BURR FORMATION MODEL FOR ORTHOGONAL CUTTING AND ITS EXPERIMENTAL VERIFICATION

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ABSTRACT

The mechanics of burr formation at the exit workpiece edge is considered. A burr formation model on the ground of ideal material plasticity is proposed. Formulas for calculation of burr dimensions are given. The influence of different cutting conditions, tool and workpiece geometry is considered. The experimental verification was conducted. Comparison of analytical and experimental data shows good correspondence of model to the real burr formation process.

1. INTRODUCTION

Burrs formed during machining are the cause of many industrial problems. Their presence on part's edges reduces the product quality, makes difficulties in machining sequence and assembly, hinders the industrial automation and causes the problems during work of product. Therefore burrs usually must be removed from part's edges. There are a lot of deburring methods; their choice depends on burr dimensions, type of workpiece, burrs accessibility and other conditions. To decrease deburring cost it is necessary to select mostly proper deburring way and to reduce burr size. These goals can be reached if burr formation mechanism is known, which make it possible to predict burr dimensions and to minimize their appearance by optimum choice of cutting conditions, tool and workpiece geometry.

There have been a lot of work devoted to the burr formation process in different kinds of machining and different research methods have been used including analytical and experimental studies, SEM observation and FEM modeling. Until now the base model to research metal cutting and burr formation is orthogonal cutting scheme [1-6]. Consecutive complication of this model can be spread to the oblique and complex cutting and applied for real machining process. Burr formation in orthogonal cutting was studied as plastic bending of non-cut part of material [1], using the minimum energy and incompressibility assumptions [3,4] and FEM modeling [6]. These models describe burr formation process very well but theirs application either have no desirable accuracy or require additional experimental data or take a lot of time to have a result. In this paper another approach to study burr formation is proposed, which is based on theory of plasticity.

2. BURR FORMATION MODEL

Here is considered the case when tool is absolutely sharp and rigid and workpiece material has ideal plastic properties. The constant of plasticity τ_Φ (shear yield strength) defines depending on material properties as [7]

$$\tau_\Phi = \sigma_u(1+0.5\delta)\,, \tag{1}$$

where σ_u is ultimate tensile strength and δ is percent elongation.

In general case exit workpiece surface is inclined to the cutting direction at workpiece angle *W* (fig.1). During stable cutting the deformation area is concentrated conditionally on shear line *AB* as shown in fig.1. At this time this line pass tool rake face in point A at the angle $\pi/4+\alpha_f$ according to the boundary conditions for slip lines [8]. Angle α_f, which is sometimes called “plastic friction angle”, expressed by the formula

$$\alpha_f = \frac{\pi}{4} - 0.5\cdot a\cos\frac{\tau_f}{\tau_\Phi}, \tag{2}$$

is the parameter that defines the direction of slip line relatively to the boundary. τ_f in formula (2) is average friction stress on tool rake face. Here and below angles are given in radians.

