

Distribution of contact loads over the flank-land of the cutter with a rounded cutting edge

V Kozlov¹, A Gerasimov² and A Kim¹

¹Tomsk Polytechnic University, 30, Lenina ave., Tomsk, 634050, Russia

²Tomsk State University, 36, Lenina ave., Tomsk, 634050, Russia

E-mail: kozlov-viktor@bk.ru

Abstract: In this paper, contact conditions between a tool and a workpiece material for wear-simulating turning by a cutter with a sharp-cornered edge and with a rounded cutting edge are analysed. The results of the experimental study of specific contact load distribution over the artificial flank wear-land of the cutter in free orthogonal turning of the disk from titanium alloy (Ti6Al2Mo2Cr), ductile (63Cu) and brittle (57Cu1Al3Mn) brasses are described. Investigations were carried out by the method of ‘split cutter’ and by the method of the artificial flank-land of variable width. The experiments with a variable feed rate and a cutting speed show that in titanium alloy machining with a sharp-cornered cutting edge the highest normal contact load ($\sigma_{h \max} = 3400 \dots 2200$ MPa) is observed immediately at the cutting edge, and the curve has a horizontal region with the length of 0.2...0.6 mm. At a distance from the cutting edge, the value of specific normal contact load is dramatically reduced to 1100...500 MPa. The character of normal contact load for a rounded cutting edge is different – it is uniform, and its value is approximately 2 times smaller compared to machining with a sharp-cornered cutting edge. In author’s opinion it is connected with generation of a seizure zone in a chip formation region and explains the capacity of highly worn-out cutting tools for titanium alloys machining. The paper analyses the distribution of tangential contact loads over the flank land, which pattern differs considerably for machining with a sharp-cornered edge and with a rounded cutting edge.

Abbreviation and symbols: m/s – meter per second (cutting speed v); mm/r – millimeter per revolution (feed rate f); MPa – mega Pascal (specific contact load as a stress σ or τ); h_f – the width of the flank wear land (chamfer) of the cutting tool, flank wear land can be natural or artificial like the one in this paper [mm]; x_h – distance from the cutting edge on the surface of the flank-land [mm]; σ_h – normal specific contact load on the flank land [MPa]; τ_h – tangential (shear) specific contact load on the flank land [MPa]; HSS – high speed steel (material of cutting tool); P_y – radial component of cutting force [N]; P_{y_r} – radial component of cutting force on the rake face [N]; P_z – tangential component of cutting force [N]; γ – rake angle of the cutting tool [°]; α – clearance angle of the sharp cutting tool [°]; α_h – clearance angle of the flank wear land [°]; ρ – rounding off radius of the cutting edge [mm]; b – width of the machined disk [mm].

1. Introduction

Cutting tool wear causes a change in its geometry – a wear-land with width h_f forms on the flank surface, the cutting edge rounds with radius ρ , a wear crater forms on the tool face. In machining of titanium alloys, which are widely used in aerospace and chemical industry, shipbuilding, etc., very



intensive wear occurs on the flank surface with rounding of the cutting edge. Contact loads vary on the face and flank surfaces of the cutting tool, as well as the temperature in the chip formation zone.

In machining of difficult-to-machine titanium alloys the width of wear-land h_f reaches 2.5...5 mm, and cutting edge rounding radius reaches $\rho = 0.3...5$ mm [1, 2], but even with this big value, cutting tool is still capable of working, which is obscure. It is necessary to know distribution of contact loads and temperature over the surfaces of the cutting tool for estimation of cutting wedge strength at various stages of the wear process.

The investigation of specific contact loads distribution over the work surfaces of the cutting tool is a difficult task due to large values of contact loads, especially in machining of difficult-to-machine materials, to which the widely used in aerospace industry titanium alloy BT3-1 belongs.

2. Research Methods and Preparation for Experimental Study of Contact Load Distribution

The distribution of specific normal σ_h and tangential τ_h contact loads over the wear-land of the flank surface was studied by the method of 'split cutter', and by the method of the artificial flank-land of variable width near the cutting edge [1].

