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RESEARCH ON COHERENCES BETWEEN THE RESIDUAL STRESSES AND TOOL RAKE ANGLE BY HARD TURNING

A broad base of researchers are concerned in studying chip removal by hard turning. The reason for that is the most of the accurate selection of the cutting conditions to be able to exploit the advantages of hard turning. Among the parameters influencing the material removal, the geometry and edge formation of the cutting tool play a decisive role too. The efficient chip removal from hardened surfaces of about 60 HRC hardness can be ensured by edge formation that can be called special. In this paper the effect of the tool rake angle on the chip removal process is investigated, within this more detailed is the effect on the residual stress formation. The main method of the investigation is the FEM simulation, with which investigations were done in a wide interval of rake angle values.

1. INTRODUCTION

PCBN tools needed for hard turning are used in three standard versions from the point of view of edge formation, such as

- sharp
- honed and
- chamfered

edged tools. From the point of view of edge geometry, generally the negative rake angle is preferred, often fit up with facets. The size of the facet is mostly 0.1x-20°and if γ=-6°coming from the formation of the tool holder is taken into account, a γ=-26° one facet tool comes into being which is most frequently applied. The proper smoothness of the cutting edge is gained by abrasive precision machining after grinding, however, its cutting characteristics are improved by coating (TiN, TiAl, etc.) The geometry and preparation of the cutting edge may have a significant effect on the physical and mechanical characteristics of the workpiece, on the extent of tool wear, the residual stress state forming in the surface layer of the workpiece and several other characteristics. Because the surface layer quality of the machined components has become an important factor in the recent decades, its examination is crucial when qualifying the workpiece. It is so especially in case of procedures that consume high specific energy and besides the cutting force the temperature of the chip root also plays a role. The changes on the surface is called surface integrity in short, and its importance is characterized by the creation of a separate engineering sector for its operation, the so called Surface Engineering. Not only professional articles do appear in this field but also books covering its all aspects in details. Such is the book by Davim [1] for example which displays the four segments –stated by him- of Surface Engineering in Figure 1. One of them is the segment of residual stresses.

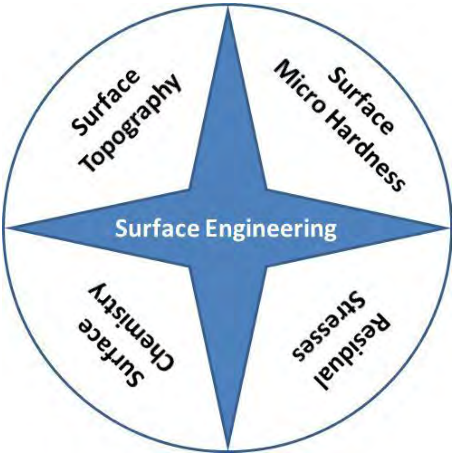

Figure 1 – The most important areas of surface engineering [1]

Residual stresses emerge during some machining process or after heat treatment because due to their effect the surface layer or the inner force system of the whole cross section is disrupted. The investigation of that for different machining types was done by Kloos and Kaiser [2], they also analysed the residual stresses. They stated that residual stresses are static stresses with three centerlines that emerge under the influence of external mechanical load and/or heat, for example cutting force components and torques. They occur in the cross-sectional plane of a multi-layered surface formed by external and inner forces plastically and flexibly in microscopic scale [2]. From the point of view of the workpiece wear resistance the compressive residual stresses have got a decisive role, because they influence the fatigue limit of the components favourably [1, 13]. According to the experience published in technical literature the change of the tool rake angle has got the greatest influence on the change of the compressive residual stresses in the surface layer of the workpiece [1, 5]. In technical literature several research results are published [1, 2, 3, 12, 13] concerning how the change of the rake angle influences the stress state concretely and that it does not necessarily show linearity with the change of the rake angle. Some researchers proved that certain decrease of the rake angle value increases the compressive residual stresses, but further decrease leads to smaller compressive stress [1, 3]. It also must be noted that residual stresses is not the only parameter that significantly influences the choice of the rake angle size. The strength conditions of the cutting edge prevail over that, because it is crucially important that the cutting insert must be able to take over the shear and bending load coming from the cutting force. In the negative range of the rake angle it is easier to solve than in the positive one.