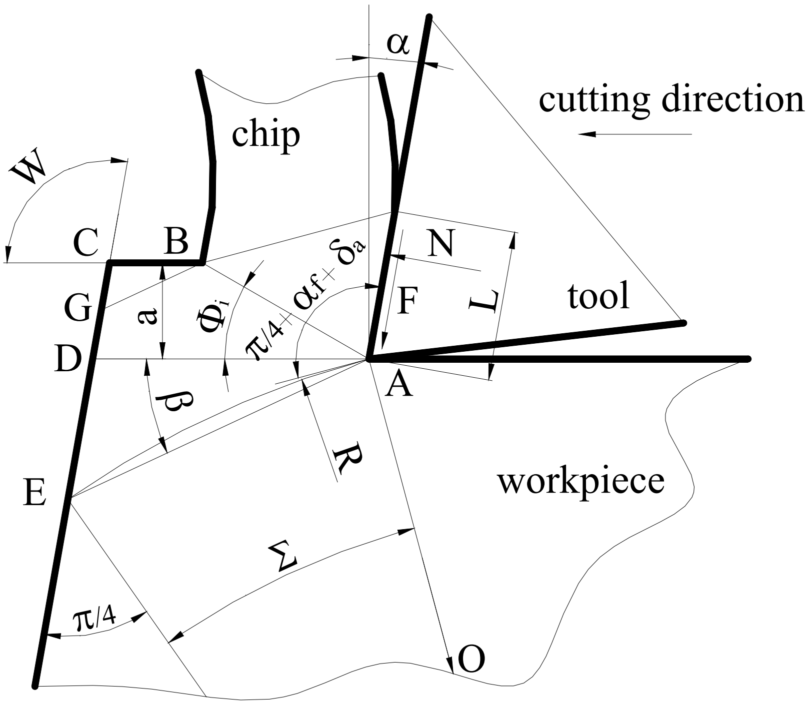

Fig.1 Initiation of Burr Formation

As tool moves to the workpiece edge the deformation zone is enlarged and burr formation begins. The lower boundary of this area is slip line *AE*. Previous researches [3-6] have shown that the character of this line is complicated. As first approximation it is possible to assume that this line is straight one. However actually this line has some curvature and thus as the second approach here is assumed that this line is an arc of circle with radius *R*. According to the boundary conditions [8] line AE passes exit surface EC at the angle $\pi/4$ and tool rake face at the angle $\pi/4+\alpha_f+\delta_a$, i.e. as tool moves to the workpiece edge the slip line rotates at an angle δ_a relatively to the rake face. In previous report [9] angle δ_a was assumed to be equal $\pi/4$ as first estimation. More accurately *R* and δ_a parameters can be found under the assumption that non-cut part ABCE of workpiece material deforms like topped equilateral wedge ABGE, which is loaded by the pressure from shear line AB. As shown in previous researches [4-6] part BCG is really stayed undeformed during burr formation. According to the theory of plasticity [8] the wedge ABGE is deformed in such a way that AB=EG. Thus we can find geometrically the negative shear angle β, angle δ_a and sector angle Σ as followed

$$\beta = \frac{1}{2}(\pi - W - \Phi) \tag{3}$$

$$\delta_a = \frac{\pi}{2} - \alpha_f + \alpha - \Phi \tag{4}$$

$$\Sigma = \frac{\pi}{2} - W + \Phi \tag{5}$$

where α is rake angle and Φ is conditional shear angle.

Radius R is found by solving of balance moment equation relatively point O, which is the center of arc AE, as followed

$$R = \frac{-(N\cos(\theta) + F\sin(\theta)) - \sqrt{(N\cos(\theta) + F\sin(\theta))^2 - 2\tau_\Phi \Sigma \cdot N \cdot L}}{-2\tau_\Phi \Sigma}, \tag{6}$$

where L is tool/chip contact length; F and N are friction and normal forces on the rake face. Angle θ is geometrically expressed as

$$\theta = \frac{-\pi}{4} + \alpha_f + \delta_a . \tag{7}$$

Here is assumed that on tool/chip contact length L normal σ_n and friction τ_f stresses are distributed uniformly. Normal stress can be found according to the Henky equations. In extreme cases when no friction on the rake face (α_f=0) or friction is maximum ($\alpha_f=\pi/4$) formula for normal stress was proposed by Loladze [10]. In general case, when plastic friction angle α_f lies between 0 and $\pi/4$, normal stress is expressed as followed [11]

$$\sigma_n = -2 \cdot \tau_\Phi \cdot (0.5 - \alpha + \alpha_f - \Delta a + 0.5\arccos 2\alpha_f), \tag{8}$$

where Δa is inclination angle of machined surface (on fig.1 Δa=0).

