INVESTIGATION OF MACROSCOPIC RESIDUAL STRESSES DISTRIBUTION AFTER PROGRESSIVE MACHINING OF TOOL STEELS

K. Kolarik[1], N. Ganev[1], Zd. Pala[1], J. Barcal[2]
T. Bakalova[3], M. Svanter[4]
[1]*Department of Solid State Engineering*
Faculty of Nuclear Sciences and Physical Engineering CTU in Prague
Prague, Czech Republic
[2] *Department of Manufacturing Technology*
Faculty of Mechanical Engineering, CTU in Prague
Prague, Czech Republic
[3] *Department of Machining and Assembly*
Faculty of Mechanical Engineering, TUL of Liberec
Liberec, Czech Republic
[4] *New Technologies Research Centre*
Termomechanics of Technological Processes
Pilsen, Czech Republic

e-mail: kamil.kolarik@email.cz

HSC (High Speed Cutting) and EDM (Electro Discharge Machining) belong to the progressive and harsh machining operations. They differ markedly in the manner of material removal and, consequently, in the process of a final surface formation. While HSC represents the so called chip machining, EDM embodies a utilization of controlled thermal material reduction. With respect to the usage of these technologies, tool steels K110 and W300 were chosen for the experiments. Samples made from both the materials were primarily subjected to either HSC or EDM and residual stresses were investigated by means of X-ray diffraction, Barkhausen noise, hole-drilling, and layer removal methods.

Keywords
X-ray diffraction, residual stress, high speed cutting, electro discharge machining

1. Introduction

The goal of this research was an investigation of HSC [Vivancos 2005] and EDM [Barcal 1989] technologies. They differ significantly in the fundamentals of material removal and, consequently, in the process of the final surface formation.

HSC was chosen as a typical operation representing chip machining, when the energetic balance is determined above all by the intensity of transformation of mechanical work into heat originating in the cutting zone [Sato 2007]. EDM epitomizes a specific utilization of a controlled thermal material reduction with the energetic balance given directly by the amount of energy present in the machining area during revolving discharges and successive melting [Kunieda 2005].

Although the adoption of these progressive machining methods in manufacturing is becoming more spread, the questions regarding applicability especially in respect to the desired surface characteristics and hence utility properties has not been fully answered. The knowledge of the state of the surface layers and evaluation of changes which took place due to machining by means of HSC and EDM is indispensable [Halama 2005] if their usage is to be broadened. Such information are usually grouped under the term of surface integrity which involves important and even vital parameters related to the surface quality seen from both industrial experience and surface engineering point of view.

In this context, state of residual stress in the surface layers belongs to the foremost parameters of surface quality with crucial impact on surface reliability and lifetime. Detailed analysis of residual stresses plays an increasingly important role in the diagnostics of utility properties and supplements classic methods of material characterisation, i. e. hardness, wear resistance etc. [Halama 2008] Various methods employing wide range of physical phenomena are used for residual stress determination. This contribution includes results from X-ray diffraction (XRD) tensometry, hole-drilling method (HD), Barkhausen noise (BN) and method of layer removal (LRM). All these methods determine the state of residual stress in an indirect manner, from the change in lattice parameters due to elastic strain in the case of XRD, from released deformation in HD and LRM and from change in magnetic parameter in BN. However, it should be emphasized that these methods are based on different principles and might therefore lead to discrepant results; moreover the magnetic method of BN is sensitive not only to strains in ferromagnetic materials, but to the microstructure of the material as well. Application of LRM is limited to investigation of residual stress depth profiles in beam shaped samples

2. Investigated specimens

Samples under investigation were made from two high-quality tool steels; cold work ledeburitic K110 tool steel (X153CrMoV12) and hot work ferritic-perlitic W300 tool steel (X38CrMoV5–1); chemical composition in to be seen in Table 1. Both hardened and unhardened samples were at disposal. Material K110 was hardened and twice tempered onto secondary hardness of 58 – 60 HRC, W300 was hardened and twice tempered onto hardness of 53 – 54 HRC.

	C	Si	Mn	Cr	Mo	V
K110	1.15	0.25	0.35	11.80	0.80	0.95
W300	0.38	1.10	0.40	5.00	1.30	0.40

Table 1. *Chemical composition of studied tool steels*

Before treating of HSC milling and EDM, the plates of dimensions 30×20×8 mm^3 were subjected to face grinding in order to guarantee homogeneous and uniform initial surface quality. The thickness of removed layer was 0.02 mm, the last grinding operation was sparking-out. Eventhough the grinding itself induces new residual stresses to the surface layers. It has been shown [Vivancos 2005] that homogeneous surface before machining is highly desirable.

