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Experimental Stress Analysis

Effect of Machining Conditions on Residual Stresses due to Milling

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Abstract: The goal of the contribution is to present results of X-ray diffraction study of residual stresses in the surface layers of guide gibs for machining centres made from hardened 14 100.3 steel. Investigated samples were side-milled using a cutter head with tool tips. While the cutting depth was kept constant, various cutting speeds, and feeds were applied. Surface integrity was studied in order to assess the effect of the varied machining parameters on both the surface and depth distributions of residual stresses. The state of residual stresses was determined in two azimuths by means of X-ray diffraction technique. Considering that the penetration depth of CrKα X-ray radiation in steels is less than 5 μm, electrochemical etching was applied for depth profiling.

Keywords: Residual stresses, X-ray diffraction, Milling, Impact of cutting feed and cutting speeds

1. Introduction

Milling belongs to traditional machining methods which are widely used and studied from various points of view. Quality of milled surface is most commonly considered by roughness, hardness and microhardness measurement, but as the demands for hi-tech surfaces grow, other parameters must be studied in order to obtain detailed information about surface structure and properties. State of residual stress (RS) embodies one of these parameters which are being increasingly measured and whose effects are being studied. So far, it is known that these stresses can be beneficial via increasing the fatigue limit in the case of compressive surface stress, but they can have a negative effect, e.g. decreasing the stress corrosion resistance of a material with tensile residual stresses [1, 2]. Working conditions have appreciable impact on creation and/or redistribution of residual stresses in the work-piece. This

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contribution aims at finding relationship between machining conditions and the resulting state of residual stress [3, 4].

2. Samples under Investigation

The effect of cutting feed and cutting velocity on residual stresses in a machined surfaced layer of guide gibs was studied on the milled steel of Czech grade 14 100.3 (58 – 61 HRC) at seven different cutting conditions. Samples of dimensions $70 \times 30 \times 7$ mm^3 were cut from machine shears of cast iron 42 2425 (180 – 230 HB) after milling (Fig.1). All the working and cutting conditions are outlined in Table 1.

Fig. 1. Segment of a machine guide gib.

Table 1. Working and cutting conditions used in the experiments.

Sample	**1**	**2**	**3**	**4**	**5**	**6**
Cutting operation	parallel milling					
Cutter head	F2254-1000097 Ø160					
Tool diameter [mm]	Ø160					
Toll tips	P3400-100345R 2143					
Number of tool teeth [-]	24					
Axial depth a_p [mm]	2 x 0,5					
Cutting feed [mm]	**400**	**300**	**200**	400	400	400
Speed [rpm/min]	120	120	120	150	200	250
Feed per tooth [mm]	0,14	0,10	0,07	0,11	0,08	0,07
Cutting speed [m/min]	60	60	**60**	**75**	**100**	**126**

X-ray diffraction analysis of the surface was realised on two chosen areas P1 and P2 (Fig. 2). Investigated area of 5×5 mm^2 was measured both in the direction of the feed cutting tool σ_L and in the perpendicular direction σ_T.

The analysis of depth profile macroscopic residual stress was made only in the centre (area P1) of examined samples.

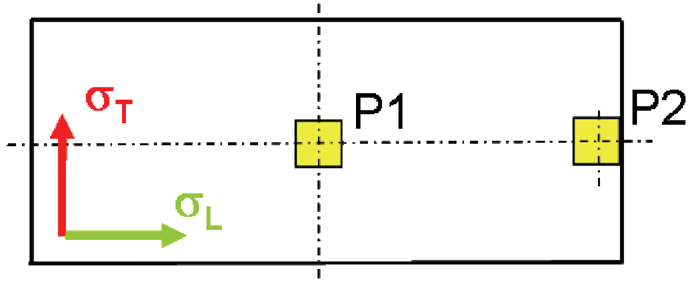


Fig. 2. Scheme of the measured surface on samples with marked directions of stress determination σ_L, σ_T and the measured areas P1 and P2.

3. Experimental

3.1. X-ray diffraction technique

The measurements were performed on a θ/θ goniometer ***X´Pert PRO*** with CrKα radiation. The diffraction line {211} of α-Fe phase was analysed. The $\sin^2\psi$ method [5] with eight different tilt angles ψ was used. The X-ray elastic constants $½s_2 = 5.76 \cdot 10^{-6}$ MPa^{-1}, $-s_1 = 1.25 \cdot 10^{-6}$ MPa^{-1} were used in macroscopic stress calculations.

3.2. Determination of residual stress depth profile

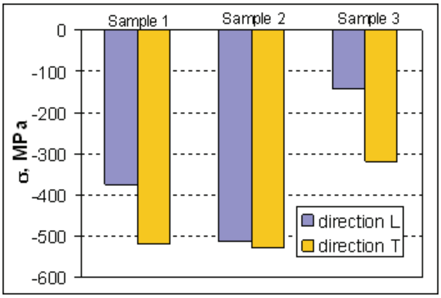
Due to limitations of X-ray penetration depth, the X-ray diffraction technique can be used only for surface layers of few micrometers in thickness. In the case of conventional X-ray diffraction apparatus, investigation of stress depth profiles is performed in combination with electrochemical etching. The process of anodic dissolution takes place during electrochemical etching while the anode is formed by the sample itself; the product of this process is a solution of high electrical resistance which is embedded into microscopic wells in the surface of the sample and, therefore, preferential removal of roughness proceeds [6]. The ***LectroPol-5*** by ***Struers***, a device for automatic micro-processor controlled electrolytic polishing and etching of metallographic specimen was used for surface layer removal.