As Kushner [12] found, average friction stress τ_f depends on the temperature t_r on the rake face and express by the formula

$$\tau_f = \tau_\Phi \cdot (1 - 0.5 \cdot 10^{-3} \cdot t_r). \tag{9}$$

On the ground of experimental and theoretical researches Kushner [12] proposed also to define average tool/chip contact temperature t_r as followed

$$t_r = 0.82 \cdot \frac{S_u}{C_v} \cdot \varepsilon + 105 \cdot \left(\frac{S_u}{100 \cdot C_v}\right)^{0.8} \cdot \left(\frac{v \cdot a}{\omega}\right)^{0.4}, \tag{10}$$

where S_u is real tensile strength, ε is shear strain, C_v is thermal capacity and ω is temperature conductivity of workpiece material; v and a are cutting speed and undeformed chip thickness respectively.

Chip/tool contact length can be found as proposed by Lee and Shaffer

$$L = a \frac{\sqrt{2}}{2\sin\Phi \cdot \sin\left(\frac{\pi}{4} + \Phi - \alpha\right)}. \tag{11}$$

Shear angle Φ is defined as proposed in [11] as

$$\Phi = \frac{1}{2} \cdot \left(\frac{\pi}{2} + \alpha - \alpha_f - \Delta a - \Phi_m\right), \tag{12}$$

where Φ_m is constant of workpiece material.

After definition of value R we can find geometrically the distance between A and E points:

$$AE = R\sqrt{2(1-\cos\Sigma)} \qquad (13)$$

Here is assumed that the plastic friction angle α_f value is not changed up to final burr formation. After initiation of burr formation as tool moves to point A_1 chip formation continues [4] and exit surface EC deforms and rotates at some angle Δ (fig.2 a). According to the new boundary conditions and formula (3) current negative shear angle increases at $\Delta/2$ in this position.

