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EXPERIMENTAL APPLICATION OF CONTOUR METHOD FOR DETERMINATION OF RESIDUAL STRESS IN SUBSURFACE LAYERS OF MILLED SAMPLE

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Abstract

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Determination of residual stress close to the sample surface is in the most cases performed by hole-drilling method, X-Ray diffraction or neutron diffraction. Each of these methods has its benefits and disadvantages. In case of diffraction methods the measurement speed is the main disadvantage. It is also very problematic to apply diffraction method in case of sample with mechanically deformed surface, for example by standard machining operations. Therefore, determined results are very often confusing and hard to interpret. On the other side, hole drilling method is less sensitive to quality of sample surface than diffraction methods, but measurement realization is quite expensive and equipment demanding (strain gage rosettes, miniature milling cutter, high speed milling machine, pc equipment,…).
Recently introduce contour method used for determination of residual stress inside the sample is very fast, can be performed with almost common laboratory equipment and combines traditional stance with modern numerical methods by FEM. Contour method was selected for determination of residual stress below the milled surface and the dependency of milling process quality on residual stress value is demonstrated.

residual stress, surface, contour method, milling, cooling

Geometrical characteristics of surfaces, such as shape accuracy, surface texture and its micro-structure, are in the most cases defined by the quality of the finishing operations during the manufacturing process. The final surface quality and its mechanical properties are influenced the most by the chemical composition of the base material and the type and amount of energy that affects the surface during the machining process. That is the main reason why the mechanical properties of the surface are very often different from the properties of material of the basis. Due to inappropriate choice of properties of surface finishing operations the residual stress can be generated in the subsurface layer. The presence of residual stress significantly affects the initiation and the subsequent dissemination of subsurface cracks in material. The existence of residual stress in material can be very often predicted based on the nature of machining process. The exact determination of the value of residual stress is still very difficult. There are a large number of numerical and experimental methods for determination of residual stress, but none of them can be described as the most beneficial. The most often used methods are the hole-drilling method, based on relaxation of residual stress right after the drilling of hole of small diameter, X-Ray diffraction method and neutron diffraction method. The contour method combines the traditional principle of stress relaxation after material removal (superposition principle) and modern numerical calculation by use of finite element method. The method is very fast and relatively cheap in comparison to other methods.

That is the main reason for selection of contour method for determination of residual stress in surface milled under different milling conditions. The article follows the problematic of measurement of residual stress in grinded samples that was published in compilation of papers from conference *Quality and reliability of technical systems* in Nitra, 2011.

MATERIAL AND METHODS

Set of samples from material S235JRG2 was prepared for experimental measurement. The main dimensions of each sample were 30 × 15 × 100 millimeters. Chemical composition and the main mechanical properties are shown in the Tab. I.

Three different types of milling were chosen – milling by tool made of sintered carbides with cooling (see Fig. 1), milling by worn tool with cooling (see Fig. 2) and milling by worn tool without cooling (see Fig. 3). Visual comparison of surface quality on Fig. 1–3 and comparison of subsurface residual stress value demonstrate the dependence of surface quality on the quality of machining process.

Contour method principle is described in Fig. 4. Milled samples were cut in two pieces in direction perpendicular to milled surface. There is wire electric discharge machining (EDM) used for cutting in *Prime, 2009*.

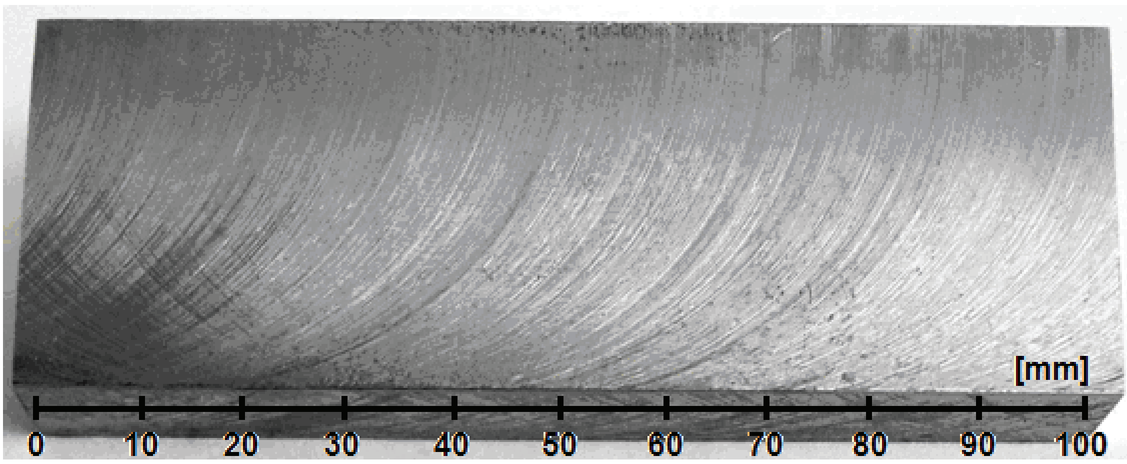
For the purpose of this article the metallographic cutter MIKRON 110 produced by company MTH Hrazdil s.r.o. was chosen to perform the cut, because of higher cutting speed, lower price with sufficient quality of cross-sectional surface. It is important to use cold cutting process with temperature lower than 30 °C to avoid additional residual stress formation.