2. THE MODELLING OF RESIDUAL STRESSES WITH FEM SIMULATION

The numerical examination of the influence of the tool rake angle change on the tangential stresses was completed by means of the 2D version of Third Wave AdvantEdge^{TM} 5.5 which had been optimized for the modelling of cutting processes [21]. For the material quality 16MnCr5 (AISI 5115) used by us, we have to find the proper ―deformation-stress" model which has to meet two important requirements: high accuracy and relative mathematical simplicity because of the high counting speed. To describe the behaviour of the workpiece material that we use the Johnson-Cook equation was applied. This is a viscoplastic material model depending on deformation and temperature that is suitable for the task, where the speed-range of deformation is 10^2-10^6 [s^{-1}]. The change of temperature, however, occurs because of the plastic deformation due to the heat sensitivity [8, 13, 16]. The form of the equation by Johnson-Cook recommended by the technical literature, too, is used:

$$\sigma_{eq} = \left(A + B\bar{\varepsilon}^{n}\right)\cdot\left(1 + C\cdot\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right)\cdot\left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right)$$

Where σ_{eq} -is the equivalent stress, $\bar{\varepsilon}$ - is the plastic strain, $\dot{\bar{\varepsilon}}$ - is the plastic strain rate, $\dot{\bar{\varepsilon}}_0$ - is the reference plastic strain rate, T- is the temperature of the workpiece, T_{melt}– is the melting temperature of the workpiece material, T_{room}- is the temperature of the machining environment, A- is the yield limit, B- is the tensile strength, C- is the sensitivity coefficient of plastic strain, n- is the hardening up factor, m- ,however, is the softening coefficient. The constant of the Johnson-Cook equation for the steel 100Cr6 to be examined are as follows: A= 588 MPa, B= 680 MPa, C= 0.057, m= 0.7, n=0.4. The definition and detailed interpretation of the above marks is not possible here because of the lack of space, but they can be found in the quoted technical literature [1, 2, 3, 4, 6, 8]. The material equation by Johnson and Cook is a three-variable function with which, on the basis of the three variables, the flow stress can be calculated that is characteristic of the formation process in the given moment. (The flow stress is often called equivalent stress in the technical literature). The three variables are: plastic strain ($\bar{\varepsilon}$), the plastic strain rate ($\dot{\bar{\varepsilon}}$), and the temperature (T). The specificity of the relationship is that it is also valid for the very high plastic strain ($\bar{\varepsilon}$ =2…7) occurring in cutting, for the very high speed of plastic deformation ($\dot{\bar{\varepsilon}}$ =10^5…10^6 s^{-1}), and for the very high temperatures too (T~1000°C).

3. PRELIMINARY EXPERIENCE OF THE APPLICABILITY OF FEM SIMULATION

Through our examinations we made certain of the reliability of the results from FEM simulation. That is why measurement results coming from earlier experiments [23] were compared to the values of numerical simulation. Through this we can be convinced that the values of residual stresses created by further simulations approach the measured values with proper accuracy. Earlier when the measurement of residual stresses were done by removing material layers, several examinations were done to learn about the residual stresses following different procedures, including hard turned specimens. The removal of material layers was done by acid etching while a 0.001 mm meter registrated the deformation of the prismatic specimen. The calculation of residual stresses was completed from the deformation by means of strength relationships. When FEM methods became widespread in the numerical examination of technical problems, first of all we were curious about how the measured results related to FEM simulation results. The experimental conditions were as follows:

Workpiece material:	100Cr6 (63 HRC)
Tool material:	PCBN (40…60% CBN)
Tool rake angle:	γ=-6°
Tool relief angle:	α=15°
Cutting speed:	v_c=160 m/min, 81 m/min
Feed:	f=0.1 mm/rev
Depth of cut:	a_p=0.2 mm
Workpiece geometry:	200x20x3mm, R100mm