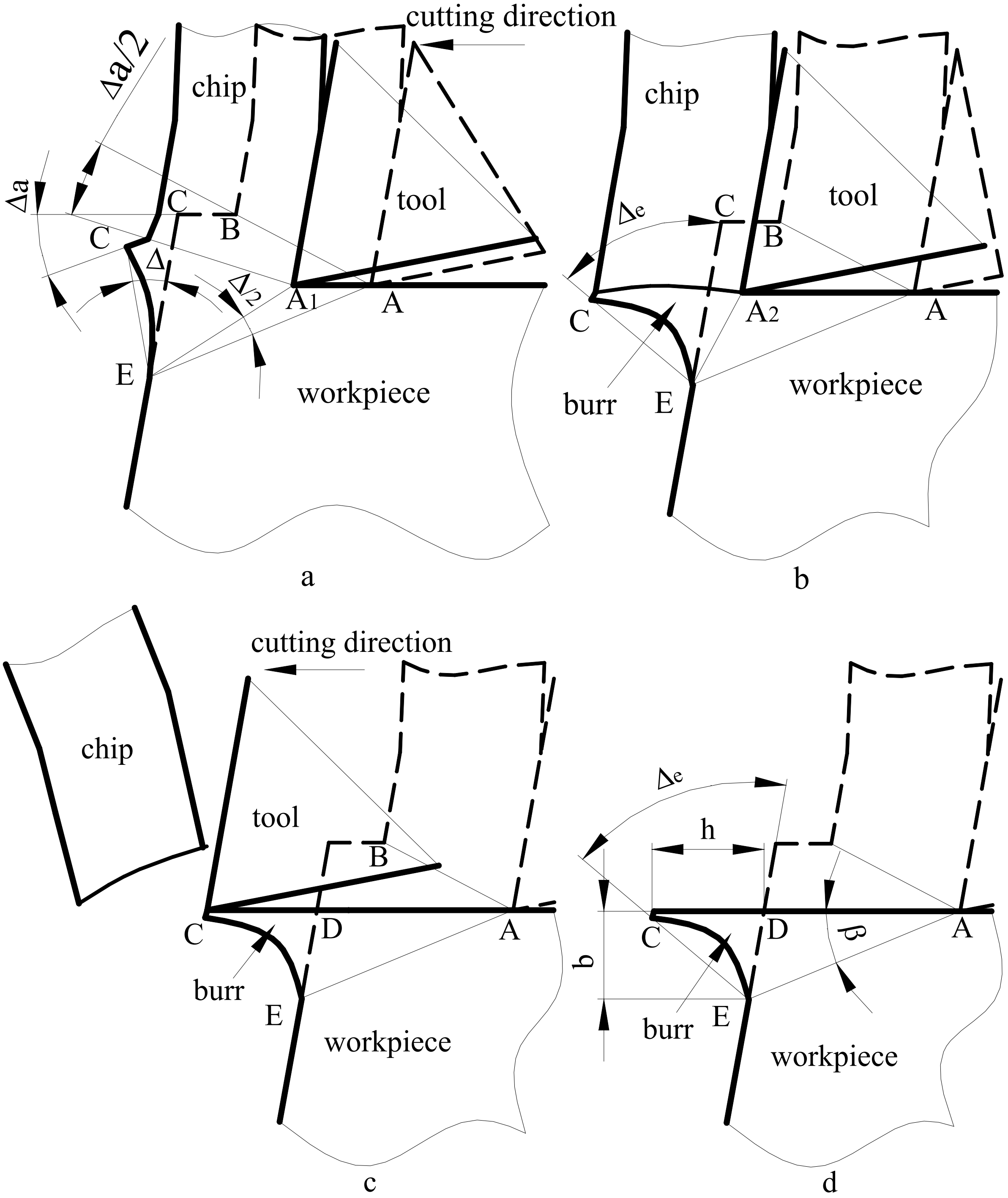

Fig.2 Burr Formation Stages

At the same time during burr formation machined surface BC rotates at some angle Δa. On the base of experimental observations [3,4] here is assumed that $\Delta a = \Delta$. When machined surface BC rotates at an angle

$$\Lambda_e = \frac{\pi}{2} + \alpha - \alpha_f - 2\Phi_i - \Phi_m \tag{14}$$

then shear angle according to the (12) is zero. Φ_i in (14) is initial shear angle when in stable cutting $\Delta a=0$. It is assumed that in these conditions the destruction begins on shear line, chip aspires to tear off the workpiece and burr formation is almost finished (fig.2 b). At the time of crack propagation chip is removed from the workpiece (fig.2 c). In final stage of burr formation the end of chip can be thicker and usually the curvature of positive shear line is changed. Formed burr and final burr dimensions are shown in fig.2d.

It is obvious that burr thickness b is defined by the location of point E. From geometrical relation it can be easily found that

$$b = AE \sin\beta\,. \tag{15}$$

Burr height h is found under the assumption that burr formation stops when exit surface EC rotates at the angle Δ_e. Using geometrical relations this burr dimension expressed by the formula

$$h = \left(\frac{K\cos(\Delta_e - W)}{\sin W}\left(a + AE\sin\beta\right) + b\tan\left(W - \frac{\pi}{2}\right)\right), \tag{16}$$

where K is the constant characterizing the distortion of exit surface during burr formation.

Theoretical analysis of presented model shows that undeformed chip thickness mostly influence on burr dimensions; the burr sizes increase practically linearly as undeformed chip thickness grows. Rake angle increasing leads to the reducing of burr dimensions but no so significantly. As workpiece angle W grows, burr becomes smaller and at some critical angle, depending on the other cutting conditions, it is disappeared. As followed from the model this workpiece angle must be $\pi/2+\Phi_1$. In practical range of cutting speeds the influence of this parameter is most insignificant among other cutting conditions. If cutting velocity increases the burr dimensions reduces but very slightly.

