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Experimental study of burrs formed in feed direction when turning aluminum alloy Al6061-T6

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Abstract

The paper represents an experimental study of the burr formation mechanism in feed direction. The influence of tool angles and workpiece angles, as well as and other cutting conditions on burr dimensions is considered. The work contains experimental graphs of burr cross-sections obtained using a laser measurement system at various stages of burr formation. The analysis of the experimental work shows that, depending on the cutting conditions, a few mechanisms of burr formation can be discerned: sideward burr formation, bending of the uncut part of allowance, and the shearing of residuary material at the final stage. This study could be useful in the search for optimal tool geometry for burr minimization and for the modeling of a burr formation mechanism.

Keywords: Burr; Feed direction; Turning

1. Introduction

The presence of burrs on the edges of parts is the cause of various problems in manufacturing. Consequently, the deburring processes are included in manufacturing. The additional deburring operations increase the production cost and these additional expenses may contribute up to 30% of the total product price [1]. Furthermore, deburring normally requires a significant amount of time. This, coupled with the deburring cost, increases as the amount of burrs rises.

Presently, about 100 deburring methods have been developed [2]. The selection of an appropriate deburring method depends on the dimensions and the location of the burr. Thus burr sizes must be controlled for the optimal choice of a deburring process or cutting parameters for burr minimization. One of the ways to solve this problem is to accumulate the experimental data about burrs and then to develop expert system using the compiled database. The other way is to make analytical models of burr formation processes. However the latter method requires a clear understanding of burr formation mechanism which is based on experimental observations of burr development processes.

Significant success in this field has been achieved in the study and modeling of burr formation in orthogonal and oblique cutting [3–7]. However, the burrs formed in feed direction normally have the largest dimensions and therefore cause bigger problems in deburring. There are many research papers devoted to the study of burr formation in feed direction [8–12]. However the existing studies are mostly concentrated on final burr geometry whereas the direct observations of burr formation process have not been investigated. The application of cinematic techniques [8] and acoustic emission technique [9] did not provide any data about variation of burr cross-section during burr formation. The so-called ‘destructive method’, applied to the observations of burr formation in drilling [12], cannot be used for small sensitive burrs since it can damage the burr, resulting in incorrect burr form. The burr measurement system [13] used in this study is based on the scanning of the workpiece edge by a laser. This method provides data with satisfactory reliability without any destruction of work material, and the combination of two graphs obtained from scanning the two

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surfaces which form the workpiece edge gives the real view of burr form in cross-section.

In spite of significant success in studying burr formation in feed direction, the mechanism of that process remains unclear. It particularly concerns the determination of the nature of forces predominant in the process. Two kinds of forces can cause burr formation: those acting on the tool rake face and those acting on the clearance face. Determining the prevalent forces is an important aspect since it would provide the basis for burr modeling and would help to control burr formation processes. The influence of tool lead angle has also been studied insufficiently despite the significant influence of that parameter on burr dimensions. The same can be said of the combined influence of workpiece and lead angles.

This paper is devoted to the study of the burr formation process in turning. Turning is a comparatively simple machining operation. However, if we understand the burr formation mechanism in the simple case and can model it, then we can describe burr formation mechanism by applying reasonable assumptions to more complicated cases such as face milling and drilling.

The paper considers the case of burr formation when tool is unworn. Short-time cutting of aluminum alloy Al6061-T6 by tungsten carbide tool does not produce any significant tool wear. Thus the experiments can be regarding as a cutting using a perfectly sharp tool. Besides, aluminum alloy Al6061-T6 is one of the widespread work materials which plastic properties are sufficient to allow complete burr formation in feed direction without brittle failure of a burr. These points determined the choice of tool and work materials for the given experimental work.

2. Experimental setup and procedure

The experiments on burr formation were carried out on a CNC turning machine tool. The experimental setup, tool and burr geometry are shown in Fig. 1. The length L of the workpiece was controlled for every experiment in order to prevent significant vibrations which in turn causes specific noise, worsens surface roughness and changes burr dimensions.

K10 grade of tungsten carbide–cobalt alloy was chosen as a cutting tool material. Al6061-T6 belongs to the group of silicon aluminum alloys. According to the classification [14], K10 grade is recommended for turning, milling, drilling and boring of silicon aluminum alloys, and thus it is suitable for the given experiments.