Right after the cut the cross-sectional cutting surface should deform by the influence of subsurface residual stress. The deformation is measured by analog flatness measuring device SOMET according to standard CSN 25 1816 and shown in Fig. 5.

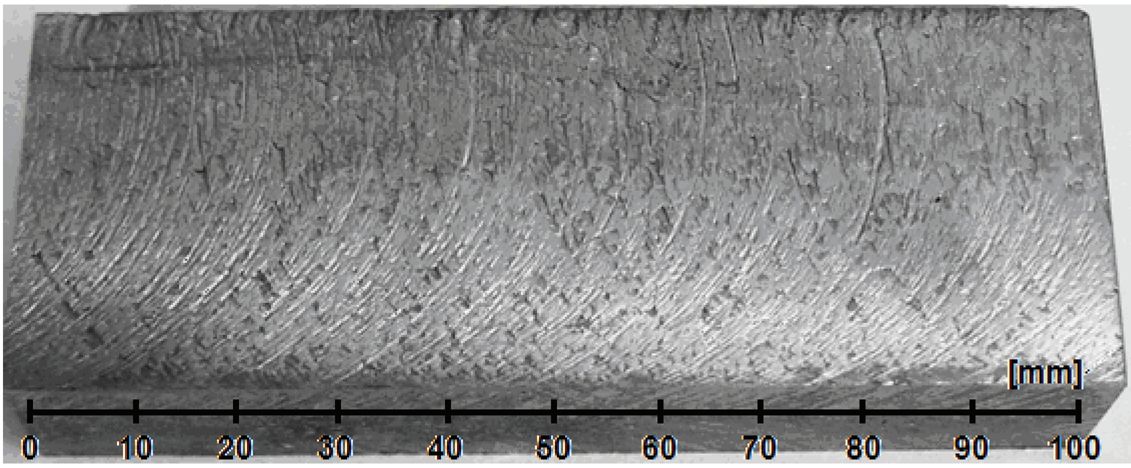
Measured rough data has to be approximated by the appropriate regress function as it is shown in Fig. 6 to be able to use the data as an input in FEM solver. In this case ANSYS Multiphysics v11 solver

I: *Chemical composition and mechanical properties of material S235JRG2 (Bogdan Bolzano, 2011)*

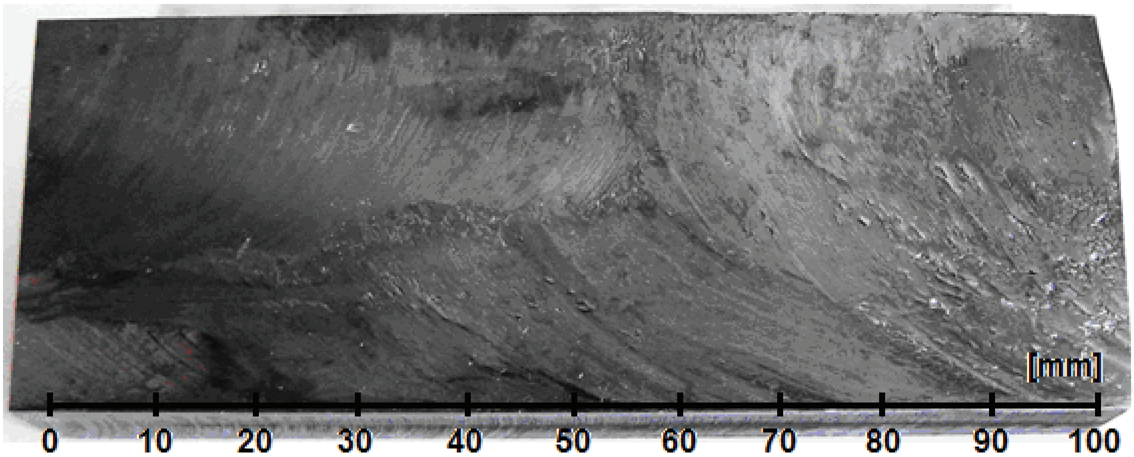
Chemical composition [%]	C max. for thickness in mm			Mn max.	Si max.	P max.	S max.	N max.
	≤ 16	>16 ≤ 40	> 40					
	0.19	0.19	0.23	1.50	-	0.045	0.045	0.014
Mechanical properties in longitudinal direction	Minimal yield limit R_{eH} [MPa] for parts with thickness in mm:							
	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 150	> 150 ≤ 200	> 200 ≤ 250
	235	225	215	215	215	195	185	175
	Ultimate tensile strength R_m [MPa] for parts with thickness in mm:							
	≥ 3 ≤ 100		> 100 ≤ 150			> 150 ≤ 250		
	360–510		350–500			340–490		
	Minimal elongation in % ($L_0 = 5.65.\sqrt{S_0}$) for parts with thickness in mm:							
	> 3 ≤ 40	> 40 ≤ 63	> 63 ≤ 100	> 100 ≤ 150	> 150 ≤ 250			
	26	25	24	22	21			



