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Study on effect of tool edge geometry on residual stress in metal cutting

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Abstract
The objective of this study is to investigate the effects of tool edge geometry and friction on residual stress through orthogonal cutting experiments and finite element analysis (FEA), and to clarify the mechanism of residual stress formation. The workpiece material used was A6061 aluminium alloy, and the analysis was conducted using the FEA software DEFORM-2D. Instead of a simple circular arc, the tool edge roundness was modelled as an elliptical shape, configured as either horizontally elongated or vertically elongated. This approach represents one of the novel aspects of this study. FEA results revealed that tool edge roundness, edge geometry, and friction significantly influenced material flow and stress distribution within the workpiece. A stagnation zone was observed in front of the tool edge, where the material first moved upward and was then pushed downward beneath the edge. The extent of this upward movement varied depending on the edge geometry: it was smaller for the vertically elongated ellipse and larger for the horizontally elongated ellipse. This deformation history during tool passage manifested as residual stress in the machined surface. According to the FEA results, the vertically elongated elliptical edge promoted compressive residual stress, whereas the horizontally elongated elliptical edge tended to result in a more tensile residual stress state. In addition, friction at the tool–chip interface affected both material flow and the resulting residual stress state.

Cutting, FEM, Tool edge radius, Residual stress, Machined surface

1. Introduction

Cutting processes are widely employed in various industrial fields, including automotive, aerospace, and medical applications. When cutting is used as a finishing operation, it is well known that residual stresses are generated on the machined surface of the workpiece. Because residual stresses affect the durability, fatigue life, and deformation of workpieces [1, 2], a deeper understanding of the underlying mechanisms is essential for preventing or mitigating their occurrence. To date, numerous studies have investigated residual stresses induced by cutting, and it has been reported that their magnitude and distribution vary depending on machining conditions and material properties [3-5]. However, the generation mechanism itself remains insufficiently understood [6].

Therefore, this study investigates the influence of tool edge radius, tool edge geometry, and friction on the tool rake and flank faces on residual stress through a series of two-dimensional cutting experiments. In addition, analytical investigations are conducted using the finite element method (FEM) with the software DEFORM-2D to examine their effects on residual stress under two-dimensional cutting conditions. In this study, the influence of pure mechanical interaction at the tool edge, such as indentation, shear and the material flow, on the residual stress distribution was investigated by selecting cutting speeds that minimize thermal effects. This approach allowed us to suppress variations in flow stress and thermal expansion/contraction caused by temperature and strain rate changes. By comparing and discussing the results obtained from both experiments and simulations, the objective of this work is to clarify the mechanism of residual stress generation in cutting processes depending on the tool edge geometry and the friction between the tool and the workpiece.

2. Influence of Tool Edge Geometry on Residual Stress

2.1. Analytical Modelling

A finite element model was developed using the FEM simulation software DEFORM-2D to predict cutting forces and residual stresses during machining. Using this model, analyses were conducted under extremely low cutting speeds to investigate the effects of tool edge radius, tool edge geometry, and friction conditions.

Figure 1 shows the simulation model employed in this study. The model consists of three components: the workpiece, the tool, and the bottom die. The bottom die is a virtual plate introduced to prevent chip–workpiece contact that would otherwise cause interruption of the computation during analysis.

Figure 2 and Table 1 summarize the tool edge geometries used in the simulations. The tool edge geometry was defined by the combination of the major axis Sa and minor axis Sb of an elliptical arc at the tool edge.

In addition, the cutting simulations incorporated an exponential friction model using a user subroutine in DEFORM, expressed by Eq. (1), where τ_t and σ_t are the frictional stress and normal stress at tool-chip interface, k and λ are the yield shear stress and the frictional characteristic constant respectively [7]. As a larger λ value corresponds to higher friction, a value of λ = 1.0 was used to represent dry cutting, while λ = 0.1 was used to simulate lubricated conditions when cutting oil was applied [8]. Cutting speed was 0.1 m/min, depth of cut was 0.1 mm, rake angle and clearance angle were 6 degrees and 5 degrees respectively.

$$\tau_t = k\left(1 - e^{\frac{\lambda\sigma_t}{\kappa}}\right) \qquad (1)$$

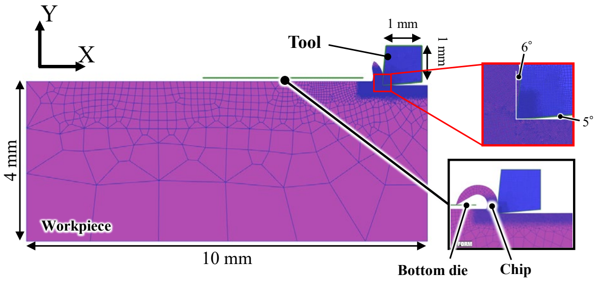


Figure 1. Simulation model.