The experiments were carried out in free orthogonal turning of a disk made from the above-mentioned materials, i.e. with radial feed f of a cutter. The ductile brass (63Cu), which forms continuous chip, the brittle brass (57Cu1Al3Mn), which forms discontinuous chip, the difficult-to-machine titanium alloy BT3-1 (Ti6Al3Mo2Cr), which forms discontinuous chip, were used as a workpiece material.

Brass was selected to fine-tune the method of a split cutter and to compare its results with the results received by the method of the artificial flank-land of the variable width. The latter method was used to study contact load distribution over the artificial flank-land near the cutting edge in machining of titanium alloy BT3-1, since the split cutter, which is made from cemented carbide BK8 (WC8Co), does not have sufficient strength when a split between its parts approaches to a cutting edge at a distance smaller than 0.6 mm. The comparison of the results received by both methods in brass machining, has displayed good coincidence, the deviation did not exceed $\pm 15\%$.

The wear was simulated by sharpening a chamfer with width h_f on a flank surface ground with clearance angle $\alpha_h = 0^\circ$. To study influence of the cutting edge rounding, artificial rounding of a cutting edge stimulated the wear to required radius ρ . The width of artificial flank-land h_f was measured by means of a toolmaker's microscope. The length of the artificial flank wear land was accepted equal to the width of disk b , since ordinary wear of a cutting tool occurs along the cutting edge and its length is usually bigger than its width.

The change in length of a flank-land insignificantly affects distribution of specific contact loads over the face of a cutting tool – only through the change of cutting temperature. It allows us to use the data on contact load distribution over the rake surface of the cutting tool, received in cutting by a sharp cutting tool. Therefore, the focus was given to an experimental research of the contact loads distribution over a flat section of an artificial flank-land, which was used to simulate flank wear.

3. Results of experiments

In the ductile brass (63Cu) machining with a sharp cutter an artificial flank-land (width $h_f = 2.4$ mm, clearance angle $\alpha_h = 0^\circ$) extreme pattern of σ_h curves is observed, i.e. the highest normal contact loads $\sigma_{h\max}$ are at some distance from the cutting edge (Figure 1 and 2). In the brittle brass (57Cu1Al3Mn) machining by a cutter with the same geometry and cutting speed, the highest contact loads $\sigma_{h\max}$ are near the cutting edge (Figure 3).

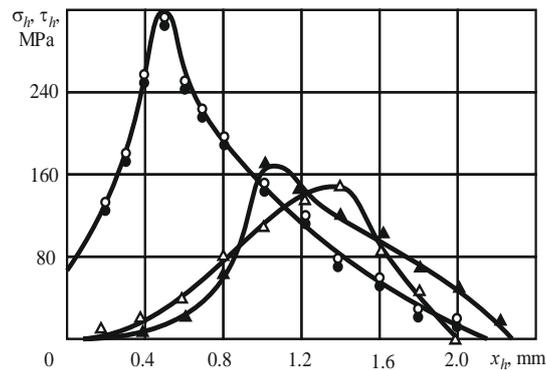


Figure 1. Distribution of contact loads over the flank-land of the cutter in ductile brass (63Cu) machining. $\gamma = 0^\circ$, $\alpha = 18^\circ$, $\alpha_h = 0^\circ$, $v = 1.7$ m/s, \circ, \bullet – $f = 0.06$ mm/r; Δ, \blacktriangle – $f = 0.21$ mm/r; \circ, Δ – normal contact load σ_h ; \bullet, \blacktriangle – tangential contact load τ_h . Ordinate – normal σ_h [MPa], and tangential τ_h [MPa] specific contact load over the flank-land; abscissa – distance from the cutting edge on the surface of the flank-land x_h [mm]

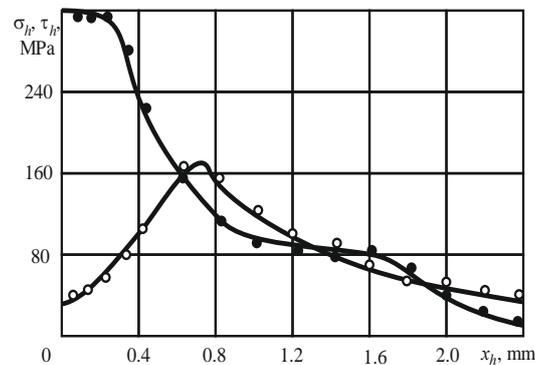


Figure 2. Distribution of contact loads over the flank-land of the cutter in cutting of the ductile brass (63Cu). $\gamma = 0^\circ$, $\alpha = 18^\circ$, $\alpha_h = 0^\circ$, $v = 3.6$ m/s, $f = 0.21$ mm/r; \circ – normal contact load σ_h ; \bullet – tangential contact load τ_h . Ordinate – normal σ_h [MPa], and tangential τ_h [MPa] specific contact load over the flank-land; abscissa – distance from the cutting edge on the surface of the flank-land x_h [mm]