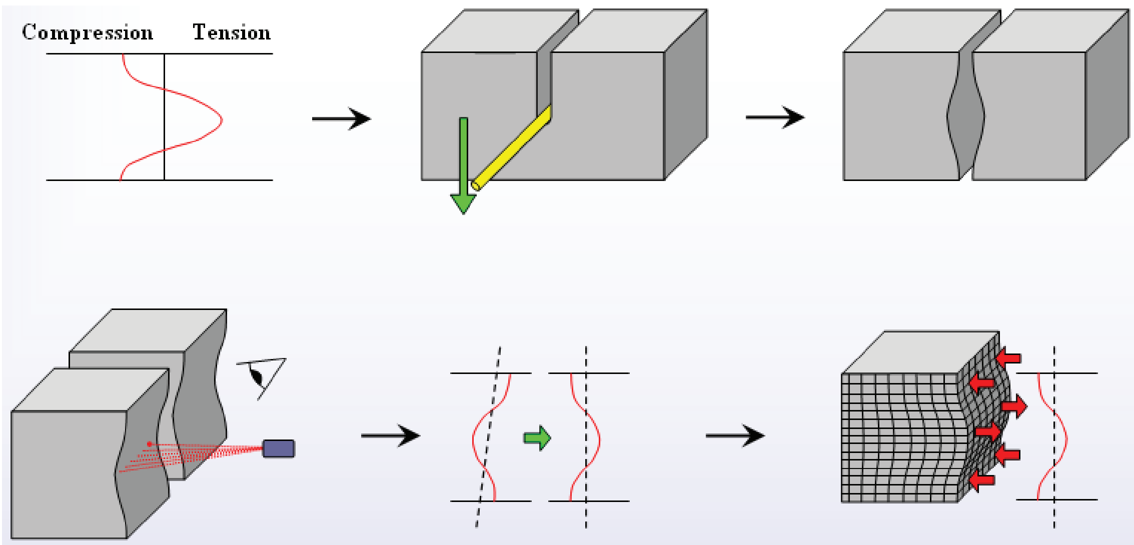
1: *Sample milled by tool made of sintered carbides with cooling*



2: *Sample milled by worn tool with cooling*



3: *Sample milled by worn tool without cooling*



4: *Principle of contour method (Kelleher, 2008)*

was used. Input was prepared in the form of macro programmed in APDL language. Created 3D model of the sample was meshed by PLANE82 element and the task was solved as plane stress with thickness. Material was defined as linear elastic isotropic with Young modulus 2,1E+005 Pa and Poisson's ratio 0.3.

5: *Flatness measuring device SOMET*

The value of subsurface residual stress (von Mises stress) was calculated from the measured deformation of cross-sectional cutting surface that was used as a boundary condition in FEM calculation.

RESULTS AND DISCUSSION

Deformation of the cross-sectional cutting surface was measured in 15 points.

First measured value was taken in a distance of 0.5 mm from milled surface that is the lowest distance allowed by the analog measuring device SOMET. Plane perpendicular to milled surface and coincidence with the last point of measurement (in distance of 14.5 mm from milled surface) was selected as zero line. Deformation of cross-sectional cutting surface measured on the sample milled by new tool made of sintered carbides with cooling is shown in the Tab. II. Approximation of arithmetic value of measured deformation *y* by the polynomial regress function (blue curve) and linear regress function symbolizing the surface without residual stress (red curve) are shown in Fig. 7.