3. EXPERIMENTAL VERIFICATION

Experimental verification of presented model was conducted on the turning machine by cutting of cylindrical workpiece in axial feed direction. Cutting tool edge was parallel to the feed direction to have the conditions of orthogonal cutting. As workpiece material pure copper was used. The workpiece had special radial slots (see on fig.3a), inclined to the tangent tool path to make different workpiece angles.

a b

Fig.3 Experimental specimen (a) and setup (b)

Axial feed rate was fixed at 4 mm/rev to have the conditions of two-dimensional deformation around the center of cutting width. Experimental specimen and setup are shown on fig.3. Mechanical and thermal properties of workpiece material are pointed in Table 1. During the experiment undeformed chip thickness (depth of cut), rake angles and workpiece angles were varied. Experimental conditions listed in Table 2.

Table 1. Mechanical and Thermal Properties of Copper

Tensile yield strength (MPa)	Ultimate tensile strength (MPa)	Percent elongation	Thermal capacity ($\times 10^6$Joule/($m^3\cdot$deg))	Temperature conductivity ($\times 10^{-6} m^2$/sec)
108	243	51.8	3.81	94.5

In result of experiment it was assumed that K=0.7 for calculation of burr height according to (16). Average value of shear strain ε in (10) was accepted to 5. As was found in experiment constant Φ_m for copper is approximately equal to 0.5 radians.

Table 2. Experimental Cutting Conditions

Cutting speed (m/sec)	15 (fixed)
Radial Depth of Cut (mm)	0.1 0.2 0.3 0.4 0.5
Axial Feed Rate (mm/rev)	4 (fixed)
Exit Angle (degree)	90 – 122
Rake Angle (degree)	-5, 0, 5, 10, 20,
Coolant	Air cutting
Tool nose radius (mm)	0

After each experiment actual exit angle was controlled and burr height and thickness were measured by Laser Measurement System [13] and compared with theoretical values, which were calculated by the program created in Mathcad 2001. The results of comparison are pointed in fig.4-6.

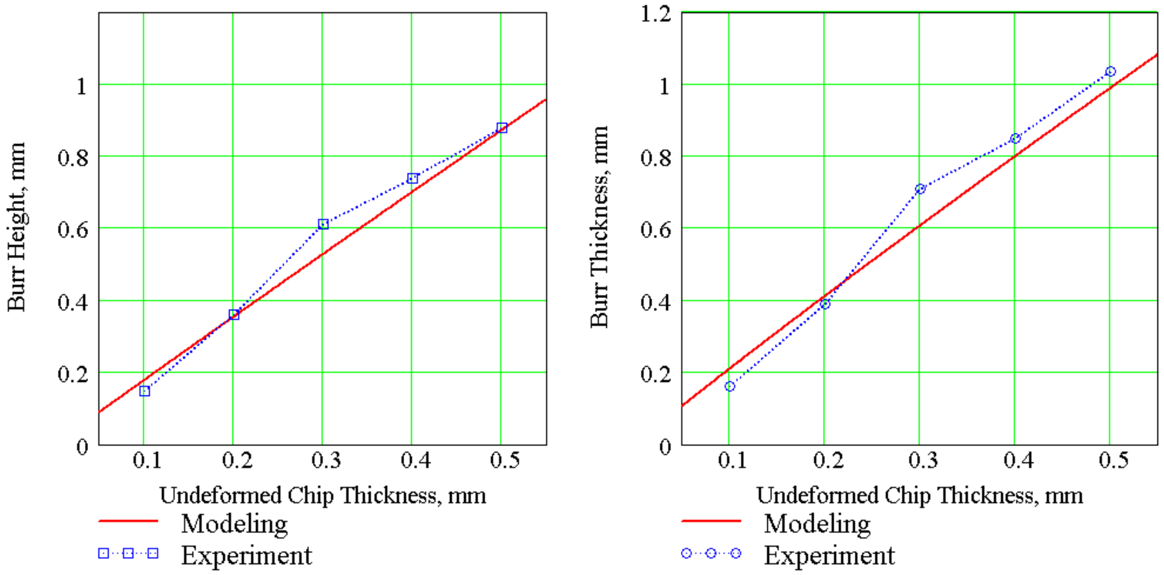

Fig.4 Burr Dimensions under Different Undeformed Chip Thickness (rake angle 20°, workpiece angle 90°)