Table 1 presents tool geometry used in the experiments, and Table 2 lists the cutting conditions. The cutting conditions were selected in order to exclude built-up-edge formation in experiments.

Burr height h and burr thickness b were measured after every experiment using the laser measurement system [13] as shown in Fig. 2, and average values of burr dimensions

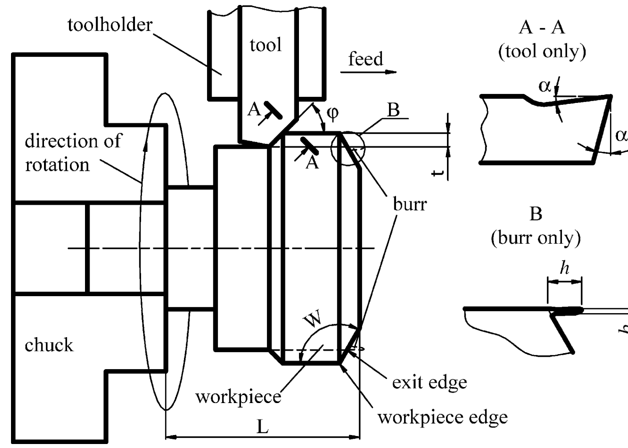

Fig. 1. Experimental setup, tool geometry and final burr dimensions.

were calculated. Burr dimensions b and h are shown in Fig. 1. Special experiments were executed to allow observation of the burr formation process. The essence of the method is as follows. The machining was stopped at various distances from the exit surface, starting from the point when the tool major edge reaches the workpiece edge. The burr formed at each stage was scanned using the laser measurement system along the two surfaces, which form the workpiece edge. The two graphs obtained from the scanning of those surfaces were combined to get a cross-section of the burr. This process was done for each step until the burr was fully formed. Using the described method, the development of burr was observed for all lead angles listed in Table 1. The cutting conditions used in these experiments are listed in Table 3.

3. Experimental results and discussions

3.1. Influence of lead angle

Fig. 3 shows the influence of the lead angle ϕ on the burr dimensions for the cutting conditions listed in Table 3. The stages of burr development for those conditions are presented in Figs. 4–6. The experimental data show that burr formation mechanism depends significantly on the lead angle.

For small lead angles, the formation of the burr is most probably related to the formation of sideward (or Poisson) burr comprehensively investigated by Nakayama and Arai [3]. When the major tool cutting edge and machining surface form an angle of $180°-\phi$ as shown in Fig. 7(a), the formation of side burr is not possible because of the high rigidity of material. When the tool major cutting edge reaches and goes beyond the workpiece edge, this angle becomes $W-\phi$. Fig. 7(b) shows this situation when $W=90°$ and $\phi=30°$. In this state, the top of the uncut part becomes weak and the stresses exerted by the tool tend to deform

Table 1
Tool geometry used in experiments

Rake angle α (deg)	Clearance angle α_c (deg)	Lead angle ϕ (deg)	Inclination of major cutting edge (deg)	End cutting-edge angle (deg)	End relief angle (deg)
−5, 0, +5, +10, +20	5, 10, 15, 20	16, 32, 47, 66, 81	0	5	5

Table 2
Cutting conditions used in experiments

Cutting speed v (m/min)	Feed f (mm/rev)	Depth of cut t (mm)	Workpiece angle W (deg)
800	0.05, 0.1, 0.15, 0.2	0.5, 1.0, 1.5, 2.0	90, 109, 118, 133, 147

sideward the topmost part of the allowance. This process is presumed to occur ahead of the tool rake face in the chip formation zone and depends on the stress state in this zone. When the lead angle is 16°, this deformation is most likely caused by the Poisson effect, i.e. the lateral flow of material under the action of normal stress. The thickness of sideward burr depends on the angle $W-\phi$ [3], and for the constant $W=90°$, the smaller the lead angle ϕ, the thinner the burr that forms. When the lead angle is 16°, the burr is so thin that it is removed by the next revolution of the workpiece since tool feed f exceeds the thickness of the burr in the direction of feed b_f (see Fig. 7). In this case, each revolution of the workpiece produces a new side burr of the same size as is shown in the experimental graphs (see Fig. 4).