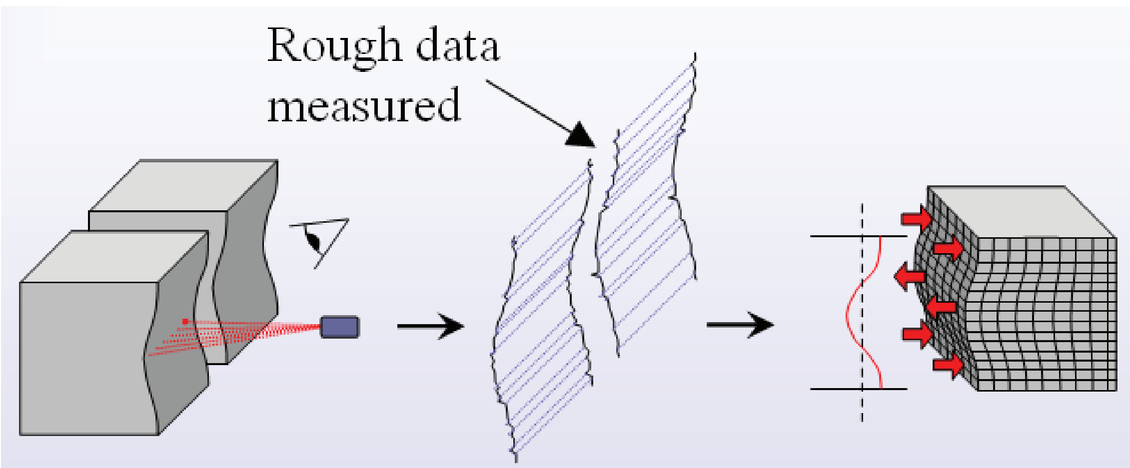
Arithmetical value of deformation (blue line in Fig. 7) reaches the value of 0.201 mm in the distance of 0.5 mm from milled surface. Linear approximation of the surface slope by function y = 0.015x – 0.2173 reaches the value –0.210 mm for x = 0.5 mm. That means that the existence of milling operation causes additional deformation of cross-sectional cutting surface of (–0.201) – (–0.210) = 0.009 mm. This value of deformation was used as an input for FEM solver and corresponds to compressive residual stress of 167 MPa (see Fig. 8).

In case of sample milled by worn tool with cooling it is also beneficial to approximate the cross-sectional cutting surface without influence of residual stress by linear regress function in type y = 0.0133x – 0.1927 (see Fig. 9). Arithmetic value of measured deformation (shown in Tab. III) is approximated by polynomial regress function (see Fig. 9).

Subsurface residual stress induced by milling operation by worn tool affects the surface to depth of 2.5 mm as it is shown in Fig. 9. Additional deformation of cross-sectional cutting surface in the depth of 0.5 mm below the milled surface is (–0.1715) – (–0.186) = 0.0145 mm. This value of additional deformation corresponds to compressive residual stress of 205.67 MPa as it is shown in Fig. 10.

The values of measured deformations of cross-sectional cutting surface in case of sample milled by worn tool without cooling are shown in Tab. IV.

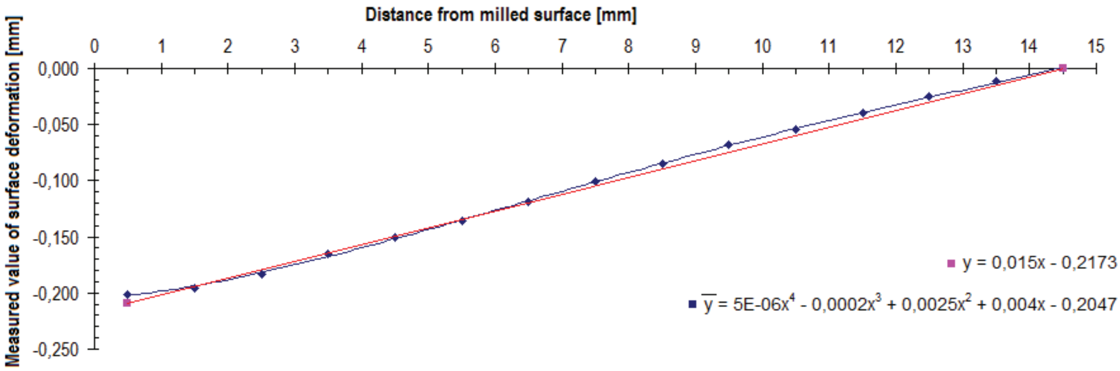
Cross-sectional surface without influence of residual stress specified by linear base function *y*