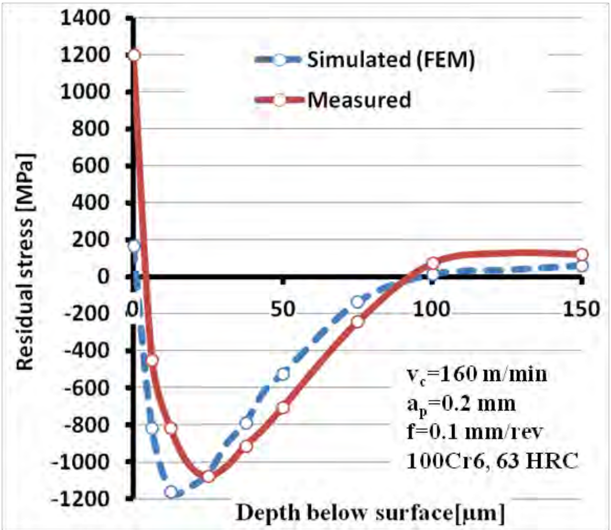

Figure 2 – The profile and extent of residual stresses at cutting speed v_c=160 m/min

In Figures 2 and 3 one can see the concrete comparison of the measured and the numerically simulated values. The simulated and the measured residual stresses surprisingly well correspond with each other, despite the several years' time between the simulation and the measurement. The same examinations were also done with a lower cutting speed v_c=81 m/min and a higher one, too, v_c=160 m/min. the profiles agree well in this case , too, the maximum compressive stresses, however, well approach each other numerically, too, the difference is in their depth distribution. The simulated maximum lies about 25 µm deep, while the measured maximum 50 µm deep. The preliminary examinations proved that FEM is suitable to simulate residual stresses. The differences can be traced back to the uncertainties of the measuring method which were not possible to eliminate. Such is the continuous decrease of acid concentration, the continuous increase of the acid temperature, the inhomogeneity errors inside the specimens, etc. All these uncertainties are screened out by the x-ray diffraction method used today which, however, does not measure macro- but micro stress. Micro stresses emerge in crystallites since their position under the influence of the atom planes' stresses, differs from the regular one.

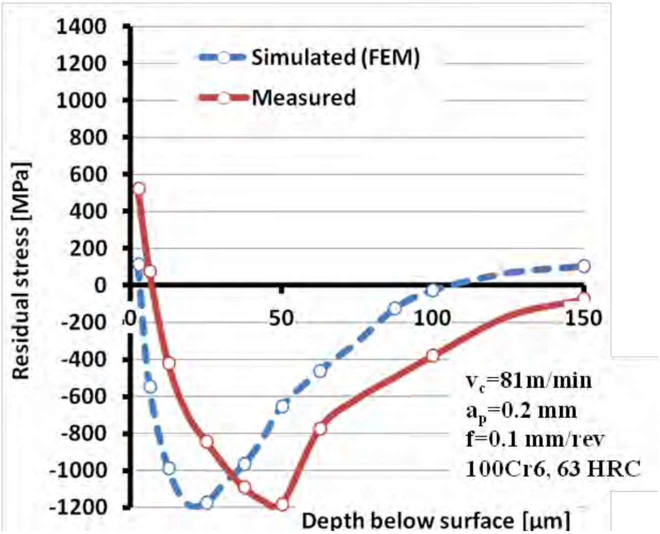

Figure 3 – The profile and extent of residual stresses at cutting speed v_c=81 m/min

4. FEM EXPERIMENTS UPON THE RAKE ANGLE INFLUENCE ON RESIDUAL STRESSES

In the previous chapter it was stated that the results of the FEM simulation we used approach the measured values with proper accuracy. Therefore the examination of the influence of the rake angle change on the values of surface compressive residual stress can be done relatively accurately. In accordance with the requirements of AdvantEdge™ software the input parameters of FEM simulation can be found in Table 2. In our examinations the influence of rake angle was analysed between 0°…-25° at 5°-by-step. Already at γ=0° compressive residual stress emerges in the surface layer. It is characteristic that on the surface, starting from low tensile stress, at small depth there are high compressive residual stresses in the surface layer. Decreasing the rake angle, the maximum value of compressive stress increases. Reaching the γ=-25° rake angle, the value of compressive stress increases from 800 MPa to 1200 MPa, that is to its one and a half fold in the examined depth of layer. The emerge of compressive residual stresses, if not in all cases but most cases is beneficial. Through experiments we proved that they increase the fatigue limit [22] and also beneficially influence the life of the ball tracks of roller bearings.