When the lead angle is 32 or 47°, bending becomes a predominant factor in the burr formation mechanism because the rigidity of the uncut part, determined by the angle $W-\phi$, is reduced. In this case, with every revolution of the workpiece a new portion of material bends sideward extending the burr formed during the previous revolution. However, the extent of bending of the previous burr allows some portion of the material at the top of the burr to be cut off during the next revolution of the workpiece. This results in a burr whose height is smaller than the depth of cut t. The less rigid the material (the less the angle $W-\phi$), the greater the extent of bending and the bigger the burr forms (see Fig. 3).

When the lead angle is 66°, the stresses that arise due to cutting combined with the rigidity of material result in the deformation of the remaining part of allowance without cutting off the tip of the burr. Consequently, the burr height is equal to the depth of cut in this case (see Fig. 5).

When the lead angle is 81°, the formation of a burr starts before the tool major cutting edge reaches the workpiece edge (see Fig. 6). After the burr starts to form, the removal of the remaining part of allowance takes place close to the tool tip because the material has sufficient rigidity to allow cutting only in this area. As a result when the tool tip reaches

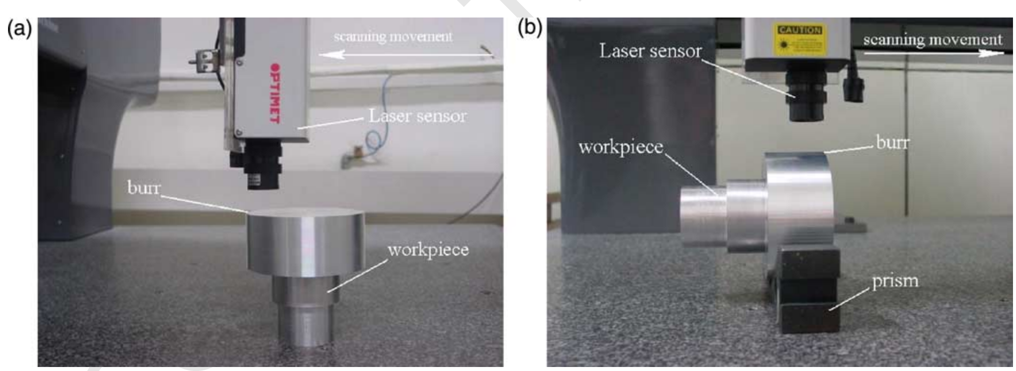

Fig. 2. Measurements of a burr using the laser measurement system: (a) along exit surface, (b) along machining surface.

Table 3
Constant conditions used in experiments

Cutting speed v (m/min)	Feed f (mm/rev)	Depth of cut t (mm)	Workpiece angle W (deg)	Rake angle α (deg)	Clearance angle α_c (deg)	Inclination of major cutting edge (deg)	End cutting-edge angle (deg)	End relief angle (deg)
800	0.1	1	90	0	10	0	5	5

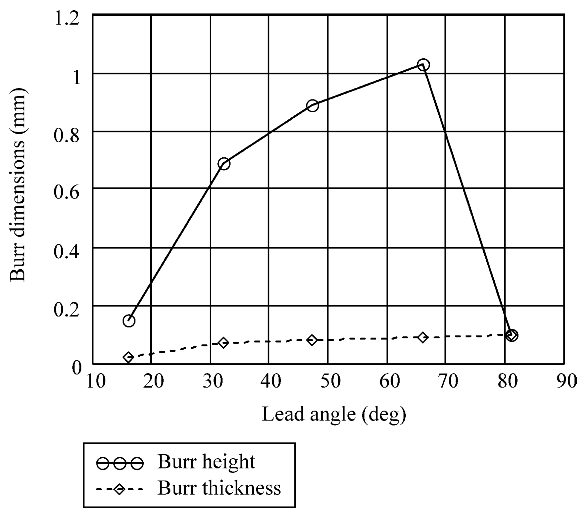

Fig. 3. Burr dimensions vs. tool lead angle (cutting conditions as in Table 3).

the exit edge, the remaining part of the material becomes progressively thinner in this zone, and the final step of burr formation is accompanied by a shearing of the work material resulting in a burr of a small height *h* (see Fig. 6).