6: *Creation of regress function as an input for FEM solver*

II: *Surface deformation of sample milled by new tool made of sintered carbides with cooling*

Distance from surface	Sample milled by new tool made of sintered carbides with cooling Surface deformation [mm]						$\bar{y}$
[mm]	Measur. 1	Measur. 2	Measur. 3	Measur. 4	Measur. 5	Measur. 6	[mm]
0.5	–0.191	–0.204	–0.205	–0.210	–0.203	–0.192	–0.201
1.5	–0.189	–0.202	–0.197	–0.201	–0.196	–0.189	–0.196
2.5	–0.179	–0.188	–0.187	–0.189	–0.181	–0.177	–0.184
3.5	–0.151	–0.161	–0.176	–0.170	–0.169	–0.162	–0.165
4.5	–0.140	–0.148	–0.156	–0.156	–0.154	–0.152	–0.151
5.5	–0.121	–0.133	–0.140	–0.140	–0.143	–0.137	–0.136
6.5	–0.104	–0.112	–0.118	–0.120	–0.129	–0.127	–0.118
7.5	–0.088	–0.097	–0.094	–0.104	–0.112	–0.111	–0.101
8.5	–0.075	–0.077	–0.075	–0.084	–0.097	–0.099	–0.085
9.5	–0.061	–0.057	–0.056	–0.071	–0.079	–0.084	–0.068
10.5	–0.050	–0.052	–0.041	–0.055	–0.061	–0.070	–0.055
11.5	–0.036	–0.037	–0.024	–0.043	–0.047	–0.052	–0.040
12.5	–0.020	–0.024	–0.011	–0.027	–0.033	–0.036	–0.025
13.5	–0.006	–0.009	–0.005	–0.015	–0.017	–0.019	–0.012
14.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000



7: *Approximation of measured data by polynomial regress function*

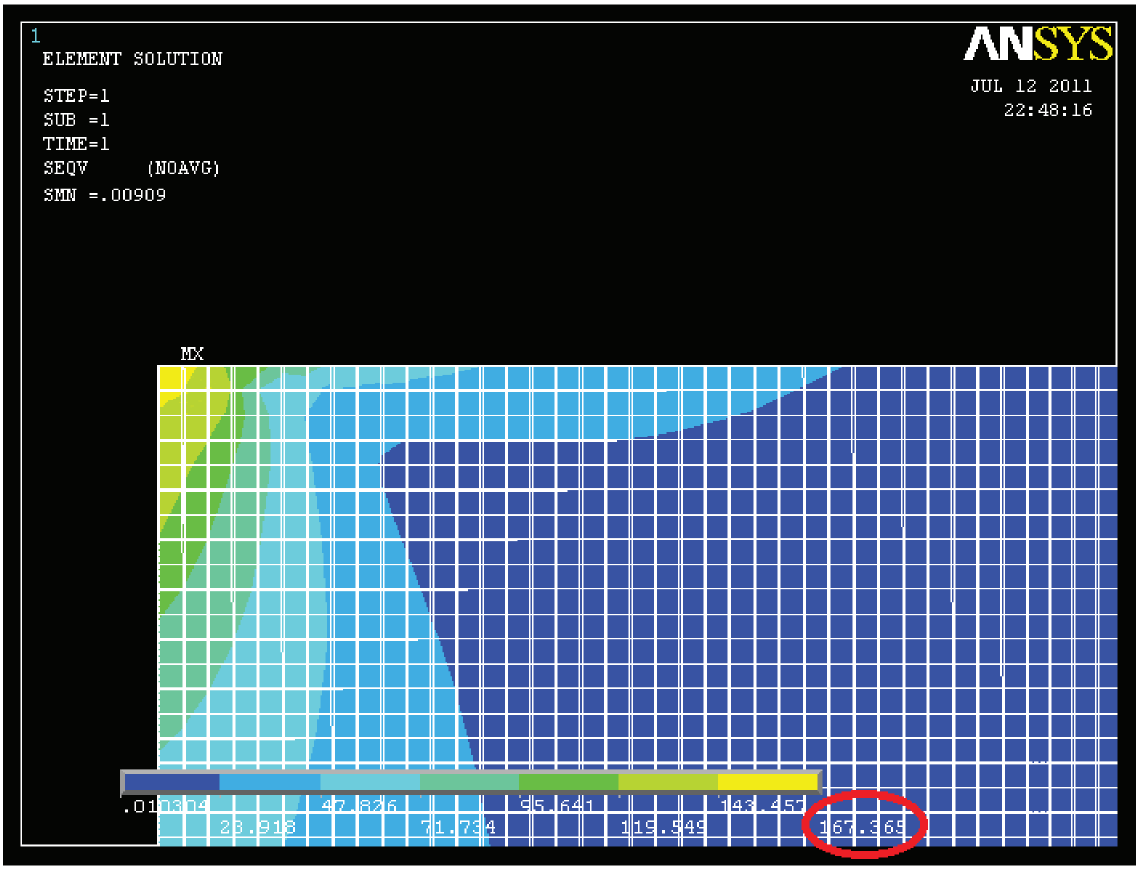
= 0.0041x – 0.0591 (red curve) and arithmetic values of deformed surface approximated by polynomial regress function (blue curve) are shown in Fig. 11.

