Experimentální Analýza Napětí 2009
Experimental Stress Analysis

CHARACTERIZATION OF UP-CUT AND DOWN-CUT MILLED SURFACES BY X-RAY DIFFRACTION

Zdeněk Pala[1], Nikolaj Ganev[2], Jan Drahokoupil[3] & Kamil Kolařík[4]

Abstract: Choice of either up-cut or down-cut milling is, in the majority of manufacturing processes, done according to the machined material and the scope of possible damage it possess to the used tool. Besides, the milling modes have also non-neglectable impact on the surface integrity, most notable being surface roughness. It is worth investigating the final state of residual stress since it results from effects of inhomogeneous plastic deformation and from thermal fields which are not the same for both the milling modes; especially, the mechanism of material removal is significantly different for up-cut and down-cut mode. Results and their discussion in this contribution characterize the milled surfaces by three quantities, macroscopic residual stress, microstrains, and grain size, which were evaluated from X-ray diffraction data measured on either up-cut or down-cut milled specimens made from carbon steel C45.

1. Introduction

Surface is, in fact, a two dimensional defect and as such can have properties which differ from the material in the bulk. The most frequently cited differences are in surface hardness, yield strength, Poisson ratio and Young's modulus [1] and, hence, the elastic and plastic behaviour of surface layers is often not the same as those observed in the bulk [2]. Even some discrepancies between a prediction model and observed experimental results of stress-strain curves may arise from the usage of bulk input data and, therefore, a model of continuum with variable material properties has to be employed in order to obtain a trustworthy estimate. Despite of all the complications the presence of surface causes, the role it serves is a crucial one since it forms an interface between the bulk and its neighbourhood. Knowledge of surface structure and state is paramount for understanding various surface-related processes as well as for surface quality assessment.

The process of surface creation has apparently considerable impact on its final structure and properties. Most often several physical and chemical processes are in progress during the surface creation; the most notable being plastic deformation, presence and evolution of thermal fields and occurrence of phase transitions [3]. The effect of phase transitions on the final state of the surface is not considered in this contribution.

There are several attitudes for polycrystalline materials' surface characterization ranging from macroscopic qualities like morphology, roughness, hardness to microscopic parameters like dislocation density, type and structure of inter-grain boundaries or chemical reactivity. An aggregate of structural parameters describing deviations from the perfect structure of ideal crystal is known as real structure. It contains information about the state of

[1] Ing. Zdenek Pala, Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Trojanova 13, 120 00 Prague 2, 22 435 8624, zdenek.pala@cvut.fjfi.cz
[2] Doc. Ing. Nikolaj Ganev, CSc., Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Trojanova 13, 120 00 Prague 2, 22 435 8604, nikolaj.ganev@fjfi.cvut.cz
[3] Ing. Jan Drahokoupil, Department of Metals, Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, tel. 266 052 898, jandrahokoupil@seznam.cz
[4] Ing. Kamil Kolařík, Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Trojanova 13, 120 00 Prague 2, 22 435 8624, kamil.kolarik@email.cz

macroscopic residual stress, microstrains, grain size distributions, texture etc. An effective and reliable source offering diverse array of real structure parameters can be found in analysis of data from suitably designed diffraction experiments.

It is almost unnecessary to emphasize how important is the quality of an objects' surface. Good wear and fatigue resistance, lesser susceptibility to crack propagation and increase corrosion resistance can substantially increase the service life of the object. State of macroscopic residual stress and microstrains are characteristics which bear high predicative information about the processes mentioned above.

This contribution deals with milled surfaces and describes them by three qualities, macroscopic residual stress, microstrains and grain size, which were evaluated from X-ray diffraction data measured on either up-cut or down-cut side milled specimens.

2. Samples under investigation

The squared samples 50 mm in dimensions were 5.5 mm thick and made from mild carbon steel C45 (ČSN 12 050). All plates were first annealed at 550 °C in argon atmosphere for 2 hours; the decline of temperature after annealing was gradual in order to rule out any additional thermal stresses. The machining by side milling cutter was carried out either in up-cut or down-cut mode with three various conditions: (i) the end-mill speed 125 m/min and 0.2 mm thickness of removed layer, (ii) the end-mill speed 90 m/min and 0.3 mm thickness of removed layer, (iii) the end-mill speed 90 m/min and 0.4 mm thickness of removed layer. The cooling during the milling was realized only by surrounding environment, i. e. the performed machining was the so-called dry side milling.