Table 2 **FEM-software input parameters**

Workpiece		*Process*	
Workpiece length	5 mm	Depth of cut (a_p)	0.2 mm
Workpiece height	3 mm	Length of cut	3 mm
Workpiece material	16MnCr5 (63HRC)	Feed (f)	0.2 mm/rev
Tool		Cutting speed (v_c)	180 m/min
Rake angle (γ_o)	0°…-25°	Friction coeff. (μ)	0.35
Rake face length	1.2 mm	Coolant	Not used
Relief angle (α_o)	6°	*Simulation*	
Relief face length	2 mm	Max. nodes	24000
Cut. edge radius	0.01 mm	Max. element size	0.1 mm
Material	PCBN	Min. element size	0.01 mm

5. DISCUSSION

Our simulation examination unambiguously proved that significant compressive residual stresses emerge in hard turning. The maximum of compressive residual stresses increases by the decrease of γ rake angle [23] in the angle range examined by us. The reason for that is the increasing plastic deformation ($\bar{\varepsilon}$) caused by the decrease of angle γ. For its calculation several formulas are known, the newest is the formula by Guo and Dornfeld [15]:

$$\bar{\varepsilon} = \frac{2 \cdot \cos\gamma}{\sqrt{3} \cdot (1 - \sin\gamma)} \cdot$$

Our investigations confirm the results of research teams working on this theme: Byrne et al. [1, 4] did experiments to examine the characteristics of residual stresses in case of finish precision machining of hard materials by tools with definite edges. According to their experience the values of residual stresses are in relationship with the value of friction coefficient between the workpiece and tool, besides the geometrical characteristic [4]. Dahlman et al. [5], who examined the effect of the rake angle and the cutting parameters on the residual stresses emerging in the surface layer of the workpiece in hard turning came to results similar to the phenomenon experienced by us. The examined material quality was hardened steel (100Cr6) with hardness 62 HRC. The effect of the rake angles between -6°…-61°on the residual stresses was examined. In case of -61°rake angle the highest value of residual stress was about six fold of the value measured in case of -6°[1, 4]. Rech and Moisan [6] examined the residual stresses in case of hardened steel (27MnCr5), 850 HV (65.7 HRC). Their investigations were done on external conic surfaces of gear wheels within the frame of mass production. On the basis of their investigations residual stresses are influenced by the tool material, the tool coating, the edge geometry and also the different cutting parameters [1, 6, 18, 20]. The physical change of the surface layer, however, is caused by the cutting temperature [1, 6]. Figure 4 shows an example for the characteristic shape of residual stress emerging in hard turning (v_c=110 m/min, a_p=0.1 mm, f=0.1 mm/rev). Figure 4 is taken from the article by Dahlman [5] and it depicts the residual stress in both directions emerging at γ=-21°. Stress $\mathbf{v}_c$ means stresses with tangential direction ($\boldsymbol{\sigma}_{||}$), however, stress **f** with axial direction (**σ⊥**). Having done our numerical experiments we experienced similar stress changes and stress characteristics.

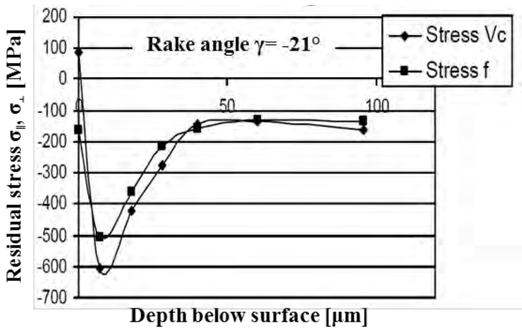

Figure 4 – Residual stresses at rake angle of -21° [5]

The creation of residual stresses, as it is expressed by the Johnson-Cook equation, too, can be explained by two effects: mechanical and thermal. They cannot be separated, they emerge together and effect each other. In case of mechanical effect two layers must be taken into account: the external one that plastically deforms and the one below that deforms only flexibly. The elements (that is the crystallites) of the flexibly deformed layer want to gain back their original sizes after the tool passed by, and because they are in material (atomic) relationship with the external layer, they constrict that, thus compressive stresses emerge. In technical literature

Gunnberg et al. [9, 13] also confirm that basically residual stresses emerge due to two mechanisms the theory of which can be seen in Figure 5. Figure 5/a represents the creation of residual stress in mechanical way. In this case the residual stress develops during the chip removal, due to the plastic deformation (A) in the surface layer, and the flexible deformation below the surface layer. To maintain the balance of the inner force system, compressive residual stress develops (B). In figure 5/b the thermal mechanism of the formation of compressive residual stress is represented. This phenomenon is caused by the spread of the large amount of machining heat in the surface layer (C). If the workpiece were cooled during machining, it would give advantage to the creation of constricting stresses (D) [9, 15].