The highest deviation of deformed surface is achieved in the depth of 1.5 mm. The linear base function (red curve) reaches the value of –0.053 mm in the depth of 1.5 mm below the milled surface. Arithmetic value of measured deformation (blue curve) in the depth of 1.5 mm is –0.074 mm. The additional deformation caused by existence of subsurface residual stress is (–0.074) – (–0.053) = –0.021 mm. This value corresponds to tensile residual stress of 516 MPa (see Fig. 12).

CONCLUSION

Measurement of residual stress by contour method has verified the influence of parameters of milling process on quality of surface texture. The influence is well described and obvious from visual quantification of milled surfaces as it is shown in Fig. 1–3. Milling operation by worn tool with cooling caused creation of cavities and the surface was primarily damaged by mechanical deformation. Main damage caused by milling by worn tool without cooling is caused by height temperature where the plastic deformation was the driving force of surface change. Value of residual stress measured by contour method differs from 167 MPa (measured in sample milled by new tool with cooling) to 516 MPa (measured in sample milled by worn tool without cooling). Measurement accuracy is significantly influenced by accuracy of cross-sectional cut and especially by quality of cross-sectional flatness measurement.

However, the main contribution of the paper is the application of contour method itself. The method was successfully applied for determination of residual stress inside the sample as it is described in *Prime, 2009*. But the application close to surface of the sample is very special. The paper demonstrates additional possibilities of usage of contour method. As it is shown in the paper it is

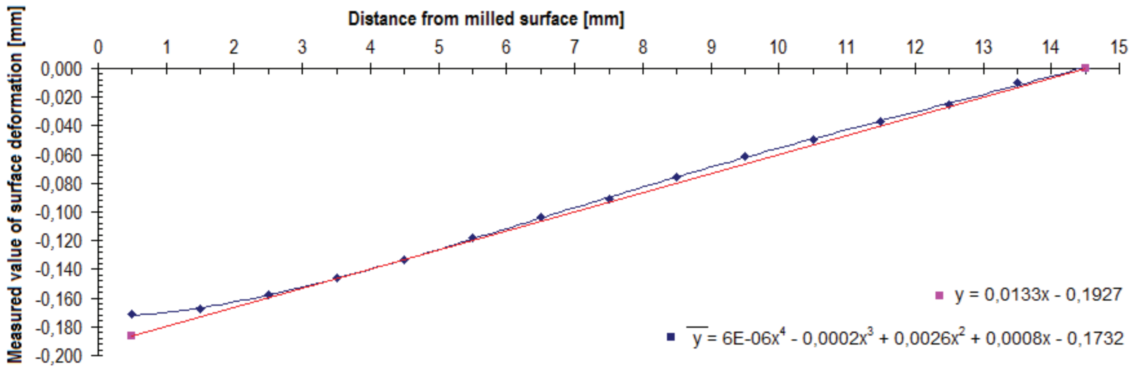


8: *Subsurface residual stress for sample milled by new tool made of sintered carbides with cooling*