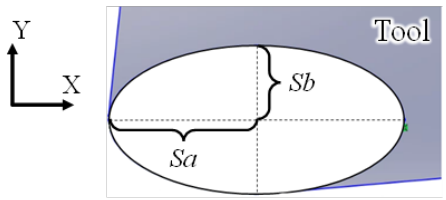


Figure 2. Tool edge profile.

Table 1 Tool edge parameters.

	(*Sa*, *Sb*) [µm]		
Ellipse① ($Sa < Sb$)	(30, 60)	(30, 60)	
Round ($Sa = Sb$)	(15, 15)	(30, 30)	(40, 40)
Ellipse② ($Sa > Sb$)	(60, 30)	(90, 30)	(120, 30)

2.2. Simulation results

Figure 3 shows the velocity distribution inside the workpiece during cutting for tool edge radii of *R* = 15 µm to *R* = 40 µm. The material flow is visualized using vector arrows. It can be observed that the material first flows upward toward the tool edge and then descends along the tool profile.

When comparing the material flow for different edge radii, the upward flow height decreases as the tool edge radius decreases from *R* = 40 µm. Consequently, the area of material that is pushed downward toward the machined surface by the tool edge becomes smaller. In addition, as the edge radius increases, the stagnation zone—shown in dark blue arrow—at the tool tip becomes noticeably larger.

Next, the effect of friction is examined. Regardless of the magnitude of the tool edge radius, the stagnation zone becomes smaller under the low-friction condition (λ = 0.1), and the upward displacement of material increases. Differences also appear in the velocity of the material along the rake face, indicating that chip formation behaviour is influenced by friction.

Figure 4 shows the velocity distribution inside the material when the tool edge geometry is varied. Compared with the case of *R* = 30 µm shown in Fig. 3(c), the vertically elongated edge geometry in Fig. 4(a) produces a larger stagnation zone at the tool tip. In contrast, the horizontally elongated elliptical geometry exhibits a smaller stagnation zone.

For the vertically elongated elliptical shape, the increased stagnation zone suppresses the upward flow of material in front of the tool. Furthermore, regardless of tool geometry, reducing friction decreases the size of the stagnation zone and increases the height of the upward material flow.

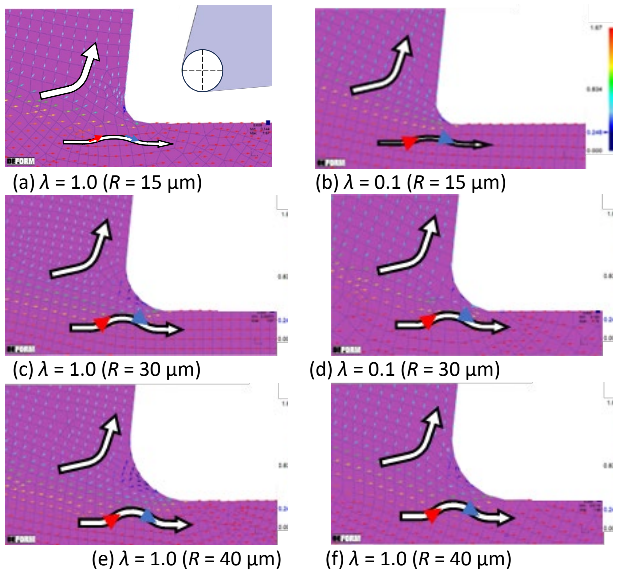


Figure 3. Analysis results of velocity distribution with round tool edge.