2.1 HSC milling

Face milling was carried out on a *DMC 104V LINEAR* milling machine by end milling cutter which had five embedded round tool tips. Since the hardness of material in basic and hardened state differed significantly, two types of tool tips had to be used (*02 10 835 PVTi* for hardened and *02 10 842 P40* for unhardened). The remaining machining conditions were as follows: tool diameter – 32 mm, number of tool teeth – 5, cutting operation down-milling, cutting speed: 150–1250 m.min^{-1}, feed per tooth – 0.05 mm, axial depth of cut – 0.2 mm, radial depth of cut – 22 mm. The cutting was done in natural environment (i. e., no coolant was used). The above mentioned range of cutting speed corresponds to the volume output Q_V = 39 – 330 mm^3.s^{-1} and to the specific work 5 –10 J.mm^3.

2.2 EDM

A *Walter Exeron S 204* device with a pulse generator with power of 9 kW and current of 180 A was used. The polarity was indirect, i. e., tool (–) and workpiece (+). Two modes of machining were applied: (i) stocking characterized by higher material reduction, high energy of discharges and lower values of discharge frequency with estimated surface roughness Ra not exceeding 6,3 μm; (ii) finishing with lower energy and higher frequency of discharges with desired surface quality up to 1,6 μm. The used device enabled the following operational conditions: UZ = 100 – 260 V, I_e = 10 – 160 A, f = 10 – 100 kHz, QV up to 20 $mm^3.s^{-1}$, corresponding to the specific work ranging from 100 to 1000 J. mm^3.

3. Experimental methods

Surface and near-surface states of residual stress (RS) were analysed by means of following experimental techniques: X-ray diffraction (XRD) *one tilt method* [Kraus 2004] and *sin^2 ψ method* [Ganev 1986], *Barkhausen noise* (BN) [Gauthier 1998], *layer removal method* (LRM) [Neckář 1991] and *hole-drilling method* (HD) [Schajer 1988]. These methods were complemented by micrographs and by microhardness measurements.

X-ray diffraction (XRD) "one-tilt" method with no reference substance was applied to study biaxial state of RS. The incident X-ray CrKα beam directed by a cylindrical collimator of 1.7 mm in diameter reached the sample surface at an angle of ψ_0 = 45° in the longitudinal and transversal direction, in which the surface components of stress σ_L and σ_T, respectively, were analyzed. The record of the {211} α-Fe diffraction line intensity curve was obtained from a position sensitive detector based on imaging plates. The experimental inaccuracy does not exceed 40 MPa.

During the RS measurement by XRD *sin^2 ψ method,* {211} diffractions of α-Fe were investigated with CrKα radiation (diffraction angle 2θ ≈ 156°) and an ω-diffractometer equipped with a scintillation detector. The goniometer was adjusted in reference to a strain-free reference specimen of α-Fe powder. The differential ψ–method, when the azimuth is kept constant and the tilt is changing, was employed.

Measurement of microhardness using method of chamfer cut was carried out with microhardness testing machine SHIMADZU HMV–2, all samples were ground at α = 4°. The conditions of microhardness measurement according to Vickers HV 0.2 were: compressive force 1.961 N, time of load 12 s.

4. Results

A representative selection of the obtained results is displayed in Figs. 1 – 4.

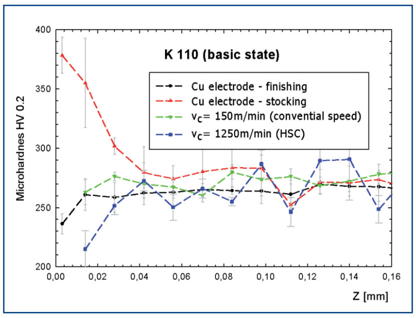

Figure 1. *Distribution of microhardness in surface layers of unhardened K110.*

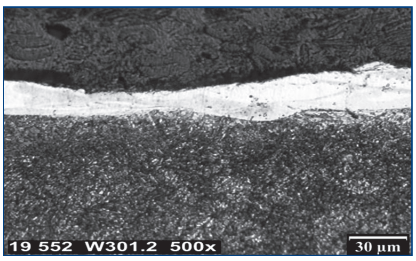

Figure 2. *Microstructure of hardened steel W300 after EDM (stocking, Cu electrode)*

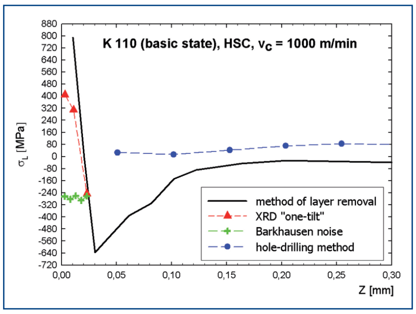

Figure 3. *Macroscopic RS σL, determined by XRD (one tilt method), Barkhausen noise and hole-drilling method*

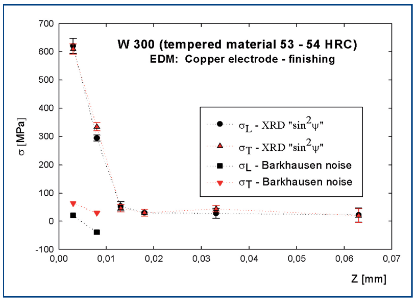

Figure 4. *Macroscopic RS σL, σT determined by XRD (sin2ψ method)*

5. Conclusions

It should be emphasized that the methods applied for residual stress determination are based on different physical principles which might lead, and actually did, to differences in obtained results.