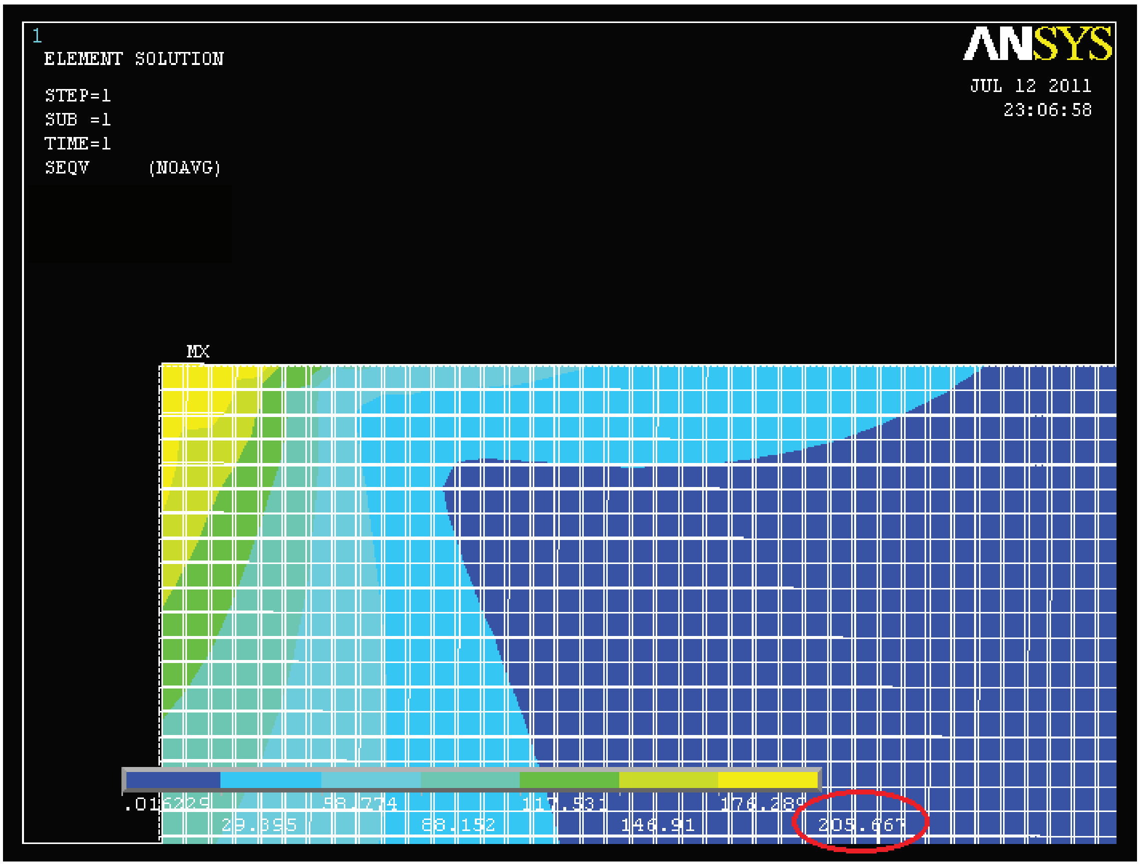
III: *Surface deformation of sample milled by worn tool with cooling*

Distance from surface	Sample milled by worn tool with cooling Surface deformation [mm]						$\bar{y}$
[mm]	Measur. 1	Measur. 2	Measur. 3	Measur. 4	Measur. 5	Measur. 6	[mm]
0.5	–0.173	–0.166	–0.183	–0.161	–0.166	–0.180	–0.172
1.5	–0.173	–0.155	–0.178	–0.159	–0.162	–0.180	–0.168
2.5	–0.163	–0.143	–0.172	–0.153	–0.151	–0.166	–0.158
3.5	–0.153	–0.134	–0.157	–0.139	–0.138	–0.156	–0.146
4.5	–0.136	–0.126	–0.139	–0.123	–0.131	–0.145	–0.133
5.5	–0.117	–0.118	–0.120	–0.108	–0.115	–0.130	–0.118
6.5	–0.105	–0.099	–0.106	–0.091	–0.102	–0.120	–0.104
7.5	–0.089	–0.094	–0.091	–0.076	–0.086	–0.108	–0.091
8.5	–0.072	–0.083	–0.075	–0.062	–0.072	–0.092	–0.076
9.5	–0.055	–0.070	–0.057	–0.049	–0.058	–0.080	–0.062
10.5	–0.049	–0.061	–0.043	–0.039	–0.040	–0.067	–0.050
11.5	–0.034	–0.047	–0.028	–0.030	–0.028	–0.052	–0.037
12.5	–0.020	–0.030	–0.018	–0.020	–0.017	–0.044	–0.025
13.5	–0.006	–0.016	–0.007	–0.005	–0.006	–0.020	–0.010
14.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000

possible to use contour method for determination of residual stress below the surface influenced by machining operations and other processes used in manufacturing process. The method is not difficult to proceed and it does not require usage of technically demanding equipment. From the economical point of view the contour method is more efficient than other mostly used methods (hole-drilling method, X-Ray diffraction, Neutron diffraction,…), because of its speed and financial



9: *Approximation of measured data by polynomial regress function*



10: *Subsurface residual stress for sample milled by worn tool with cooling*

modest. On the other side, exact dependency of measurement accuracy on measurement properties needs to be determined.