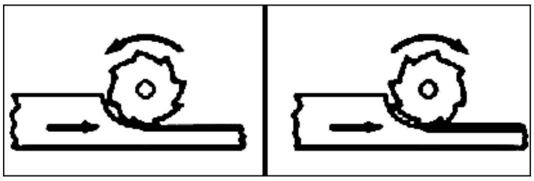

Figure 1: *Schematic diagrams of down-cut (left) and up-cut (right) side milling [4].*

3. Up-cut and down-cut milling

Milling is accompanied by plastic deformation and thermal fields which are inherently inhomogeneous due to the anisotropy of directional movements of the used tool. In general, two dominant physical processes are under way. Firstly, energy of plastic deformation and friction between the tool and the machined object generate heat whose presence causes creation of inhomogeneous thermal fields. These fields dynamically evolve as the whole system strives to get into thermal equilibrium and as the tool goes back and forth. Secondly, the surface layers of machined object are being removed and plastic deformation is, thus, inherently inhomogeneous. Moreover, external forces and moments are present and as soon as they cease to be in action, the object proceeds to the state of mechanical equilibrium [5] while the unloading can be elastic or plastic. As seen in Fig. 1 milling can be carried out in either up-cut or down-cut modes which differ significantly in the incidence of machining forces and, hence, in the mechanism of material removal.

4. X-ray diffraction stress analysis

Considering the surface after milling, there exist two possibilities for milling direction assignment. Being aware of this freedom and having the information about the geometry of milling, the diffraction measurements were performed for both options, i.e. in two coordinate systems mutually rotated by 180°. In order to obtain full stress tensor, the diffraction line {211} of *α-Fe* phase was measured in both positive and negative tilts in three azimuths 0°, 45°, 90° on an θ/θ Bragg-Brentano ω-goniometer X´Pert PRO with *CrKα* radiation. The goniometer was adjusted in respect to a strain-free reference specimen of *α-Fe* powder. For all samples, the azimuth 0° was chosen in the direction of material removal progress, and in the opposite one.

Since the ground surfaces exhibit psi splitting, calculation of tensor for state of triaxial RS was done according to modified $sin^2\psi$ (Dölle and Hauk) method [6]. X-ray elastic constants for measured *α-Fe {211}* diffraction planes were computed following the Eshelby-Kröner theory [7].

Microstrains and mean coherent scattering domain sizes were evaluated by single line profile-fitting method [8] for each obtained {211} diffraction peak of ferrite in order to unveil possible direction-dependent dissimilarities.

5. Results

Table 1: *Stress tensors' components [MPa] of milled surface, parameters of milling: the side milling cutter speed 125 m/min and 0.2 mm thickness of removed layer*

Assignment of milling direction	UP-CUT	DOWN-CUT
φ = 0° in the direction of material removal progress	$\begin{pmatrix} -125 & & \\ -3 & -243 & \\ 66 & 1 & -104 \end{pmatrix} \pm \begin{pmatrix} 19 & & \\ 0 & 18 & \\ 5 & 8 & 9 \end{pmatrix}$	$\begin{pmatrix} -89 & & \\ -49 & -209 & \\ -51 & 11 & -113 \end{pmatrix} \pm \begin{pmatrix} 20 & & \\ 7 & 15 & \\ 6 & 3 & 9 \end{pmatrix}$
φ = 0° in the opposite direction	$\begin{pmatrix} -113 & & \\ 14 & -259 & \\ -44 & 17 & -103 \end{pmatrix} \pm \begin{pmatrix} 21 & & \\ 3 & 23 & \\ 5 & 8 & 11 \end{pmatrix}$	$\begin{pmatrix} -87 & & \\ -16 & -228 & \\ 72 & 8 & -143 \end{pmatrix} \pm \begin{pmatrix} 20 & & \\ 6 & 15 & \\ 11 & 9 & 8 \end{pmatrix}$