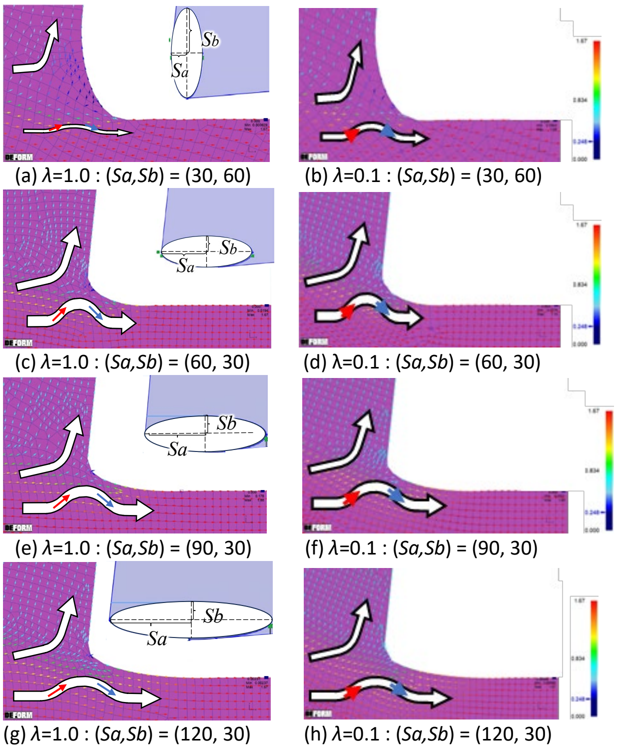


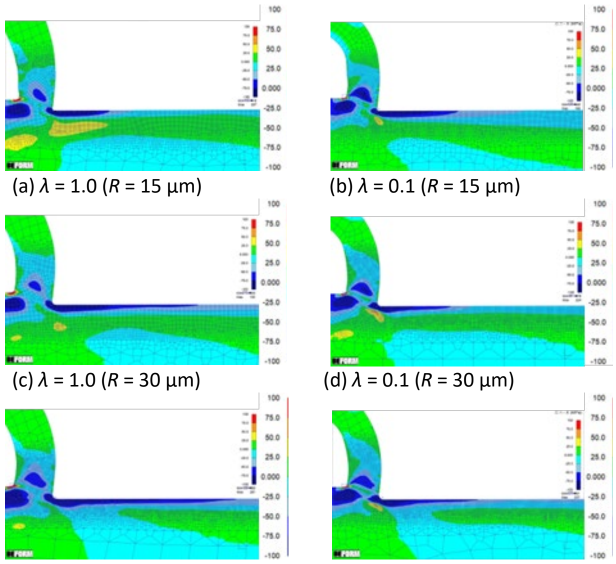
Figure 4. Analysis results of velocity distribution with elliptical tool edge.

Figure 5 shows the distribution of the residual stress σ_x for circular tool edge radii ranging from *R* = 15 µm to 40 µm. A compressive residual stress is generated along the machined surface after the tool passes. As the edge radius increases, this compressive residual stress extends over a wider region and its magnitude also becomes larger.

Furthermore, when the friction coefficient is reduced, the region of compressive residual stress becomes wider at *R* = 15 µm.

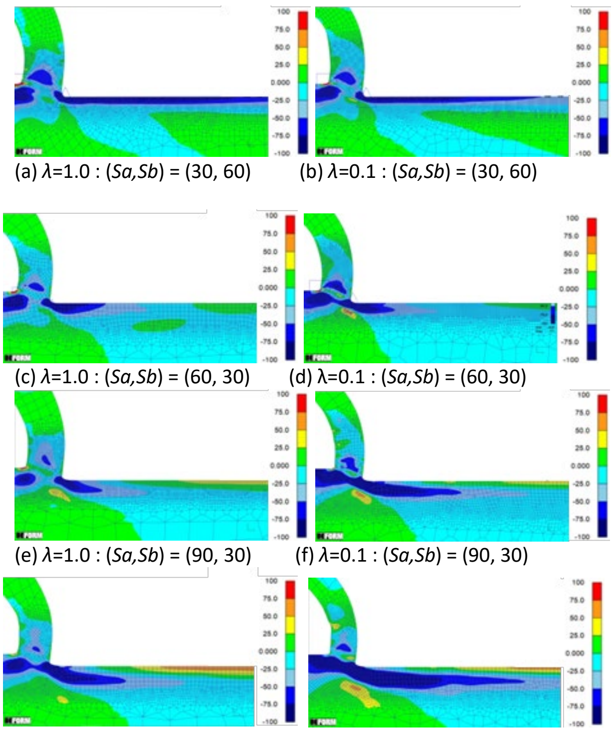
Figure 6 shows the σ_x distribution after cutting when the tool edge is modelled as vertically or horizontally elongated elliptical shapes. For the vertically elongated elliptical geometry, the residual stress distribution is similar to that of the circular geometry with *R* = 40 µm, but the compressive residual stress extends to a greater depth compared with the *R* = 40 µm case.

