Research Results Of Stress-Strain State Of Cutting Tool
When Aviation Materials Turning

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Abstract. Titanium alloys and stainless steels are hard-to-machine of all the machining types. Cutting edge state of turning tool after machining titanium and high-strength aluminium alloys and corrosion-resistant high-alloy steel has been studied. Cutting forces and chip contact areas with the rake surface of cutter has been measured. The relationship of cutting forces and residual stresses are shown. Cutting forces and residual stresses vs value of cutting tool rake angle relation were obtained. Measurements of residual stresses were performed by x-ray diffraction.

Keywords – rake angle, x-ray diffractometer, hard alloy, turning tool, aviation materials cutting

1. Introduction

Most of published scientific works are devoted to study of stress-strain state (SSS) of processed material [1–7].

Residual stresses influence on the durability, corrosion resistance, fatigue strength, working life and other properties of the workpiece material. If material has high rigidity, and value of residual stresses is more than tensile strength, surface cracks appear. Deformation occurs with low rigidity and large residual stresses. Numerous studies of different authors showed that residual stresses could be controlled through adjustment of technical processes. A value, sign and distribution of residual stresses along the surface layer depth depend on types and modes of machining of workpiece. Changing the parameters of machining and the sequence of processing techniques, it is possible to eventually obtain the required value and distribution of residual stresses along the depth of a surface layer.

In aeronautical materials machining (titanium alloys, stainless steels) large cutting forces are applied, which lead to intense heat generation. Temperatures in the cutting zone reach high values [8]. Tool and workpiece material heating leads to negative changes in the microstructure and properties of them both. Impact of high cutting forces and temperatures cause the accelerated wear of the cutting edges of the tool itself. Hereupon, the permissible cutting speeds and process performance are reduced. Optimization of cutting tool configuration [9, 10] and other measures are taken to enhance machinability. Hardness increase of a cutting tool and whole technological system leads to a decrease of vibrations amplitude [11], improves the accuracy and surface quality of the workpiece [12].

In turning or milling operations residual stresses form in the surface layers of a cutting tool as well as in the material machined. Modern instrumental methods are rarely used for measuring residual stresses in cutting tools. Residual stresses in cutting tools are often evaluated on the basis of mathematical calculations and/or simulations [13, 14]. In the works [15, 16] x-ray method was used to study the SSS of tool. It is confirmed that residual stresses are associated with manufacturing techniques of tool materials and cutting tools. Many researchers suppose the residual compressive stresses contribute to the improvement of cutting tool wear resistance. However, a defining influence of the sign and value of residual stresses on the efficiency of tool is discussed.
2. Statement of the problem

Authors studied the stress-strain state of brazed inserts cutting edge of turning tools with different rake angle "gamma". The objective of the study was to determine the relationship between the cutter geometrics, cutting forces and a value and sign of residual stresses in the cutting edge. Taking to account the hypothesis about influence of a value and sign of residual stresses on tool life the indicated relationship may be the basis for further research on optimization of cutting edge geometrics and optimal cutting conditions for different materials. Turning was performed on lathe machining center DMG NEF 400. Straight-turning tool was used as a metal cutter. The cutter was brazed a cemented-carbide tip to (8% WC-Co). This hard alloy is a composite tool material. Its mechanical properties are hardness 88 HRA; bending strength 1670 MPa; compressive strength 4410 MPa.

Rake angle of turning tools («gamma») was ranged from -2 to -8 and from +2 to +8 degrees. Piped workpieces with a diameter of 46 mm and a thickness of 3 mm were machined. The workpiece was mounted in the three-jaw chuck. Workpiece weight was measured before and after turning to determine the shrinkage factor and chip thickness. Cutting data are shown in Table 1.

