Investigation of Output Parameters of Titanium Reverse Turning

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Abstract. Titanium alloys are hard to machine by all types of cutting. The cutting data influence on the output parameters of the turning process after the VT20 titanium alloy machining has been studied. The turning cutters with carbide inserts were used that enable cutting in a forward and reverse direction. Cutting forces, vibration, surface roughness and residual stresses were measured. Measurements of residual stresses were performed by x-ray diffraction. The relationship of output parameters and the cutting data are shown.

1. Introduction

Many studies are devoted to an investigation of different output parameters of the general turning process, including analysis of a relationship between cutting forces and cutting data [1-4]. The results of these investigations are very topical for aerospace industry and other areas where a power is used for chip volume removing as an important factor. They enable one to reach a maximal productivity by the criterion of the cutting process for a certain machine tool.

Some scientific works are devoted to study of stress-strain state (SSS) of processed material [5-8]. Residual stresses influence 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 cutting data of machining a 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.

When machining titanium alloys, large cutting forces are applied, which lead to intense heat generation. Temperatures in the cutting zone reach high values [9]. The heating of tool and workpiece material leads to negative changes in the microstructure and properties of both. Impact of large cutting forces and high temperatures cause the accelerated wear of the cutting edges of the tool itself. Hereupon, the permissible cutting speeds and process productivity are reduced.

The investigation of a tool geometry and cutting data influences on a surface roughness is in focus. The mathematical simulation is used for this [10-13]. It is very important to note that the modern high productivity turning implies obtaining high surface quality even after roughing and semi-finishing.
A vibration during cutting is a highly undesirable process as it reduces machining performance, accuracy and quality of part surfaces, tool and machine lives. The vibration analysis during different methods of machining is discussed in a number of papers [14-16]. The authors offer to suppress vibrations both owing to a special cutter design and setting cutting modes that provide stable machining. Some authors offer to use special techniques as cutting speed modulation for chatter suppresses [14].

In this way, all investigations make the study of the complex of output parameters important, which consist of cutting forces, chatters, surface roughness and residual stresses. It is necessary to note that all investigations discussed above considered the classical turning process excluding reverse cutting.

2. Materials, equipment and methods
Titanium alloy VT20 (Ti-6%Al-2%Zr) was machined. Turning was performed on lathe machining center DMG NEF 400 (fig. 1). Sandvik Coromant CoroTurn Prime CP-30Al-2020-11 cutter (fig. 2a) with carbide inserts CP-A1104-L5 1115 and CP-A1108-L5 1115 (fig. 2b) was used. Geometrical parameters of the cutter are shown in Table 1.

| Table 1. The geometric parameters of cutter CP-30Al-2020-11 |
|-----------------------------------------------------------|
| Insert       | Nose radii, mm | Tool cutting edge φ, deg | Rake angle γ, deg | Relief angle α, deg |
|--------------|----------------|--------------------------|------------------|--------------------|
| CP-A1104-L5  | 0.4            | 30                       | 8                | 6                  |
| CP-A1108-L5  | 0.8            | 30                       | 8                | 6                  |

Figure 1. Working area of lathe machining center DMG NEF 400 with workpiece and measuring equipment.

Figure 2. The cutter: a - tool body CP-30Al-2020-11; b - inserts CP-A1104-L5 and CP-A1108-L5
Workpieces had a cylinder shape with the diameter of 90 mm and the length of 410 mm. The cylinder was clamped in a three-jaw chuk. Cutting forces were measured with Kistler 9129AA 3-component dynamometer. Vibrations were measured with a 3-component accelerometer, National Instruments NI9234 ADC unit and MALDAQ, which is a part of MAL CutPro/ShopPro. The surface roughness was measured with Taylor Hobson Form Talysurf i200 profilometer. Residual stresses were measured by x-ray diffractometer XStress 3000 G3/G3R [17-19]. Measurements of residual stresses were carried out in a "Modified χ" mode. Standard Cr-K-α 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. The authors used a cross correlation method for residual stresses calculation. Residual stresses were measured on the main and side surface of the insert. Analysis of samples SSS was performed using the sin²-method.

The effect of residual stresses in the surface layer of the 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. An X-ray method of residual stresses determination is based on the Wulf-Bragg law [20]:

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

(1)

where

- \( \lambda \) – wavelength;
- \( d \) – interplanar distance,
- \( \theta \) – angle of rays diffraction;
- \( n \) – an integer number, diffraction order, \( n = 1, 2, ... \)

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

\[ \varepsilon_{\psi,\psi} = \frac{d_{\psi,\psi} - d_{\psi}}{d_{\psi}} = -\left(\theta_{\psi,\psi} - \theta_{\psi}\right) \cdot \text{ctg} \theta_{\psi}. \]  

(2)

where

- \( d_0, d_{\psi}, \psi \) – interplanar distances of the crystal lattice for the undeformed and deformed material;
- \( \theta_{0}, \theta_{\psi}, \psi \) – Wolf-Bragg angles for the undeformed and deformed material;
- \( \psi \) – the azimuthal angle;
- \( \psi \) – the angle between the normals to the sample surface and to the plane of the crystal lattice (hkl).