In contrast, the horizontally elongated elliptical geometry results in a distinctly different residual stress distribution. Immediately after the tool passes, compressive residual stresses below –50 MPa appear near the surface, but the compressive tendency weakens along the machined surface and shifts toward tensile stress. As the major axis in the X-direction (Sa) increases, this trend becomes more pronounced. At Sa = 120 µm, a wide region of tensile residual stress exceeding +50 MPa appears near the machined surface.



(a) λ = 1.0 (R = 15 µm) (b) λ = 0.1 (R = 15 µm)
(c) λ = 1.0 (R = 30 µm) (d) λ = 0.1 (R = 30 µm)
(e) λ = 1.0 (R = 40 µm) (f) λ = 0.1 (R = 40 µm)

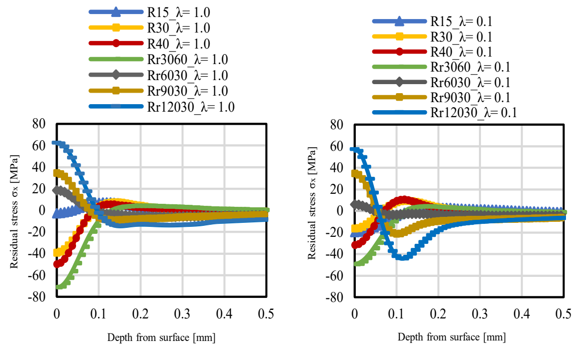
Figure 5. Analysis results of stress distribution in cutting direction (σ_x) with round tool edge.



(a) λ=1.0 : (Sa,Sb) = (30, 60) (b) λ=0.1 : (Sa,Sb) = (30, 60)
(c) λ=1.0 : (Sa,Sb) = (60, 30) (d) λ=0.1 : (Sa,Sb) = (60, 30)
(e) λ=1.0 : (Sa,Sb) = (90, 30) (f) λ=0.1 : (Sa,Sb) = (90, 30)
(g) λ=1.0 : (Sa,Sb) = (120, 30) (h) λ=0.1 : (Sa,Sb) = (120, 30)

Figure 6. Analysis results of stress distribution in cutting direction (σ_x) with elliptical tool edge.

Figure 7 shows the residual stress distribution in the surface layer for different circular edge radii and for different elliptical tool edge geometries. At the machined surface (horizontal axis = 0), the residual stress transitions from tensile to compressive in the following order: horizontally elongated elliptical edge, circular edge, and vertically elongated elliptical edge. This tendency was observed regardless of the friction coefficient.



(a) λ=1.0 (b) λ=0.1

Figure 7. Analysis results of residual stress (σ_x) after cutting.

3. Experimental validation

Orthogonal cutting experiments were conducted on the end face of an A6061 aluminium alloy workpiece to investigate the effects of tool edge geometry and friction on the resulting residual stress.

Figure 8 shows the experimental setup. A square tool holder was mounted on the spindle, the spindle rotation was fixed, and extremely low-speed cutting was performed by feeding the table. The experimental conditions and tool edge geometry are summarized in Tables 2 and 3. Residual stress on the machined surface was measured using a portable X-ray residual stress measurement device (PULSTEC µ-360) with the cosα method. The measurement conditions included a collimator diameter of 1.0 mm, an incident angle of 25°, and an irradiation time of 30 seconds. Cr-Kα radiation was used as the characteristic X-ray source. In this experiment, an increase in tool edge radius led to higher cutting forces. Moreover, the vertically elongated elliptical geometry produced larger cutting forces than the horizontally elongated elliptical geometry.

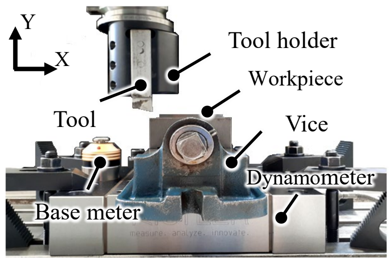


Figure 8. Experimental setup.

Table 2 Experimental conditions.

Workpiece material		A6061
Tool material		Tungsten carbide (K10)
Cutting speed	m/min	0.050
Depth of cut	mm	0.10
Width of cut	mm	4.0
Rake angle	deg.	6
Clearance angle	deg.	5
Lubricant		DH30

Table 3 Tool edge parameters.

	(Sa, Sb) [µm]		
Ellipse① ($Sa < Sb$)	(32, 52)		
Round ($Sa = Sb$)	(10, 10)	(25, 25)	(40, 40)
Ellipse② ($Sa > Sb$)	(53, 31)		

Figure 9 shows the measured residual stress distributions for circular tool edge radii *R*. For *R* = 10 µm and *R* = 25 µm in Fig. 9 (a), the residual stress exhibits a tensile distribution under the DRY condition, whereas it becomes compressive under the WET condition.