The results of investigations of contact load distribution over a flat section of the flank-land of the cutter with artificial rounding of the cutting edge in machining of brass are presented in Figure 4, and in machining of titanium alloy BT3-1 - in Figure 5.

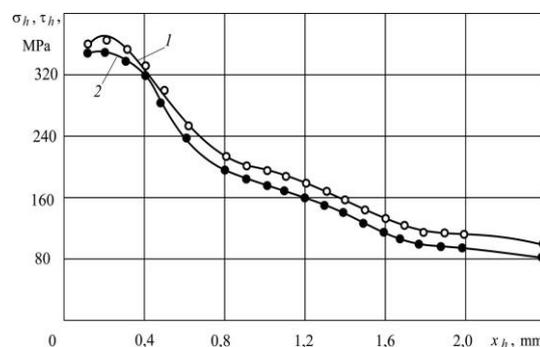


Figure 3. Distribution of normal σ_h (\circ) and tangential τ_h (\bullet) contact loads over the flank-land of the cutter in cutting of the brittle brass (57Cu1Al3Mn). $\gamma = 0^\circ$, $\alpha = 18^\circ$, $\alpha_h = 0^\circ$, $v = 1.7$ m/s, $f = 0.41$ mm/r. Ordinate – normal σ_h [MPa], and tangential τ_h [MPa] specific contact load on the flank-land; abscissa – distance from the cutting edge on the surface of flank-land x_h [mm]

4. Discussion of experiments results

The extreme pattern of the curves of normal σ_h and tangential τ_h specific contact loads in machining of ductile materials was also mentioned by other researches [2], however authors have not discovered explanations of this phenomenon.

In our opinion, the highest normal contact loads σ_h in cutting with continuous chip are at some distance from a cutting edge due to a sag of the transient surface under the radial component of the cutting force on rake surface P_{y_r} [1].

In continuous chip formation the influence of the radial component of cutting force P_{y_r} on the face is stable [3], a sag of the transient surface is constant, therefore, pressure from the elastic recovering transient surface on the flank-land is higher at some distance from the cutting edge [1].

During discontinuous chip formation at the moment when formed chip elements are separated from the workpiece, the radial component of the cutting force on face P_{y_r} quickly decreases (sometimes to zero) [3], which leads to elastic recovery of the transient surface and its pressure upon the cutting tool flank surface. To a greater degree this pressure acts near the cutting edge [1], therefore the highest normal contact loads $\sigma_{h_{max}}$ are observed near the cutting edge, which is confirmed by the results of experiments in machining of the brittle brass (57Cu1Al3Mn), which forms discontinuous chip (Figure 3).

In machining of brass, tangential contact loads τ_h are equal to normal ones σ_h , except for the case of the ductile brass (63Cu) machining at elevated cutting speed $v = 3.62$ m/s, when the highest value of $\tau_{h_{max}}$ is observed near the cutting edge, where it is not equal to normal contact loads σ_h (Figure 3). The equality of tangential and normal contact loads is associated, in our opinion, with a plastic character of the contact on the flank-land. The high coefficient of friction $\mu = \tau_h / \sigma_h \approx 1$ does not correspond to usual external friction, when coefficient of friction is equal to $0.15 \dots 0.1$. In case of plastic contact, tangential contact loads τ_h cannot be calculated by formula $\tau_h = \sigma_h \times \mu$, as they will be equal to shear strength of a material τ_{max} at the operating temperature in the contact zone ($\tau_h = \tau_{max}$).