Table 1. Cutting data.

| Machined material   | Cutting speed, \( V_c \), m/min | Feed, \( f_n \), mm/rev | Feedrate, \( V_f \), mm/min | Spindle RPM, n, rpm |
|---------------------|---------------------------------|------------------------|-----------------------------|---------------------|
| Titanium alloys     | 3                               | 60                     | 0.16                        | 76.48               | 478                 |
| Steel               | 3                               | 100                    | 0.16                        | 127.36              | 796                 |
| Aluminium alloys    | 3                               | 250                    | 0.20                        | 397.80              | 1989                |

Materials: aluminum alloys, titanium alloys and high-alloy stainless steel was machined sequentially by each cutter. Sections of insert cutting edge where there has been a turning of alloys are shown in figure 1.

Figure 1. Contact area of the chip with the rake surface of insert.

First, high-strength aluminum alloy Al-6%Zn-2.3% Mg-1.7%Cu-0.4%Mn and Al-6% Zn-2% Mg-1% Cu and duralumin Al-4% Cu and 1.4% Mg-0.6% Mn were machined on the area 1. Then, titanium alloy Ti-5%Al-5%Mo-5%V was machined by the same area of the cutter.

On the area 2 corrosion-resistant high-strength steel Fe-14%Cr-6%Ni-1.5%Mo-1%Mn-0.06%C were machined.

On the area 3 titanium alloy Ti-6%Al-2%Zr were machined.

Contact area of a chip with the rake surface was measured by the universal measuring machine for cutting tools Zoller Genius Pilot 3.0 using a 20-power magnification camera.

3. Theory

3.1. Determination of residual stresses by x-ray diffraction

The effect of residual stresses in the surface layer of insert causes displacement of the atomic planes in the material. Stresses corresponding to the deformation of the crystal lattice are calculated from the
elasticity equations of isotropic, continuous and homogeneous mediums. X-ray method of residual stresses determination is based on the Wulf-Bragg law [17]:

\[ 2d \cdot \sin \theta = n \lambda \]  

(1)

where \( \lambda \) is the wavelength, \( d \) is the interplanar distance, \( \theta \) is the angle of rays diffraction, \( n \) is an integer number, diffraction order, \( n = 1, 2,... \).

Relation (2) is given while differentiation of equation (1), it shows the relationship of material deformation with changes in the interplanar distances of material crystal lattice:

\[ \varepsilon_{\varphi, \psi} = \frac{d_{\phi, \psi} - d_c}{d_c} = - (\theta_{\varphi, \psi} - \theta_o) \cdot \text{ctg} \theta_s \]  

(2)

where \( d_0, d_{\phi, \psi} \), \( \psi \) are the interplanar distances of the crystal lattice for the undeformed and deformed material, \( \theta_o, \theta_{\phi, \psi} \), \( \psi \) are the Wolf-Bragg angles for the undeformed and deformed material, \( \varphi \) is the azimuthal angle, \( \psi \) is the angle between the normals to sample surface and to the plane of the crystal lattice (hkl).

The relationship between stress and strain in any direction \( \varphi \) takes into account the \( \sin^2 \psi \) - method.

Residual stresses were measured by x-ray diffractometer XStress 3000 G3/G3R. Measurements of residual stresses were carried out in "Modified \( \chi \)" mode. Standard Cr-K-\( \alpha \) radiation was used. The angle of diffraction is 139 degree. Young's modulus (598 000 MPa) and Poisson's ratio (0.22) were inserted as material parameters for automatic calculation of stresses. We use cross correlation method for residual stresses calculation. Residual stresses were measured on the main and the side surface of insert. Analysis of insert SSS was performed using the \( \sin^2 \psi \) -method.

3.2. Estimation of cutting forces

Measurement of cutting forces was carried out on a three-component dynamometer Kistler 9129AA, which has a measured range Fx, Fy, Fz ±10 kN. As the scheme of free rectangular cutting was considered, the cutter had been exposed to two forces \( F_t \) and \( F_f \) – tangential and axial [18]:

\[ F_t = \frac{f_n a_p \tau \cos(\beta - \gamma)}{\sin \varphi \cos(\varphi \beta - \psi)} \]  

(3)

\[ F_f = \frac{f_n a_p \sin(\beta - \gamma)}{\sin \varphi \cos(\varphi \beta - \psi)} \]  

(4)

where \( \tau \) is the tangential stresses in shear plane, \( \varphi \) is the shear angle, \( \gamma \) is the rake angle of the cutter, \( a_p \) is the cutting depth, \( f_n \) is the feed, \( \beta \) is the tool-chip interface friction angle.