XRD analysis identified equi-biaxial state of RS (i. e., $\sigma_L \approx \sigma_T$) for all the analysed surfaces and near-surface layers of samples which were subjected to EDM. The regime EDM finishing resulted in tensile RS, whereas EDM stocking produced compressive RS.

Samples machined by HSC exhibit differences exceeding measurement inaccuracy of the values σ_L and σ_T. With regard to the technological usage, the state of RS in the direction of advance (σ_L) of cutting tool will be discussed in the following.

No pronounced difference with respect to the cutting speed was found in RS distribution obtained by LRM. The initial presumption of decreasing RS with increasing cutting speed is, therefore, not fulfilled which might be caused by the finalisation character of side milling.

The surface RS, according to both LRM and XRD, are tensile in unhardened and compressive in hardened cold work K110 steel. The results of BN indicate a compressive RS without any change in depth. This might be caused by sensitivity of magnetic BN method not only to the strains, but to the microstructure of material as well.

The results of LRM and XRD are contradictory for both unhardened and hardened state of hot work W300 steel. For hardened samples XRD and BN give similar values of residual stress not corresponding with LRM, which found compressive surface RS in all samples.

The investigated steels have different structure and consequently different temperature range for their application; K110 (ledeburitic structure with hard carbides, high content of carbon – 2 %) is used for cold work since W300 (ferritic-perlitic structure with carbon content of 0.4 % and soft matrix) for hot work. K110 is harder and hence a more intensive heat flux is present during milling. As this steel is intended for cold work (at less than 300 °C), the tensile stresses on the surface arise. Distribution of RS is given by the balance of mechanical and thermal influences. On the contrary, W300 is softer and hence thermal effects are subdued by plastic deformation. Moreover, this steel is used for tools working in high temperature environment (above 300 °C); therefore compressive stresses on the finish milled surface should be obtained.

Experimental measurements by HD method proved that even tool steels can be drilled by a conveniently chosen tool. Diamond tool cutter can be used for both hardened and unhardened K110 steel. W300 steel requires tool cutter *SINTCTT* and diamond cutter is not at all suitable.

Acknowledgements
This research was supported by projects No. GACR 106/07/0805 a MSM 6840770021.

References

[Barcal 1989] Barcal, J. *Nonconventional machining methods (in Czech)*, Prague: CTU of Prague, 1989

[Ganev 1986] Ganev, N., Kraus, I. Czechoslovak journal of physics, A36, 1986, 270

[Gauthier 1998] Gauthier, J., Krause, T. W., Atherton, D. L., Measurement of residual stress in steel using the magnetic Barkhausen noise technique, *NDT & E Int.*, 31, 1, 1998, 23 – 36

[Halama 2005] Halama, R. Solution of Elastoplastic Contact Problem with Two Arbitrary Curved Bodies Using FEM: PhD thesis. Ostrava: VSB-TU, 2005.

[Halama 2008] Halama, R. Numerical and Experimental Analysis of Residual Stresses Induced by Contact Loading. In Proceedings of the 46th International Conference Experimental Stress Analysis, Czech Republic, Horní Becva, June 2.-5., 2008. Ed. J.Fuxa et al., Ostrava: VSB Technical university of Ostrava, 2008, pp.95-98, ISBN 978-80–248–1774–3

[Kraus 2004] Kraus, I., Ganev, N. *Technical applications of diffraction analysis (in Czech)*. CTU of Prague FJFI, 2004. ISBN 80-01-03099-7.

[Kunieda 2005] Kunieda, M. et al. Advancing EDM through fundamental insight into the process, *In: CIPR Annals, 55th general assembly of CIRP*, 2005, vol. 54, pp. 599-622

[Neckar 1991] Neckar, F., Kvasnicka I. *Selected chapters from material removal methods (in Czech),* CTU of Prague, 1991

[Sato 2007] Sato, M., Ueda, T., Tanaka, H. An experimental technique for the measurement of temperature on CBN tool face in end milling, *Int. J. of Machine Tools and Manufacture*, 2007, 47, pp. 2071–2076

[Schajer 1988] Schajer, G. S. Measurement of Non-Uniform Residual Stresses Using the Hole-Drilling Method, *J. of Eng. Mater. Techn.,* 110, 1988, pp. 338–343

[Vivancos 2005] Vivancos, J., Luis, C. J., Ortiz, J. A. Analysis of factors affecting the high-speed side milling of hardened die steels, *J. of. Mat. Proc. Tech.*, 2005, 162 – 163, 696 – 701

Contacts:

Kamil Kolarik, MSc.
Czech Technical University in Prague
Department of Solid State Engineering
Trojanova 13, Prague 2, 120 00, Czech Republic
tel.: (+420) 224 358 624, (+420) 224 358 601
e-mail: kamil.kolarik@email.cz