At elevated cutting speed $v = 1.17$ m/s (Figure 2), the higher temperature of cutting promotes adhesion of contact surfaces, thus strong seizure takes place even at insignificant pressure ($\sigma_h \approx 40$ MPa), what was observed near the cutting edge. A high value of $\tau_{h_{max}} = 320$ MPa is explained, in our opinion, by increased strain rate and hardening of the work material. Softening of the work material due to influence of temperature at increased cutting speed does not have time to occur [5].

In case of the rounded cutting edge, the workpiece material hardens as it moves under the rounded section, therefore there is an increase in tangential contact load τ_h (Figure 4) compared to cutting with a sharp cutting edge (Figure 1 and 2).

In machining of plastic brass the cutting edge rounding leads to change in the distribution pattern of contact loads and their value (Figure 4). When a cutting edge is rounded, the volume of the work material, pressed under the rounded section of the cutting edge, is increased, therefore the sag of the transient surface affects pressure on a flank surface to a lesser degree. Normal contact load σ_h on a flat section of the flank land near the cutting edge is not equal to zero in machining of the plastic brass (63Cu), and the distribution pattern of contact loads becomes uniform (Figure 4). Normal and tangent contact loads are equal in magnitude ($\sigma_h \approx \tau_h \approx 130$ MPa), which indicates plastic character of contact on the flank-land. The magnitude of these loads is a bit higher than the magnitude of the highest loads on the flank-land of the rounded cutting edge (Figure 1, 2), this is associated with dragging of additional material under the rounded section of the cutting edge and with an increase of elastic deformation of the work material in the chip forming zone.

The work material is work-hardened when it moves under a rounded section, thus an increase of tangential contact load τ_h is observed (Figure 4) compared to cutting with a sharp cutter (Figure 1 and 2).

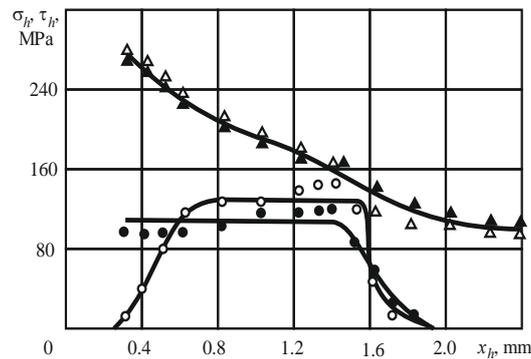


Figure 4. Distribution of contact loads over the flank-land of the cutter in brass machining by the cutter with rounding off cutting edge with radius $\rho = 0.3$ mm. $\gamma = 0^\circ$, $\alpha = 18^\circ$, $\alpha_h = 0^\circ$, $v = 1.7$ m/s, \circ , \bullet – ductile brass (63Cu), $f = 0.21$ mm/r; Δ , \blacktriangle – brittle brass (57Cu1Al3Mn); $f = 0.41$ mm/r; \circ , Δ – normal contact load σ_h ; \bullet , \blacktriangle – tangential contact load τ_h

The distribution pattern of the contact loads does not change for the brittle brass machining with a rounded cutting edge (Figure 4), and the magnitude of the highest contact load even decreases ($\sigma_{h \max} \approx \tau_{h \max} = 280$ MPa) compared to cutting with a sharp cutting edge ($\sigma_{h \max} \approx \tau_{h \max} = 360$ MPa) (Figure 3). The formation of a seizure zone in the rounding region, which reduces contact of the transient surface with the flank-land, explains this fact, and this is especially true for conditions of discontinuous chip formation. The presence of the scratch marks on the rounded portion, left during sharpening of the cutting tool, proves this indirectly.

The reduction of tangential contact load τ_h , at a distance from the cutting edge, is caused, in our opinion, by softening of the work material in the contact zone due to temperature increase. The plastic character of the contact on the flank land is indirectly confirmed by a considerable amount of brass stuck to the flank-land after turning.

