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Finite element analysis of the effect of tool edge radius on residual stresses when orthogonal cutting Ti6Al4V

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Abstract. A finite element analysis is presented based on the machining simulation software AdvantEdge FEM to investigate the effect of tool edge radius on residual stresses when orthogonal dry cutting Ti6Al4V alloy. Five types of cemented carbide tools with different tool-edge radius were used in the simulation. The results obtained from this study show that the residual stress at the machined surface is residual compressive stress and become more tensile than compressive beneath the machined surface for five radii. Tool-edge radius affects the magnitude and distribution of residual stress significantly, the magnitude of residual compressive stress, the thickness of compressive layer and the magnitude of residual tensile stress increase with the increase of tool-edge radius. A theoretical guidance for the control of residual stresses and optimization of tool-edge design can be provided in this study.

1. Introduction

Metal cutting process generally involves a large amount of plastic deformation, high temperatures and pressures. Residual stresses induced after metal cutting have a major influence on working performance and fatigue life of a machined component. Moreover, high speed and dry cutting technology are generalized and applied in recent years. Therefore, understanding and predicting the distribution features of residual stresses is of a crucial importance.

Residual stresses in the machined surface and the subsurface are affected by cutting tool, workpiece, tool/workpiece interface, and cutting parameters [1].In the past, many researchers have attempted to determine relationships between tool geometry and residual stresses. Hua [1] investigated the effects of workpiece hardness, tool geometry as well as cutting conditions on the residual stress distribution in the hard machined surface by using a newly proposed hardness-based flow stress model employed in an elastic-viscoplastic FEM formulation. Chang [2] studied the effects of different tool geometry parameters (rake angle, relief angle and edge radius) on residual stresses in the ultra-precision turning process by using finite element software. An [3] investigated the influence of geometrical parameters of cutting tools on machining process and surface quality of difficult-machining aircraft materials (GH169) under dry cutting condition with cubic boron nitride cutting tools, examined the effects of rake angle, clearance angle and cutting edge radius on surface residual stress. Yue [4] used the commercial finite element software ABAQUS to investigate the generation procedure of saw tooth chip when orthogonally cutting hard steel GCr15 with PCBN tools. It was shown that cutting edge preparation has a great impact on cutting procedure. Under the same cutting condition, the residual stress of sharp-up edge, honed edge and chamfered edge increases in turn, and the three kinds of cutting edges have the same change rules for residual stress. Nasr [5] presented An Arbitrary-Lagrangian－Eulerian (A.L.E.) finite element model to simulate the effects of cutting-edge radius on residual stresses when orthogonal dry cutting austenitic stainless steel AISI 316L with continuous chip formation. Larger edge radius induced higher R.S. in both the tensile and compressive regions, while it had almost no effect on the thickness of tensile layer and pushed the maximum compressive stresses deeper into the workpiece. Mohammadpour [6] developed a finite element analysis based on the nonlinear finite element code MSC.Superform for investigating the effect of cutting speed and feed rate on surface and subsurface residual stresses induced after orthogonal cutting.

In the present study the machining simulation software AdvantEdge FEM is used to investigate the relationship between tool edge radius and residual stresses in dry orthogonal cutting of Ti6Al4V alloy. A theoretical guidance for the control of residual stresses and optimization of tool-edge design can be provided in this study.

2. Finite element modelling

2.1. Material properties

The workpiece material in this study is titanium alloy Ti6Al4V, and the cutting tool material is cemented carbide. Material properties of Ti6Al4V and cemented carbide are given in Table1.

Tab 1. Material properties of Ti6Al4V and cemented carbide [7, 8, 9]

properties	cemented carbide	Ti6Al4V
Density(kg/m^3)	14500	4428
Young's modulus(GPa)	580	114
Possion's ration	0.22	0.34
Conductivity(W/(m • K))	90	7.3
Coefficient of thermal expansion(×10-6/℃)	5.4	9.6
Specific heat(J/(kg • ℃))	220	526
Melting temperature(℃)		1659.85

The Johnson-Cook material model was used to represent the workpiece material constitutive behavior. This model is suitable for modeling case with large strains, high strain rates, and temperature dependency.The model is represented as Eq. (1):

$$\sigma=\left[A+B\varepsilon^{n}\right]\left[1+c\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \tag{1}$$

Where σ is the material flow stress, A is the initial yield stress, B is the hardening modulus, C is the strain rate dependency coefficient, n is the work hardening components, m is the thermal softening coefficient, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate, ε is the plastic strain, T_r is the room temperature, and T_m is the melting temperature. The Johnson-Cook model parameters for titanium are given in Table 2.

Tab 2. Johnson-Cook model parameters for Ti6Al4V [7]

A/MPa	B/MPa	C	m	n
1080	1007	0.013	0.77	0.635

2.2. Cutting conditions

In this study, rounded-edge tools with different radius are applied to simulate in orthogonal dry cutting. Table 3 gives the cutting conditions that are required in the simulation.

The dimensions of cutting model are 4 mm in length, 2 mm in height. Adaptive meshing techniques and updated Lagrangian FEM formulation in conjunction with continuous meshing are used in this model [10]. The maximum and minimum element size of tool are 0.3 mm and 0.03 mm, respectively. Fig.1 shows the initial finite element mesh on tool and workpiece.