It should be noted that the final stage of burr formation for a tool with a lead angle of 66° is unstable. That is, the burr can form with or without tearing off the burr body from the workpiece as experimental observation has shown. Perhaps this combination of lead angle and workpiece angle for a given material, together with cutting conditions, characterizes a scenario wherein a burr can be formed in either way.

3.2. Influence of depth of cut

Fig. 8 shows the influence of depth of cut on burr height. It can be seen that for a lead angle of 16°, the burr height is independent of depth of cut, whereas for a lead angle of 32 or 47°, the burr height increases proportionate to the depth of cut. This means that the increase of depth of cut for the same feed and lead angle increases the number of revolutions needed to cut the remaining triangular part of allowance after the major tool edge reaches the workpiece edge. An increase in the number of revolutions leads to an increase in the amount of material bent sideward and transformed into burr, which results in an increase of the burr height.

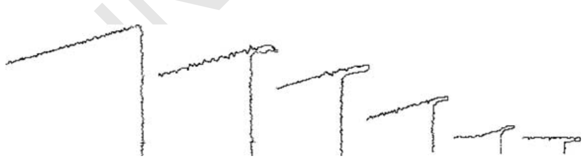

Fig. 4. Stages of burr formation for lead angle $\phi = 16°$ (cutting conditions as in Table 3).

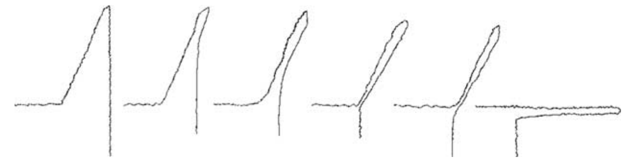

Fig. 5. Stages of burr formation for lead angle $\phi = 66°$ (cutting conditions as in Table 3).

3.3. Determination of forces that cause burr formation

The formation of the feed-burr can be theoretically related both to the stresses that arise as a result of chip formation, and to the stresses acting on the tool clearance face. This represents one of the unsolved problems in burr formation mechanics, which is the determination of the kinds of forces that cause burr formation. It is known that decreasing the clearance angle leads to the increase of forces on the clearance face, while an the increase of the rake angle causes the reduction of forces acting on the tool rake face. Fig. 9 shows the influence of those angles on burr dimensions. It can be seen that the clearance angle does not have any significant influence on burr dimensions, but increasing the rake angle does cause considerable reduction of burr thickness and height.

Indeed the stresses that arise as a result of chip formation are more significant than those under the tool clearance face. Fig. 10 shows typical stress fields in the form of isochromatic fringes observed in the cutting of celluloid [15]. It can be seen that the stress field, which appears ahead of the tool spreads deeper below the cutting surface than that which arises under the clearance face. This proves that stresses in the shear plane are more considerable than those under the clearance face. Thus the formation of feed-burr is caused by the stresses that arise in the chip formation zone, confirming our assumptions. Furthermore, the depth of the stress field that arises ahead of the tool is greater when the tool rake angle is smaller, as seen in Fig. 10. The depth of that field is most likely interrelated with the burr thickness and this explains the increase of burr thickness when the tool rake angle decreases.

3.4. Combined influence of feed and tool rake angle

At the same time, the formation of sideward burr is closely related with other cutting conditions such as

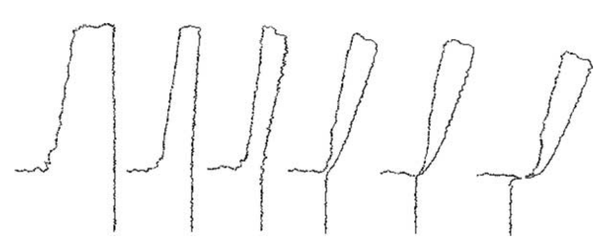

Fig. 6. Stages of burr formation for lead angle $\phi = 81°$ (cutting conditions as in Table 3).

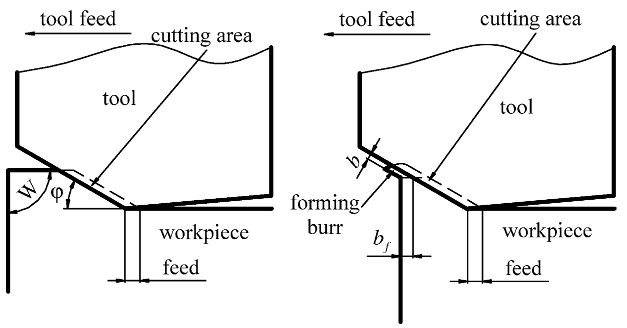

Fig. 7. Schematic illustration of cutting when tool approaches the exit surface.

