s feed.

Effect of cutting speed

In axial direction, higher cutting speed leads in all cases to lower residual stresses and higher degree of plastic deformation as qualitatively estimated by the width of diffraction profile diffraction profile, the exception is the feed 0.1 mm/rev as seen in Tab. 2 and 3.

• In tangential direction, the increase in cutting speed leads to higher tensile residual stresses and larger width of diffraction profile, the exception is the feed 0.1 mm/rev.

• Reducing of residual stresses in axial direction at higher cutting speed is caused by ratio f/v_c when this ratio is always lower for higher cutting speed. This effect is accompanied by cutting forces redistribution, which is also influenced by the previously mentioned tool´s feed when in the situation of higher tool´s feed and higher cutting speeds the increase of tensile residual stresses in axial direction is expected. This effect is well observed in Tab. 2 and 3, when $\sigma_{T45} > \sigma_{T65}$ in the surfaces machined with tool´s feed of 0.1 mm/rev. The areas which were machined with tool´s feed of 0.2 mm/rev. show $\sigma_{T45} \leq \sigma_{T65}$. The machined surfaces with tool´s feed of 0.3 mm/rev can be already characterised by $\sigma_{T45} < \sigma_{T65}$.

6.2. Magneto-elastic measurements of hysteresis loop characteristics

The effect of inhomogeneities

• All studied parameters, i.e. *mp, Br,* μ and *Hc*, exhibit significant local inhomogeneities in both directions.

• In all points, the *mp* values are more than 2.5 times larger in tangential direction compared with axial as seen in Fig. 6. This is in line with our assumptions and results of residual stresses measured by X-ray diffraction in Fig. 2 and 3. Higher tensile stress in tangential direction facilitates easier movement of Weiss domains and, thus, of Bloch walls in the direction of magnetisation; the *mp* values are hence larger.

• Remanence *Br* and permeability μ also exhibit 2.5 times larger values in tangential direction compared with axial as seen in Figs. 7 and 8.

• Coercive force *Hc* is the only parameter that shows by 30 % lower values in tangential direction as seen in Fig. 9.

Effect of tool´s feed

• Higher feed leads to higher values of *mp, Br* a μ in both analysed directions.

• For cutting speed of 45 m/min, the increase in monotonous and the parameters *mp, Br* a μ are the largest for feed of 0.3 mm/rev. The largest values of these parameters are observed for feed of 0.2 mm/rev when cutting speed of 65 m/min is applied.

Effect of cutting speed

• Higher cutting speed leads in all analysed cases to lower values of *mp, Br* a μ parameters in both directions.

• Values of coercive force are the only ones that increase when the cutting speed rises from 45 m/min to 65 m/min in both analysed directions, the exception is f = 0.2 mm/rev in tangential direction.

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