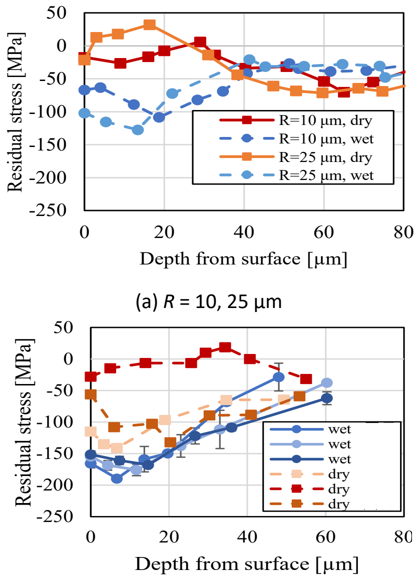
In Fig. 9(b), as the radius increases to *R* = 40 µm, the residual stress tends to shift further toward compression under both DRY and WET conditions, and under WET cutting, a highly compressive residual stress exceeding −150 MPa is observed.

Figure 10 shows the residual stress distributions for different elliptical tool edge geometries. A comparison between the horizontally elongated ellipse in Fig. 10(a) and the vertically elongated ellipse in Fig. 10(b) indicates that the vertically elongated geometry exhibits a stronger compressive residual stress tendency, particularly under the wet condition. In addition, comparison between dry and wet conditions demonstrates that the wet condition consistently results in more compressive residual stress, irrespective of the tool edge geometry.

The FEM analysis predicts that the vertically elongated elliptical tool edge generates higher compressive residual stress than the horizontally elongated geometry, and this trend is experimentally confirmed under the wet condition. However, under the dry condition, the experiments didn't show a clear difference in the residual stress between the horizontal and vertical ellipse tools. Regarding the residual stress results for the circular tool shown in Fig. 9, the experimental results under the dry condition also did not fully support the FEM analysis.

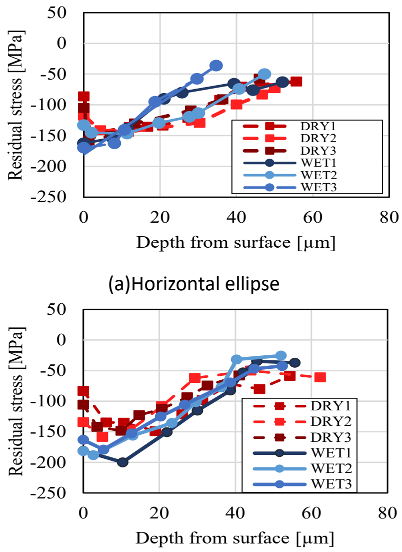
Under the dry cutting condition, a built-up edge acting as dead metal or severe adhesion was observed to form in front of the tool tip during the orthogonal cutting experiments. The formation of this dead-metal-type built-up edge effectively modified the actual tool edge geometry during cutting and reduced the effective contact area between the tool and the machined surface. As a result, the geometric differences between the horizontally and vertically elongated elliptical edges may have been obscured, leading to no clear difference in the measured residual stress under the dry condition.

It should be noted that this built-up edge formation, which was not accounted for in the FEM model, represents a limitation of the present experimental validation and may partly explain the discrepancy between the numerical and experimental results under dry conditions.



(b) *R* = 40 µm

Figure 9. Effect of tool edge radius and lubricant on residual stress on machined surface.



(b) Vertical ellipse

Figure 10. Effect of tool shape and lubricant on residual stress on machined surface.

5. Conclusions

The effects of tool edge geometry and the frictional conditions at the tool–chip interface on residual stress were investigated through finite element analysis and orthogonal cutting experiments.

(1) The depth-wise distribution of residual stress in the surface layer increased in the compressive direction as the tool edge radius became larger. This trend was consistent with that observed in the two-dimensional cutting experiments.

(2) The influence of vertically and horizontally elongated elliptical edge on residual stress was found to differ. Both the FEM analysis and the cutting experiments under the wet condition demonstrated that the vertically elongated elliptical geometry promotes higher compressive residual stress compared with the horizontally elongated geometry.

(3) According to the FEM analysis, higher friction at the tool–chip interface tended to promote compressive residual stress. However, in the cutting experiments under the dry condition, dead-metal-type built-up edge formation altered the effective cutting conditions, and experimental results fully supporting this tendency could not be obtained.

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