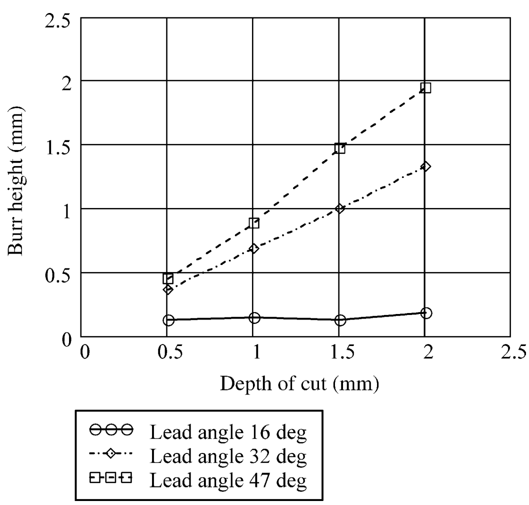

Fig. 8. Burr height vs. depth of cut when cutting with tools of various lead angles (other cutting conditions as in Table 3).

undeformed chip thickness a (or feed f). Fig. 11 shows the influence of feed on burr dimensions for a lead angle of 47° and two rake angles. As expected, when the tool rake angle is $\alpha=0$ the burr dimensions grow almost in a linear fashion as feed increases. However, this growth is rather slight. That influence of feed on burr dimensions can be explained by the causes of burr formation. It has been shown that this burr forms due to the action of stresses, which arise as result of chip formation. However, the variation of undeformed chip thickness (or feed) does not significantly influence the stress state in the chip formation zone, especially when the cutting velocity is high. This leads to the conclusion that a change of feed (or undeformed chip thickness) does not have a profound influence on the dimensions of a feed-burr.

However, when tool rake angle is high, say 20°, the stresses in the chip formation zone decrease and the burr becomes very thin. If the burr thickness in feed direction b_f (see Fig. 7b) is less than feed f, then the burr formed on the workpiece edge during the previous revolution of the workpiece can be cut off in the next revolution. During that next revolution, a new burr of the same size is formed and then cut off again and so on until the tool tip reaches the exit edge. This mechanism corresponds well to the experimental data shown in Fig. 11(b). When the feed was set at $f=0.05$ mm/rev, the measured burr thickness was $b=0.04$ mm with a corresponding burr thickness in feed direction $b_f=b/\sin(\phi)=0.04/\sin(45°)=0.057$ mm. In this case $b_f>f$, and so the burr cannot be cut off. When the feed was set to $f=0.1$ mm/rev, the measured burr thickness was $b=0.05$ mm with $b_f=b/\sin(\phi)=0.05/\sin(45°)=0.071$ mm. In this case $b_f<f$, and so the burr is cut off and cannot be extended further, which results in a burr of small height h.

3.5. Combined influence of lead angle and workpiece angle

Fig. 12 represents the influence of workpiece angle on burr height for various lead angles. The experiments show that the increase of workpiece angle leads to a significant decrease of burr height for every lead angle, and at a certain value of W the burr disappears. This effect can be caused by two factors. The first is the increasing rigidity (angle $W-\phi$) of the remaining part of allowance, which occurs when