4. Results and Their Discussion

The results of X-ray diffraction analysis of macroscopic residual stresses from areas P1 and P2 obtained from the surface as well as the average value of the width of the {211} diffraction line, which could be interpreted as a degree of plastic deformation of the crystal lattice, are shown in Table 2. Average values of residual stresses and width of diffraction line from areas P1 and P2 are illustrated in Figures 3 and 4.

Table 2. Macroscopic residual stresses in longitudinal σ_L and transversal σ_T directions and the average value of the width of the {211} diffraction line obtained from areas P1 and P2

Sample	**Area P1**		**Area P2**		**W, deg**
	σ_L, MPa	σ_T, MPa	σ_L, MPa	σ_T, MPa	
1	-317	-488	-431	-550	4.74
2	-486	-502	-542	-553	4.90
3	-127	-323	-158	-314	4.12
4	-339	-371	-445	-323	4.84
5	-332	-423	-372	-387	4.92
6	-240	-388	-200	-398	4.71



a)

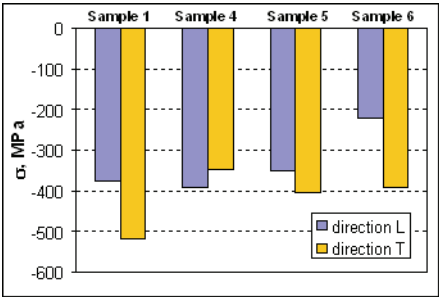


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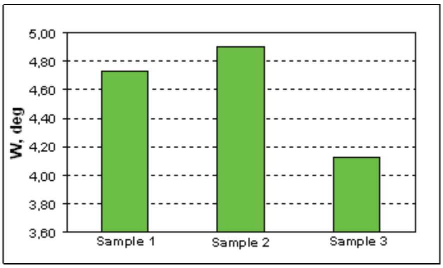
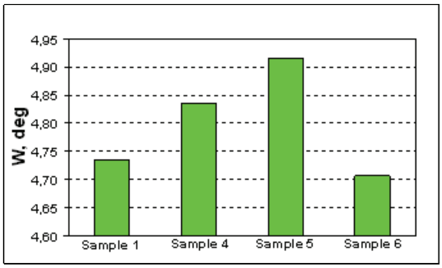
Fig. 3. Average values from areas P1 and P2 of residual stresses σ_L and σ_T from the surface; a) relation of residual stresses on the feed modification, b) relation of residual stresses on the cutting speed modification.



a)



b)

Fig. 4. Average values of the width of the {211} diffraction line obtained from areas P1 and P2 from the surface; a) relation of residual stresses on the feed modification, b) relation of residual stresses on the cutting speed modification.

The results of X-ray diffraction analysis of macroscopic residual stresses from area P1 obtained after gradual etching of the surface as well as the average value of width of the {211} diffraction line are illustrated in Figures 5, 6, and 7.

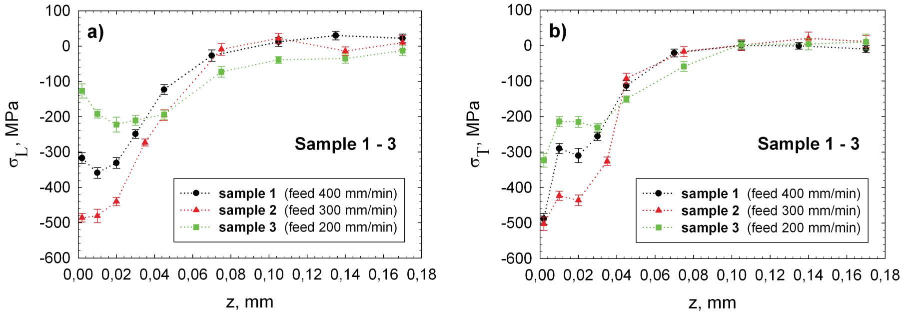


Fig. 5. Depth distribution of residual stresses σ_L (a) and σ_T (b) obtained for samples 1, 2, and 3.

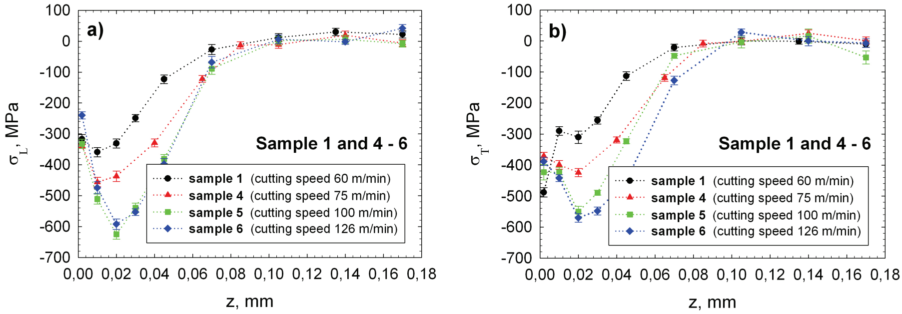


Fig. 6. Depth distribution of residual stresses σ_L (a) and σ_T (b) obtained for samples 1, 4, 5, and 6.