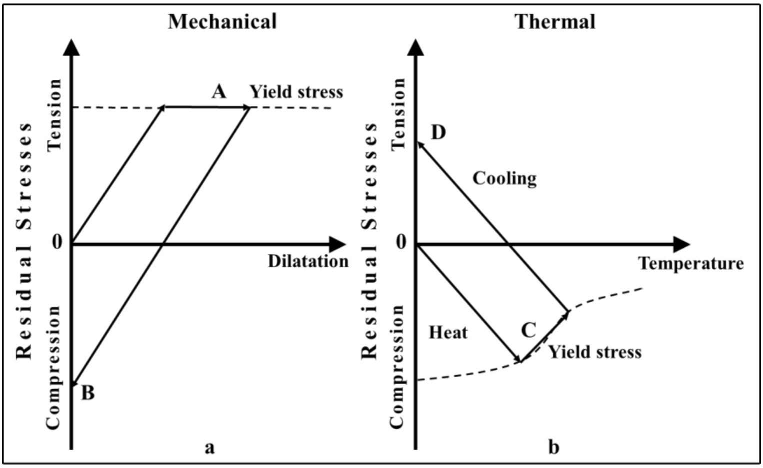

Figure 5 – Mechanism of residual stress development [12, 13]

In case of thermal effect only one layer, the external must be taken into account. Due to the high temperature it expands, plastically deforms and after the tool passes, it cools down and contracts: constriction stresses emerge in it. The influencing factor that we call time factor also should be considered with the simulation results. The problem is that all the simulation results are gained when there is the load from the cutting force and the cutting temperature on the workpiece. It is supposed that the residual stresses stated at that moment change when the specimen cools back to room temperature. The two stress profiles in Figure 6 allow concluding that this supposition is right. At further distance from the tool tip the simulation value is higher by 300 MPa, because the temperature is somewhat lower than at the tool tip. Right next to the tool tip the values are 900-1100 °C, while at further points the values are between 369-452°C according to numerical calculation. And this confirms the theory of the creation mechanism of stress published in technical literature [12, 13].

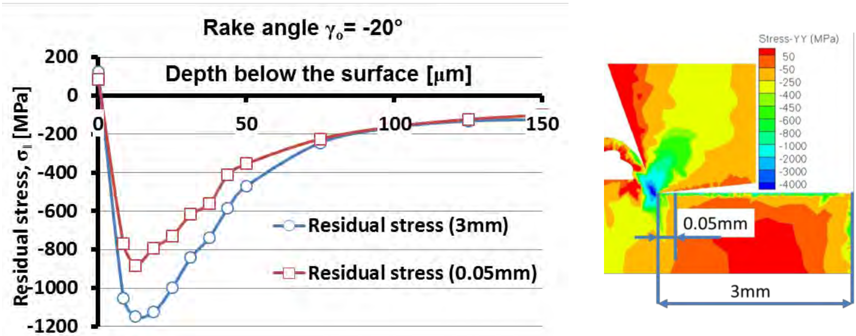

Figure 6 – The change depending on the depth of the surface layer (γ_o= -20°)

6. SUMMARY

According to the examinations by simulation it is certain that the rake angle of the tool significantly influences the extent of residual stresses. The concept is verified, that instead of expensive and lengthy examinations in laboratories, FEM simulation can be applied effectively to define residual stresses. Thus, during the technological planning it can be foreseen how big residual stress can be expected in a given case and how it can be regulated and influenced by the purposeful choice of the rake angle of the tool. In the examined material the large negative rake angle (-26°) always induces compressive residual stresses because of the dominance of the mechanical effect. The high compressive residual stress is beneficial in many cases from the point of view of the life of the components.

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