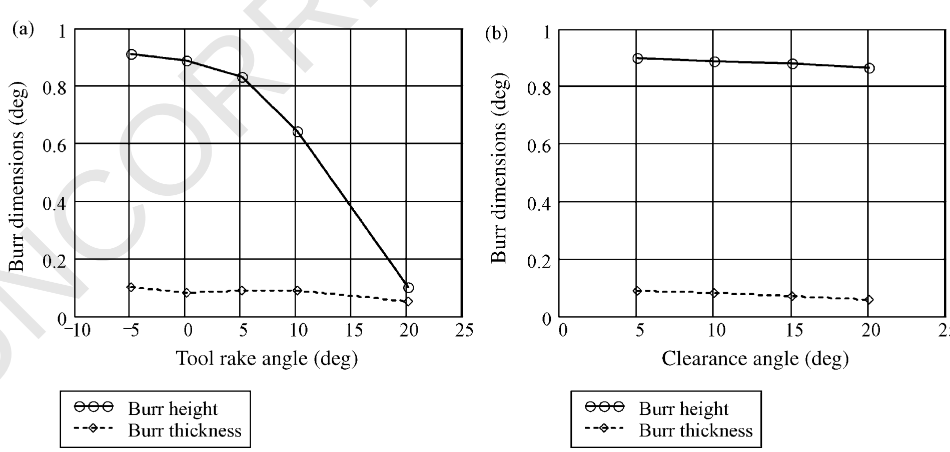

Fig. 9. The influence of tool rake angle (a) and clearance angle (b) on burr dimensions (cutting conditions: (a) $\alpha_c=10°$, the rest as in Table 3; (b) $\alpha=0°$, the rest as in Table 3).

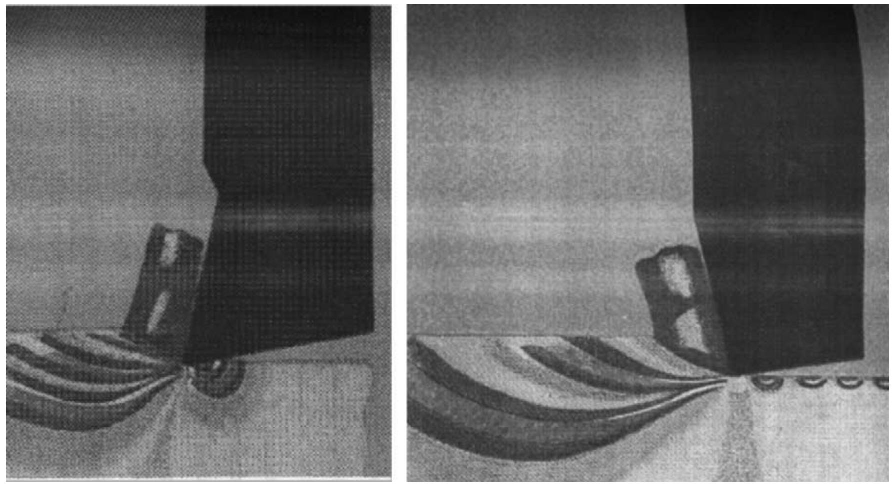

Fig. 10. Fields of isochromatic fringes observed in orthogonal cutting of celluloid [10].

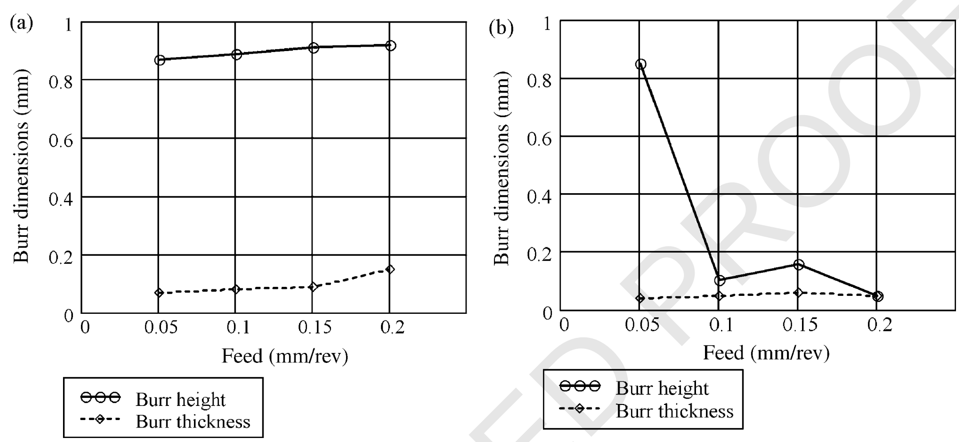

Fig. 11. Burr dimensions vs. feed when cutting with a tool having a lead angle of 47° and various rake angles [(a) rake angle $\alpha=0$, (b) rake angle $\alpha=+20°$; other cutting conditions as in Table 3].