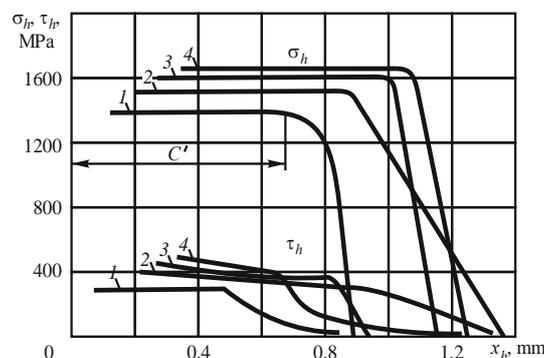


Figure 5. Distribution of contact loads over the flank-land of the cutter in machining of titanium alloy BT3-1 by the cutter with rounding off cutting edge with radius $\rho = 0.3$ mm. BT3-1 – BK8, $\gamma = 0^\circ$, $\alpha = 10^\circ$, $\alpha_h = 0^\circ$, $V = 1$ m/s, $f = 0.21$ mm/r; 1 – $\rho = 0.07$ mm; 2 – $\rho = 0.2$ mm; 3 – $\rho = 0.28$ mm; 4 – $\rho = 0.35$ mm; σ_h – normal contact load on the surface of the flank-land, τ_h – tangential contact load on the surface of the flank-land

The machining of titanium alloy BT3-1, which forms discontinuous chip, by a cutter with a rounded cutting edge (Figure 5), shows almost a 2 times reduction of normal contact loads compared to cutting without cutting edge rounding (Figure 6). We explain this paradoxical phenomenon by formation of a seizure zone on the cutter face in the region of rounding, which reduces the contact of the transient surface with the flank land. The presence of the scratch marks on the rounded part, left during sharpening of the cutting tool, proves this indirectly.

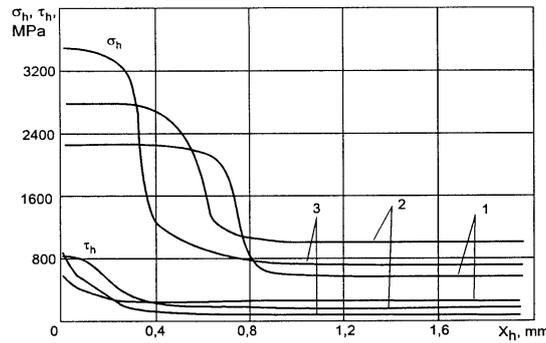


Figure 6. Distribution of normal σ_h and tangential τ_h contact loads over the flank-land of the cutter in titanium alloy cutting without rounding off cutting edge. BT3-1 – BK8, $\gamma=0^\circ$, $\alpha_h=0^\circ$, $\alpha=10^\circ$, $v=1$ [m/s]: 1 - $f=0.11$ mm/r; 2 - $f=0.21$ mm/r; 3 - $f=0.41$ mm/r. Ordinate – normal σ_h [MPa] and tangential τ_h [MPa] specific contact load on the flank-land; abscissa – distance from the cutting edge on the surface of flank-land x_h [mm].

The tangential contact loads, in the area that is more than 0.3 mm away from the cutting edge, are a bit higher in magnitude for cutting with a rounded cutting edge ($\tau_h = 350 \dots 420$ MPa) (Figure 5) than the tangential contact loads in cutting with a sharp cutting edge ($\tau_h = 300 \dots 200$ MPa) (Figure 6). The increase of τ_h for a rounded cutting edge is explained by work-hardening of the work material during its travel under the rounded section of the cutting edge. The absence of influence of normal contact loads on the tangential contact loads indicates plastic character of the contact on the flank-land, which is indirectly confirmed by presence of titanium alloy adhered to the flank-land after turning.

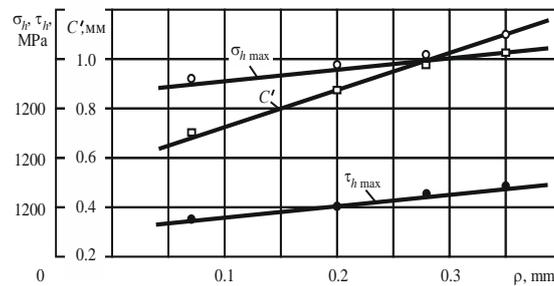


Figure 7. Influence of the cutting edge radius rounding off ρ on the highest contact loads magnitude on the flank-land $\sigma_{h \max}$, $\tau_{h \max}$ and on the length C' of the horizontal region of the curve σ_h in titanium alloy BT3-1 cutting BT3-1 – BK8, $\gamma=0^\circ$, $\alpha=10^\circ$, $\alpha_h=0^\circ$, $v=1$ m/s, $f=0.21$ mm/rev; 1 – $\rho=0.07$ mm; 2 – $\rho=0.2$ mm; 3 – $\rho=0.28$ mm; 4 – $\rho=0.35$ mm; σ_h – normal contact load, τ_h – tangential contact load