In formulas (3) and (4) when calculating \( F_t \) and \( F_f \) it has been taken into account the effect of the rake angle of insert, which allows to assess rake angle factor to the pressure on the front surface.

Resultant cutting force was calculated according to the formula (5) for further interconnection (interrelation) analysis:

\[ F = \sqrt{F_t^2 + F_f^2} \]  

(5)

4. Experimental results

Figures 2 and 3 demonstrate function of residual stress changes and insert rake angle \( \gamma \) (gamma) for different materials machined.
**Figure 2.** «Gamma» angular dependence of residual stresses on the tool rake surface.

**Figure 3.** «Gamma» angular dependence of residual stresses on the tool flank surface.

**Figure 4.** «Gamma» angular dependence of the resultant cutting forces.

Graphs numeration (1, 2 and 3) corresponds to site number in figure 1. Cutting force vs plate angle $\gamma$ relationship is shown in figure 4.

In figures 5–8 the chip contact areas with the rake surface of insert after machining of aviation materials are shown. After aluminum alloys’ turning a small contact area is revealed on the insert (figure 5), where the build-up edge has been formed.
After steel and titanium alloys machining, defects are found on all inserts: edge chipping (figure 7, a), chips and cracks (figure 6, d).

**Figure 5.** Chip contact area with the rake surface of insert after high strength aluminum alloys machining. Rake angle, gamma degrees: a) -8; b) -4; c) +2; d) +6.

**Figure 6.** Chip contact area with the rake surface of insert after titanium alloy Ti-5%Al-5%Mo-5%V machining. Rake angle, gamma degrees: a) -8; b) -4; c) +2; d) +6.

**Figure 7.** Chip contact area with the rake surface of insert after titanium alloy Ti-6%Al-2%Zr machining. Rake angle, gamma degrees: a) -8; b) -4; c) +2; d) +6.

**Figure 8.** Chip contact area with the rake surface of insert after steel machining. Rake angle, gamma degrees: a) -8; b) -4; c) +2; d) +6.

5. **Discussion of results**

Measurements on the grinded, not being turned insert surface have shown that surface residual stresses are compressive at about -901 MPa. Sign and value of residual stress is very close to the stresses obtained by the same method in the work [15].

The rake surface of insert lied in direct contact with the material being treated. Residual stresses pattern on the rake surface of the plane (Fig. 2) correlates with cutting forces changes (Fig. 4). Stresses in the insert with the rake angle "-8" are close to tensile ones. Analysis of resultant cutting forces shows (Fig. 4) when the cutter rake angle is «-8» the cutter is exposed to maximum force, and if the rake angle is «+2», there is noticeably decrease in cutting forces during machining the all materials involved in experiment.

Residual stresses on the flank surface of insert change ambiguous. In cutters with rake angle «-8», «-4», «+2» residual stresses are tensile (Fig. 2). Contact area increases after alloy Ti-5 % Al-5 %
Mo-5 %V turning. Insert heating occurs in the contact with material machined and forms a heat-affected zone (HAZ) which extends from the cutting edge deep into the insert. Also very long HAZ was discovered in inserts after of titanium alloys (Fig. 6, 7) and high-strength steel (Fig. 8) machining.

Residual stresses were measured in the area from the edge up to 2 mm. Therefore, we have analyzed the whole HAZ, and residual stress, which were defined on the flank surface of insert; characterize a destructive state of insert material. Complex experimental and theoretical studies allow us to formulate the following conclusions.

The impact of high cutting forces and temperatures cause the accelerated wear of cutting edges. Structural-phase changes in insert material yet to be explored. Minimum cutting forces were registered at rake angle value $\gamma = +2$ when all of materials machining.

That means that given feed angle provides the best parameters of power inputs per volume unit removed when material cutting. The findings can be further used for optimization of cutting modes in turning of aviation materials.

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