the workpiece angle increases for a given lead angle. In this case the effect of bending becomes less significant while the Poisson effect becomes more pronounced, resulting in a smaller burr. This burr is cut off and then re-occurs during each revolution of the workpiece, just as the previously considered situation with $W=90°$ and $\phi=16°$. This situation is most likely to occur when cutting with tools having a lead angle of 16 or 32°. The second possible factor is that in a cross-section of a burr the depth and the direction of plastic deformation change when the workpiece angle varies. Using the solution to the problem of plastic bending of a wedge exerted by uniform pressure [16], we can assume that the deformation field of the remaining part of allowance in the cross section is restricted by line AB of isosceles triangle ABC as shown in Fig. 13 (burr thickness is enlarged for better visualization). Angle β characterizing the depth of deformation can be obtained geometrically as

$$\beta = 90° + \frac{\varphi}{2} - \frac{W}{2}. \qquad (1)$$

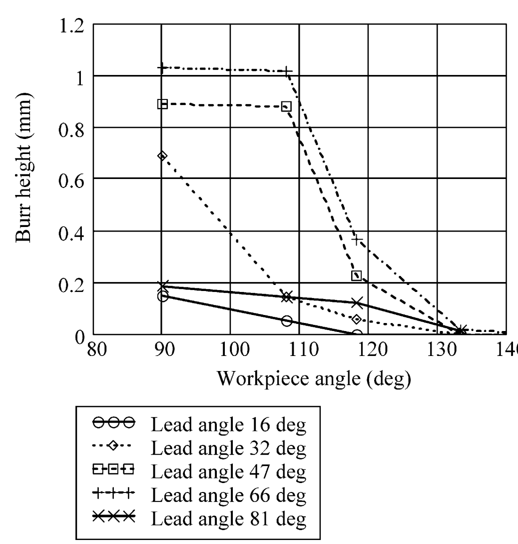

Fig. 12. Burr height vs. workpiece angle when cutting with tools of various lead angles (other cutting conditions as in Table 3).

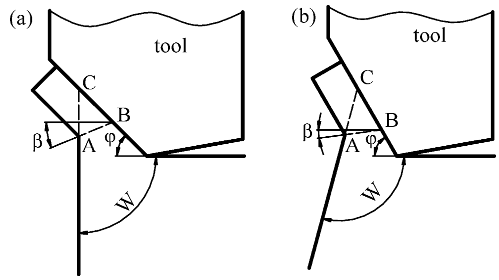

Fig. 13. Variation of angle β under different lead angles and workpiece angles: (a) $\phi=45°$, $W=90°$; (b) $\phi=75°$, $W=105°$.

Subsequently, even though angle $W-\phi$ remains constant, angle β can be different, as is shown in Fig. 13. Furthermore, the smaller β makes it more probable that the burr will be sheared at the final stage as in Fig. 13(b), resulting in a small burr. The larger β tends to lead to bending of the material, and in this case a larger burr can be expected.

Subsequent studies of the combined influence of lead angles and workpiece angles will be necessary, including further experimental observation of burr development. This is the essential aspect since it could clarify the mechanism of burr formation, which will be an effective starting point for the modeling of burr formation.

4. Conclusion

The mechanism of burr formation in feed direction when cutting aluminum alloy Al6061-T6 using a sharp tool depends essentially on tool geometry, workpiece angle, and feed. The mechanism is determined mainly by the stress state in the chip formation zone, though stresses on the tool clearance face have a very slight influence on burr formation. The increase of the tool rake angle leads to a favorable change of the stress state in the chip formation zone, which results in a considerable reduction of burr dimensions.

The rigidity of the remaining part of allowance is described by the angle $W-\phi$. When this rigidity factor is high, the formation of the burr is caused by the Poisson effect, i.e. by the lateral flow of material under normal pressure, producing small sideward burr. When the rigidity $W-\phi$ becomes low, the formation of burr occurs due to the bending of the uncut part of allowance. For the very low angle $W-\phi$, the final stage of burr formation is accompanied by shearing of the uncut part of allowance resulting in a burr of small height.

If the thickness of the burr b_f is less than feed f, then the burr is cut off and re-occurs with each revolution of the workpiece. If the thickness of the burr b_f exceeds feed rate f, then the height of this burr extends with each turn of the workpiece. The result of this is that for certain lead angles, the burr height grows as a linear function of the depth of cut t.