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

3. Results and discussion

Figure 3 demonstrates the resultant cutting force function of different cutting data. Experiments were conducted with following parameters. The depth of cut \( a_p \) was changed from 0.5 to 1.5 mm (fig. 3a) with cutting speed \( V_c \)=60 m/min and feed \( f_n=0,25 \) mm/rev. The dependence is close to linear. The feed \( f_n \) variation was in the range from 0.1 to 0.35 mm/rev (fig. 3b) with the depth of cut \( a_p=1 \) mm and the cutting speed of \( V_c \)=60 m/min. The dependence is close to linear too. The cutting speed \( V_c \) variation in the range from 40 to 80 m/min with the depth of cut \( a_p=1 \) mm and feed \( f_n=0,25 \) mm/rev (fig. 3c). The changing of the cutting speed does not significantly affect cutting force. In general, it can be noted that dependences are fit for a classical cutting theory.
Figure 3. Effect of cutting data on cutting forces: a - depth of cut \( a_p \); b - feed \( f_n \); c - cutting speed \( V_c \)

Additionally, the comparative analysis of cutting forces for forward and reverse machining with CP-A1108-L insert was carried out for following cutting data: \( a_p = 1 \) mm; \( f_n = 0.25 \) mm/rev; \( V_c = 60 \) m/min. This analysis shows that forward cutting forces are higher by about 50%.

Figure 4 demonstrates the surface roughness function of different cutting data. These figures show that roughness increases proportionally when the feed increases (fig. 4b). A changing of the depth of cut (fig. 4a) and the cutting speed (fig. 4c) does not affect significantly the roughness. Additionally, the comparative analysis of surface roughnesses for forward and reverse machining with the CP-A1108-L insert was carried out for following cutting data: \( a_p = 1 \) mm; \( f_n = 0.25 \) mm/rev; \( V_c = 60 \) m/min. This analysis shows that there is no significant difference.

The insert with larger nose radii enables one to improve significantly the surface quality.

Figure 5 demonstrates the root-mean-square (RMS) vibration acceleration function of different cutting data. These figures show that RMS increases when the depth of cut and the feed increase. The cutting speed variation does not affect significantly on the vibration acceleration. This result can be explained by a narrow range of permissible cutting speeds for titanium and the process dumping effect. The process dumping is manifested at low rpm [21]. Also, figures show that the increasing of insert nose radii leads to increasing vibration acceleration. This result is consistent with previous studies.

Additionally, the comparative analysis of vibration accelerations for forward and reverse machining with the CP-A1108-L insert was carried out for the following cutting data: \( a_p = 1 \) mm; \( f_n = 0.25 \) mm/rev; \( V_c = 60 \) m/min. This analysis shows that forward cutting vibro acceleration is three times higher than the reverse one (35.2 m/s² vs 11.03 m/s²).

The vibro acceleration is a relative parameter of a machining process assessment, which describes a certain machine tool. The RMS vibro acceleration of DMG NEF400 did not exceed 110 m/s² when machining processes were correct. This fact shows that RMS vibro accelerations for reverse turning are acceptable.
Figure 6 demonstrates the distribution of tangential residual stresses along the surface layer depth for the CP-A1108-L5 insert with the following cutting data: \( a_p = 1 \text{ mm} \), \( f_n = 0.25 \text{ mm/rev} \), \( V_c = 60 \text{ m/min} \).

![Figure 6. Distribution of tangential residual stresses along surface layer.](image)

It was found that the maximal depth of compressive stresses does not exceed 0.07 mm. All stresses, which are located above this value, become tensile. Significant tangential residual stresses were discovered. Their absolute value can reach \( \sim 300 \text{ MPa} \) and sometime they can exceed a value of normal stresses. Tangential stresses indicate about a plastic deformation, which occurs directly in the cutting zone.

4. Conclusion

Experimental studies allow one to formulate the following conclusions. The turning cutter CoroTurn Prime CP-30Al-2020-11 enables high productivity machining in both a forward and reverse direction. The reverse turning indicates comparatively higher cutting forces and vibrations than the forward one. The surface quality is practically independent of the cutting direction.

The distribution of tangential residual stresses in the surface layer allows one to calculate the correct depth of cut for roughing and finishing. This is very important for machining aviation parts, where the strict requirements are applied to the surface layer after machining. Structural-phase changes in insert material are to be explored.

A mathematical simulation of the reverse turning could demonstrate more clear cutting dynamics. However, using the general turning model is discussible.

The research results will be used for optimizing the cutting data.

5. Acknowledgments

The reported study was funded by Sandvik Coromant Russia/CIS, according to research project No. 147/17. All studies were conducted in the research laboratories of "High productivity machining, forming and strengthening" and "Study of technological residual stresses and deformations" INRTU. The authors express their gratitude to the staff of the laboratories.

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