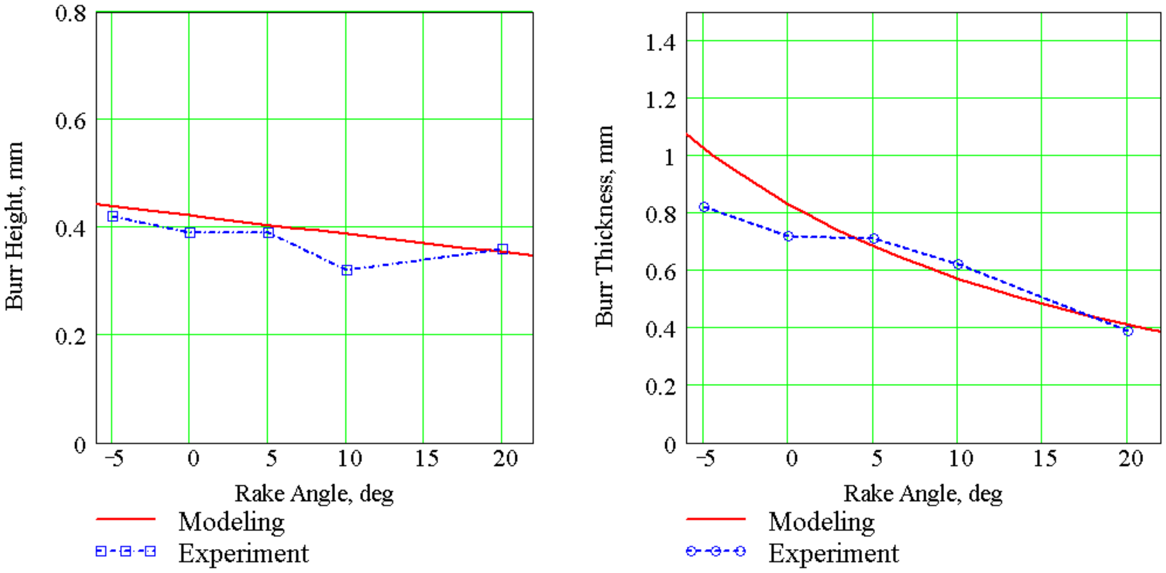

Fig.5 Burr Dimensions under Different Rake Angles
(Undeformed Chip Thickness 0.2 mm, workpiece angle 90°)