Table 2: *Stress tensors' components [MPa] of milled surface, parameters of milling: the side milling cutter speed 90 m/min and 0.3 mm thickness of removed layer*

Assignment of milling direction	UP-CUT	DOWN-CUT
φ = 0° in the direction of material removal progress	$\begin{pmatrix} -175 & & \\ 3 & -294 & \\ 67 & 8 & -155 \end{pmatrix} \pm \begin{pmatrix} 19 & & \\ 1 & 19 & \\ 5 & 9 & 10 \end{pmatrix}$	$\begin{pmatrix} -274 & & \\ -39 & -367 & \\ -51 & 18 & -183 \end{pmatrix} \pm \begin{pmatrix} 19 & & \\ 6 & 14 & \\ 6 & 4 & 8 \end{pmatrix}$
φ = 0° in the opposite direction	$\begin{pmatrix} -191 & & \\ -3 & -320 & \\ -38 & 22 & -170 \end{pmatrix} \pm \begin{pmatrix} 20 & & \\ 0 & 19 & \\ 6 & 6 & 10 \end{pmatrix}$	$\begin{pmatrix} -280 & & \\ -46 & -366 & \\ 77 & 5 & -199 \end{pmatrix} \pm \begin{pmatrix} 19 & & \\ 7 & 14 & \\ 7 & 3 & 8 \end{pmatrix}$

Table 3: *Stress tensors' components [MPa] of milled surface, parameters of milling: the side milling cutter speed 90 m/min and 0.4 mm thickness of removed layer*

Assignment of milling direction	UP-CUT	DOWN-CUT
φ = 0° in the direction of material removal progress	$\begin{pmatrix} -123 & & \\ 18 & -296 & \\ 59 & 9 & -100 \end{pmatrix} \pm \begin{pmatrix} 16 & & \\ 2 & 18 & \\ 4 & 6 & 8 \end{pmatrix}$	$\begin{pmatrix} -108 & & \\ -26 & -219 & \\ -53 & 8 & -109 \end{pmatrix} \pm \begin{pmatrix} 21 & & \\ 4 & 16 & \\ 6 & 5 & 9 \end{pmatrix}$
φ = 0° in the opposite direction	$\begin{pmatrix} -108 & & \\ 32 & -316 & \\ -47 & 17 & -93 \end{pmatrix} \pm \begin{pmatrix} 17 & & \\ 3 & 20 & \\ 4 & 6 & 9 \end{pmatrix}$	$\begin{pmatrix} -111 & & \\ -55 & -181 & \\ 67 & 9 & -107 \end{pmatrix} \pm \begin{pmatrix} 23 & & \\ 10 & 18 & \\ 8 & 2 & 10 \end{pmatrix}$

The presented errors are standard deviations derived from the evaluation algorithm.

6. Conclusions

X-ray diffraction experiments and subsequent evaluations lead to following conclusions:

- Values of microstrains and mean coherent scattering domain sizes don't show any dependence on milling modes. The computed microstrains and mean coherent scattering domains are in the range of $8\cdot10^{-4}$ to $12\cdot10^{-4}$ and 25 to 30 nm respectively.
- Shear stress σ_{31} evaluated from psi splitting in milling direction changes its sign when the reference frame is rotated by 180°, the fundamentals of this observation is explained in the *Appendix*.
- The negative σ_{31} always occurs when the primary X-ray beam impinges the surface in the opposite orientation vis-à-vis the assumed sense of end-mill rotation. The sign of shear stress σ_{31} can be, hence, used for determination of end-mill rotation direction. This conclusion is in correspondence with the observed behaviour of ground surfaces [9].
- Negative shear stresses σ_{31} are systematically lower, in an absolute value, in comparison with positive shear stresses. Causes for such behaviour can lie in an array of factors ranging from the absorption of X-rays to deviation from perfect sample alignment.
- No systematic difference between up-cut and down-cut mode can be seen in obtained values of normal macroscopic stresses for all measured surfaces.
- Normal compressive stresses σ_{11} in the milling direction are of lesser value in respect to σ_{22}.
- The largest normal compressive stresses σ_{11} were recorded after milling with 0.3 mm thickness of removed layer, moreover, these two surfaces exhibit the only pronounced difference (approx. 100 MPa) between σ_{11} for up-cut and down-cut mode.