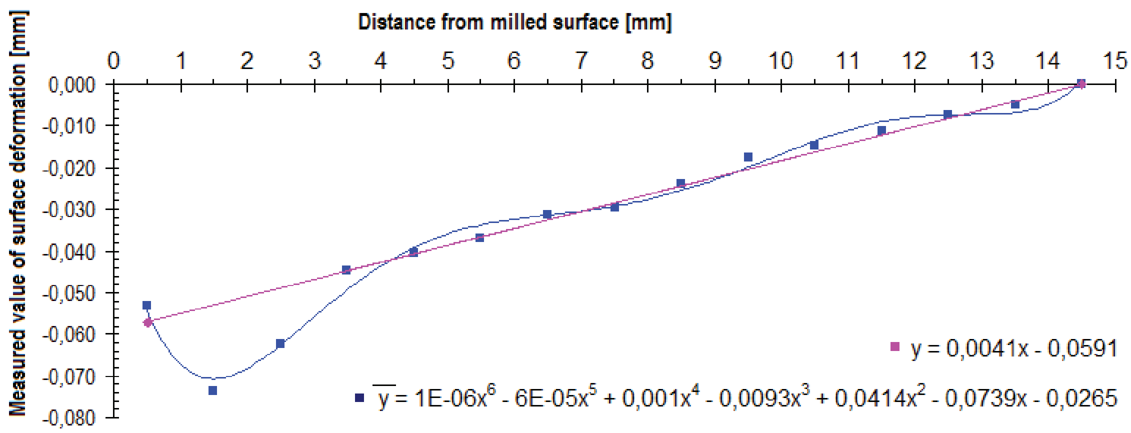
SUMMARY

Three samples milled under different milling conditions were prepared to demonstrate the influence of milling conditions on final surface quality. This influence is well-known and describe in *Handbook of residual stress and deformation, 2002.* The application of contour method for determination of residual stress in subsurface layers is the main contribution of this paper, because contour method was originally used for determination of residual stress inside the sample (creation of residual stress maps). Dependency of measurement accuracy and quality of cross-sectional cutting surface was not determined and should be included in subsequent research. Also accuracy of flatness measurement on cross-sectional surface should be improved by application of 3D measuring device. The

measurement by hole-drilling method is being performed on the same set of milled samples at this time to be able to compare the results gained by both methods. The comparison will be published in *Continuity of residual stress and texture of machined surface* in 2012.

IV: *Surface deformation of sample milled by worn tool without cooling*

Distance from surface	Sample milled by worn tool without cooling Surface deformation [mm]						$\bar{y}$
[mm]	Measur. 1	Measur. 2	Measur. 3	Measur. 4	Measur. 5	Measur. 6	[mm]
0.5	–0.050	–0.058	–0.052	–0.049	–0.056	–0.054	–0.053
1.5	–0.075	–0.067	–0.072	–0.074	–0.076	–0.077	–0.074
2.5	–0.060	–0.061	–0.065	–0.064	–0.065	–0.059	–0.062
3.5	–0.041	–0.048	–0.042	–0.047	–0.044	–0.047	–0.045
4.5	–0.037	–0.043	–0.039	–0.039	–0.043	–0.042	–0.041
5.5	–0.034	–0.036	–0.037	–0.037	–0.039	–0.038	–0.037
6.5	–0.026	–0.032	–0.033	–0.029	–0.035	–0.033	–0.031
7.5	–0.024	–0.031	–0.032	–0.027	–0.033	–0.030	–0.030
8.5	–0.020	–0.030	–0.028	–0.022	–0.025	–0.019	–0.024
9.5	–0.019	–0.025	–0.020	–0.015	–0.015	–0.012	–0.018
10.5	–0.015	–0.024	–0.019	–0.009	–0.012	–0.009	–0.015
11.5	–0.013	–0.015	–0.017	–0.007	–0.009	–0.007	–0.011
12.5	–0.009	–0.007	–0.012	–0.005	–0.007	–0.004	–0.007
13.5	–0.007	–0.003	–0.009	–0.003	–0.005	–0.002	–0.005
14.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000



11: *Approximation of measured data by polynomial regress function*

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