From this study, a few general tendencies can be extracted in burr minimization strategy. These are:

- increase of tool rake angle,
- decrease of tool lead angle,
- increase of workpiece angle by producing proper chamfers or radii on the workpiece edge before machining,
- the suitable increase of feed rate under appropriately selected high rake angle.

The investigated mechanisms of burr formation are probably common for all materials which plastic properties are similar to those of aluminum alloy Al6061-T6. For more plastic materials, such as copper, or when lateral flow of work material is more pronounced, bigger sideward burrs should be expected. For rather brittle materials, like cast iron, the considered burr formation mechanisms might not be applicable since the deformations occurred in burr formation should lead to the brittle failure of the burr. Subsequent studies should clarify the range of materials, for which the burr formation mechanisms in feed direction are common.

Further studies should be focused on the search for optimal tool geometry that can effectively minimize burr size or prevent its formation altogether and satisfy the limitations of tool performance. The results of this research will also be useful for subsequent studies and for the modeling of burr formation mechanism in feed direction for face milling and drilling in order to find optimum conditions where burr dimensions can be predicted and controlled.

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References

[1] L.K. Gillespie, Deburring precision miniature parts, Precision Engineering 4 (1) (1979) 189–198.
[2] L.K. Gillespie, Worldwide trends of burr technology and present status in the USA, in: Proceedings of the Sixth International Conference Precision Surface Finishing and Deburring Technology, St-Petersburg, 21–23 Sept. 2000, pp. 6–52.
[3] K. Nakayama, M. Arai, Burr formation in metal cutting, Annals of the CIRP 36 (1) (1987) 33–36.
[4] S.-L. Ko, D.A. Dornfeld, A study on burr formation mechanism, Journal of Engineering Materials and Technology 113 (1991) 75–87.
[5] G.-L. Chern, D.A. Dornfeld, Burr/breakout model development and experimental verification, Journal of Engineering Materials and Technology 118 (1996) 201–206.

[6] M. Hashimura, Y.P. Chang, D.A. Dornfeld, Analysis of burr formation mechanism in orthogonal cutting, Journal of Manufacturing Science and Engineering 121 (1999) 1–7.
[7] F. Klocke, S. Hoppe, R. Fritsch, FE-modeling of burr formation in orthogonal cutting, in: Proceedings of the Seventh International Conference on Deburring and Surface Finishing, University of California, Berkeley, 7–9 June 2004, pp. 47–56.
[8] K. Takazawa, S. Xiong, K. Kitajima, T. Miyake, Y. Tanaka, Burr formation mechanism in drilling and its control, in: Proceedings of the Third International Conference Precision Surface Finishing and Burr Technology, Seoul, 21–23 Nov. 1994, pp. 232–245.
[9] N.A. Lukoto, Z. Katz, On burrs formation in drilling, in: Proceedings of the Seventh International Conference on Deburring and Surface Finishing, University of California, Berkeley, 7–9 June, 2004, pp. 17–28.
[10] J. Kim, D.A. Dornfeld, Development of a drilling burr control chart for stainless steel, Transactions of NAMRI/SME 28 (2000) 317–322.
[11] A.K. Kaminise, R.A. Goncalves, A.R. Machado, M.B. de Silva, Properties of burrs formed when cutting AISI 1045 carbon steel in turning operation, in: Proceedings of the Seventh International Conference on Deburring and Surface Finishing, University of California, Berkeley, 7–9 June 2004, pp. 127–136.
[12] S.-L. Ko, J.-K. Lee, Analysis of burr formation in drilling with a new-concept drill, Journal of Materials Processing Technology 113 (2001) 392–398.
[13] S.-L. Ko, Development of burr measurement system using laser and its application, in: Proceedings of the Sixth International Conference Precision Surface Finishing and Deburring Technology, St-Petersburg, 21–23 Sept. 2000, pp. 109–123.
[14] Classification of Carbide According to Use, ISO (1975) 513.
[15] T.N. Loladze, Chip Formation in Metal Cutting, Mashgiz, Moscow, 1952 (in Russian).
[16] L.M. Kachanov, Fundamentals of the Theory of Plasticity, Science, Moscow, 1969 (in Russian).