Appendix – Effect of coordinate system rotation by 180°

Suppose that σ_{kl} (k,l = 1,2,3) are components of stress tensor in reference frame *x, y, z*, while σ'_{kl} correspond to reference frame *x´, y´, z´*. Using Einstein summation rule (m,n = 1,2,3), their mutual relation is given by [10]

$$\sigma_{kl}^{/} = a_{km} \cdot a_{\ln} \cdot \sigma_{mn} \quad (1)$$

where a_{kl} are components of transformation matrix representing direction cosines between axes x, y, z and x', y', z':

$$\begin{pmatrix} \cos(x',x) & \cos(x',y) & \cos(x',z) \\ \cos(y',x) & \cos(y',y) & \cos(y',z) \\ \cos(z',x) & \cos(z',y) & \cos(z',z) \end{pmatrix}. \quad (2)$$

As the reference frames are rotated by 180°, the transformation matrix has the form

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

The components of the stress tensor σ'_{kl} can be therefore written as $\sigma'_{kk} = \sigma_{kk}$, $\sigma'_{13} = -\sigma_{13}$, $\sigma'_{23} = -\sigma_{23}$, $\sigma'_{12} = \sigma_{12}$. Hence, the terminology of compressive and tensile shear stresses, in contrast to normal stresses, bears no physical meaning as it depends on the choice of coordinate system.

Acknowledgements

The authors would like to express their thanks to Mr. Martin Kordík who prepared the samples in laboratories of Department of Machining and Assembly at Technical University in Liberec.

The research was supported by the Project No 106/07/0805 of the Czech Science Foundation and by the Project MSM 6840770021 of the Ministry of Education, Youth and Sports of the Czech Republic.

References

[1] Chakrabarty, J.: *Theory of Plasticity*, third edition, Elsevier Buttleworth-Heinemann, ISBN-13: 978-0-7506-6638-2, Oxford, (2006)

[2] Kapoor, A. & Franklin, F. J.: Tribological layers and the wear of ductile materials, *Wear*, 245 (2000) 1-2, pp. 204 – 215

[3] Balart, M. J.; Bouzina, A.; Edwards, L.; Fitzpatrick, M.E.: The onset of tensile residual stresses in grinding of hardened steels, *Mat. Sci. Eng. A*, 367 (2004), pp 132 – 142

[4] Totten, G.; Inoue, T.; Howes, M.: *Handbook of Residual Stress and Deformation of Steel*, ASM International, ISBN-13: 978-0871707291, Materials Park, (2002)

[5] Chen, X.; Rowe, W. B.; McCormack, D. F.: Analysis of the transitional temperature for tensile residual stress in grinding, *J. Mater. Process. Technol.*, 107 (2000), pp. 216 – 221

[6] Dőlle, H.; Hauk, V.: Zur röntgenographischen Ermittlung dreiachsiger Spannungszustände allgemeiner Orientierung, *Materialprüf.*, 18 (1976), pp. 427 – 431

[7] Hauk, V.; Macherauch, E.; *Advances in X-ray analysis* 27 (1983), pp. 81 – 99

[8] de Keijser, Th.H.; Langford, J.I.; Mittemeijer, E.J.; Vogels, A.B.P.: Use of the Voigt function in a single-line method for the analysis of X-ray diffraction line broadening, *J. Appl. Cryst.*, 15 (1982), pp. 308

[9] Pala, Z.; Ganev, N.; Drahokoupil, J.: X-ray diffraction study of anisotropic state of residual stress after down-cut and up-cut face grinding, *Advances in X-ray Analysis*, Vol. 52 (2008), *in press*

[10] Noyan, I.C.; Cohen, J.B.: *Residual Stress Measurement by Diffraction and Interpretation*. Springer, ISBN-13: 978-0387963785, New York (1987)