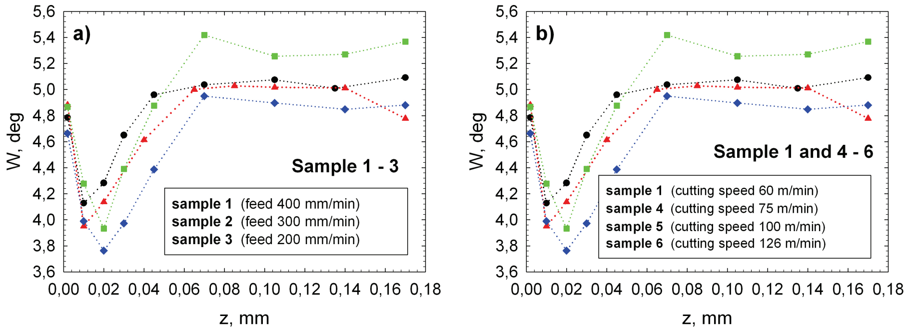


Fig. 7. Average width of the {211} diffraction line obtained for samples 1, 2, and 3 (a) and samples 1, 4, 5, and 6 (b).

Realised X-ray diffraction analysis in areas P1 and P2 enables

1. to consider inhomogenity distribution of residual stresses on the worked surface, which results from the instability of cutting process i.e. mechanical interaction of the cutting tool accompanied with local heating workpiece,
2. to evaluate influence of cutting tool feed during constant cutting speed and effect of cutting speed during constant feed on surface residual stresses and their gradients.

4.1. X-ray diffraction analysis of the investigated surfaces

- Favourable compressive residual stresses are observed on the examined surfaces in both directions σ_L and σ_T.
- Samples 1, 2, and 6 show differences in residual stress values in areas P1 and P2. In the case of the sample 1, the difference exceeds 110 MPa and 60 MPa in the direction of tool feed and in the direction of σ_T respectively. The samples 2 and 6 can be characterized by difference of approximately 50 MPa in both directions.

4.1.1. Effect of tool feed on the distribution of residual stresses

- Average absolute values of residual compressive RS measured in areas P1 and P2 are lower in the direction of tool feed compared with the perpendicular direction (Fig. 3).
- Lower cutting feed leads to decrease of differences in residual stress values measured in both selected areas P1 and P2 (Tab. 2), i.e. the stress homogenization occurs with lowering the cutting feed.
- Average absolute values of residual stresses and {211} α-Fe diffraction line widths reach maximum for the cutting feed of 300 m/min and minimum for cutting feed of 200 m/min (Figs. 3a & 4a).

4.1.2. Effect of cutting speed on the distribution of residual stresses

- Average absolute values of residual compressive RS in areas P1 and P2 measured for samples 1, 5, 6 (Fig. 3b) are always lower in the tool feed direction, the only exception is the sample 4.
- Widths of {211} α-Fe diffraction line increase with rising cutting speed, but the sample 6 machined by using the highest cutting speed of 126 m/min contradicts this behaviour since it exhibits the lowest value of diffraction line width and hence the lowest degree of plastic deformation. This effect is probably caused by differences in temperature fields in the cutting zone for the used cutting speeds which has appreciable impact on the cutting forces.

4.2. Gradients of residual stresses

- Favourable compressive residual stresses were observed on the examined samples and, in the majority of samples, the hook-like depth distributions of macroscopic residual stresses were recorded.

- Distributions of σ_L and σ_T in samples 1, 2, and 3 prove that change in cutting feed results in the change of distribution profiles, yet the affected zones remain the same, reaching approximately 80 μm (Fig. 5).
- Profiles of depth distributions are qualitatively different for σ_L a σ_T.
- Samples 1, 2, and 3 exhibit anisotropic state of macroscopic residual stress ($\sigma_L \neq \sigma_T$) which becomes isotropic ($\sigma_L \approx \sigma_T$) in depths deeper than 0.02 mm. This effect is probably caused by the nature of mechanical interaction of cutting tool with the work-piece, type of tool tips and working conditions.
- The affected zone is the same for all applied cutting speeds (Fig. 6) and its value reaches typically 80 μm.
- The effect of cutting speed is pronounced on sub-surface values of residual stresses σ_L and σ_T. The absolute values of residual compressive RS rise in both investigated directions with rising cutting speed till the threshold of 100 m/min. Further acceleration of milling process to 126 m/min has analogous consequence only for σ_T (Fig. 6b); the stress gradient of σ_L barely changes in this case (Fig. 6a).

Acknowledgements

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