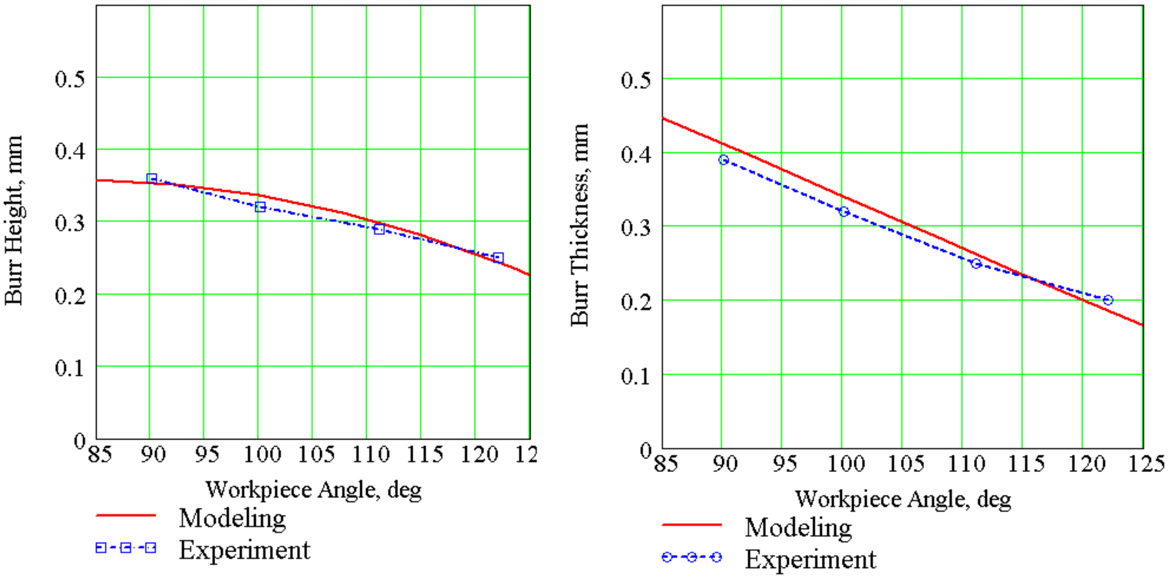

Fig.6 Burr Dimensions under Different Workpiece Angles
(Undeformed Chip Thickness 0.2 mm, rake angle 20°)

4. RESULTS AND DISCUSSION

From the figures 4-6 good correspondence can be observed between predicted and experimental burr dimensions. Maximum deviation of experimental and calculated data is 22% for rake angle -5°. In other cases this deflection is less that 20%. This result shown the possibility that presented model can be used for burr prediction. One of the advantages of the model is that its application is very convenient because its input data are only mechanical and thermal constants of workpiece material. Thus it is possible to find burr dimensions instantly if only constant parameters are known.

Since the model was verified only for copper, in the future it is necessary to test it for other workpiece materials to spread the application of this model for wider range.

5. ACKNOWLEDGEMENT

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REFERENCES

[1] Gillespie L.K. and Blotter P.T, : The Formation and Properties of Machining Burrs. *Transaction of the ASME Journal of Engineering for Industry,* Vol.98, pp. 64-74, 1976.

[2] Nakayama K and Arai M: Burr Formation in Metal Cutting. *Annals of the CIRP*, Vol.36/1, pp.33-36, 1987.

[3] Ko S.-L. and Dornfeld D.A.: A Study on Burr Formation Mechanism. *Journal of Eng. Materials and Tech.,* Vol. 113, pp.75-87, 1991.

[4] Chern G.-L. and Dornfeld D.A.: Burr/Breakout Model and Experimental Verification, *Journal of Eng. Materials and Tech.,* Vol. 118, pp.201-206, 1996.

[5] Nashimura M., Chang Y.P., Dornfeld D.A.: Analysis of Burr Formation Mechanism in Orthogonal Cutting. *Journal of Manuf. Sci. and Eng*., Vol. 121, pp.1-7, 1999.

[6] Park I., and Dornfeld D.A.: Modeling of Burr Formation Processes in Orthogonal Cutting by the Finite Element Method. *ESRC Report,* No.93-34, Dec., University of California at Berkely, 1994.

[7] Vinogradov A.A.: *Physical base of drilling of intractable materials by cemented-carbide tools*, Kiev, 1985.

[8] Kachanov L.M.: *Basis of the Theory of Plasticity.* Moscow, 1969.

[9] Toropov A.A., Baron Yu.M.: Mathematical Description of Burr Formation Mechanism in Planning. *6th International Conference "Precision Surface Finishing and Deburring Technology-2000"*, Saint-Petersburg, pp.70-80, 2000.

[10] Loladze T.N.: *Strength and Wear Resistant of Cutting Tools*, Moscow, 1982.

[11] Toropov A.A.: *The Prediction and Minimization of Machining Burrs by Burrs Formation Models*. Ph.D. Dissertation, S.-Petersburg, S.-Pb. State Technical University, 1999.

[12] Kushner V.S.: *Thermo-Mechanical Theory of Continuous Cutting of Plastic Metals*. Irkutsk, 1982.

[13] Ko S.-L.: Development of Burr Measurement System using Laser and Its Application. *4th Japan-Korea Joint Technical Conference on Surface Finishing and Burr Technology,* Incheon, pp.66-76, 1999.