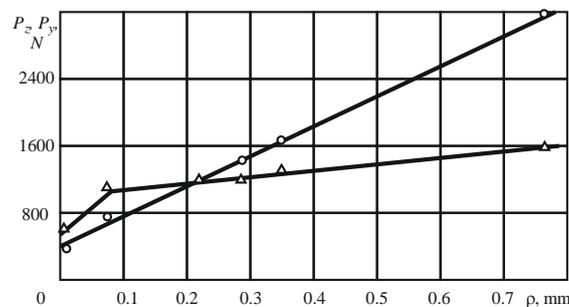


Figure 8. Dependence of cutting force component acting on the rake surface P_{Yr} и P_{Zr} on radius of cutting edge rounding ρ in titanium alloy BT3-1 machining. BT3-1 – BK8, $\gamma=0^\circ$, $\alpha=10^\circ$, $v=1$ m/s, $f=0.21$ mm/r; $\circ - P_{Yr}$ [N], $\Delta - P_{Zr}$ [N]; machined disk width $b=2.3$ mm

The magnitude of the highest contact loads $\sigma_{h \max}$, $\tau_{h \max}$ and length C' of the horizontal region of curve σ_h are directly proportional to rounding radius value ρ (Figure 7) that indicates increase of the material volume, pressed down under the cutting edge.

There is also an increase of the elastic deformation of the work material in a chip formation zone, which is proven by direct proportional dependence of the radial component of the cutting force acting on face $P_{y,r}$ on rounding radius ρ (Figure 8). The increase of cutting force components, when the seizure zone is formed, is explained by the small sizes of this zone, which cannot cope with resistance increase to chip formation from the rake surface. In order to change normal contact loads even a minor change of the seizure zone is enough due to the rigidity of the contact on the flank surface.

5. Conclusion

In machining of the ductile brass (63Cu), which forms continuous chip, the cutting edge rounding leads to pattern change of the contact loads distribution over the flank-land – it becomes uniform. It is explained by dragging of additional material under the rounded section of the cutting edge, which leads to a smaller influence of the transient surface sag.

In machining of ductile brass L63 with a rounded cutting edge, the magnitude of contact loads is a bit more than the highest loads on the flank-land in cutting with a sharp cutting edge. It is explained by dragging of additional material under the rounded section of the cutting edge.

In machining of ductile brass L63 with a cutting tool with rounded cutting edge, normal and tangential contact loads on the flank-land are equal in magnitude ($\sigma_h \approx \tau_h \approx 130$ MPa), which indicates a plastic character of the contact on the flank-land.

In machining of the brittle brass (57Cu1Al3Mn), which gives discontinuous chip, a cutting edge rounding does not lead to change in the pattern of contact loads distribution over the flank-land, but the magnitude of the highest contact load is smaller compared to cutting with a sharp cutting edge. It is explained by formation of a seizure zone on the rounded section of the cutting edge. It reduces the contact of the transient surface with the flank-land, and to a greater degree it is true for discontinuous chip.

The reduction of the tangential loads on the flank land during machining of the brittle brass (57Cu1Al3Mn), in case the hypothesis about the plastic character of the contact on the flank land is accepted, is explained, in our opinion, by the softening of the work material in the contact zone due to temperature increase.

The magnitude of normal contact loads on the flank land when cutting titanium alloy BT3-1 with a rounded cutting edge is two times as small as in cutting with a sharp cutting edge. It is explained by formation of the seizure zone on the rounded section of the cutting edge.

The two-times reduction of the normal contact loads magnitude on the flank-land with a rounded cutting edge explains the working capacity of a considerably worn cutting tool to machine titanium alloys.

The character of the contact on the flank land is plastic in machining of titanium alloy.

The increase in tangential contact loads on the flank-land in cutting of titanium alloy BT3-1 with a rounded cutting edge is explained by work-hardening of the work material due to high plastic deformations.

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