Tab 3. Cutting conditions

Parameters	Value
Rake angle (°)	10
Clearance angle (°)	16
Edge radius (mm)	0.02、0.04、0.06、0.08、0.1
Depth of cut (mm)	0.3
Feed rate (mm/r)	0.1
Cutting speed (m/min)	140

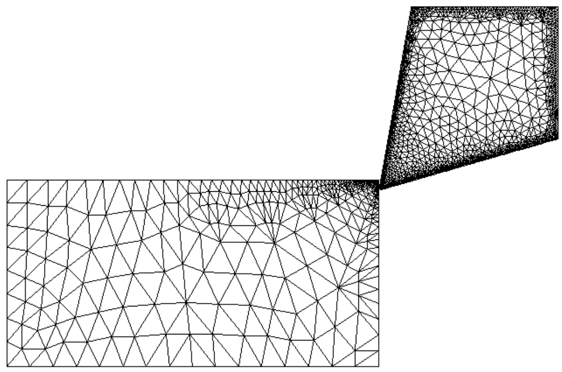

Figure 1. Initial finite element mesh

3. Simulation results and discussion

3.1. Residual stress distribution
Fig.2 shows the distribution of residual stress for different edge radius, respectively. The residual stresses induced at the machined surface are residual compressive stresses and become more tensile than compressive beneath the machined surface. The prime reason for the residual stress distribution is that the combination of thermal and mechanical impacts plays a crucial role in inducing residual stress, the residual compressive stresses at machined surface are affected more by mechanical impacts than thermal, the residual tensile stresses beneath the machined surface is just the reverse[11, 12, 13].

3.2. Residual compressive stress
Fig.3 shows the maximum magnitude of residual stresses for different edge radius. It can be seen from this figure that the magnitude of residual compressive stresses increases with the increase of tool-edge radius. Fig.4 shows the maximum depth of residual compressive stresses layer for different edge radius, where the increase of tool-edge radius increases the maximum depth. The prime reason for the above-mentioned phenomena is that the increase of tool-edge radius leads to longer contact between tool and workpiece, increasing the frictional effect on the deformation zone and the material plastic deformation [1, 2, 3, 5].

3.3. Residual tensile stress
It can be seen from Fig.5 that the magnitude of residual compressive stress increases as well with the increase of tool-edge radius. The increase of tool-edge radius produces larger contact area between tool and workpiece, which generates more heat due to friction and the rate of heat dissipated is slower

than heat generated. Eventually the cutting temperature rises (see Fig.5) and Residual tensile stress increases [3, 5, 6].

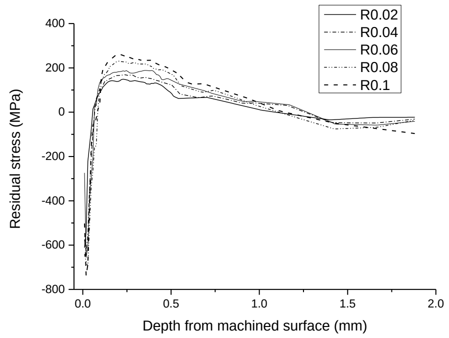

Figure 2. Results of the residual stress distribution

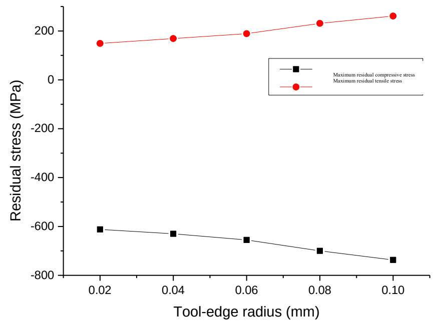

Figure 3. Effect of tool-edge radius on the maximum residual stress

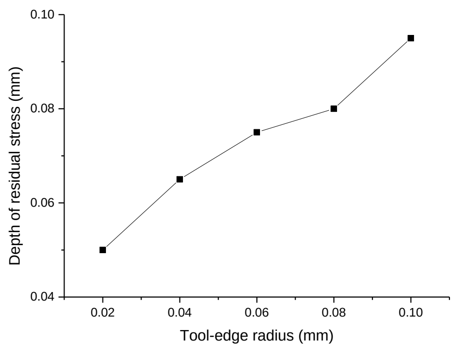

Figure 4. Effect of tool-edge radius on the maximum depth of residual compressive stress layer

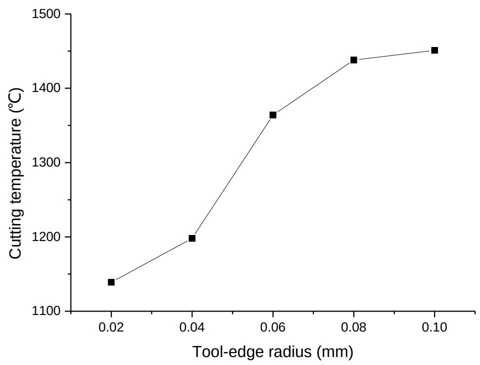

Figure 5. Effect of tool-edge radius on the maximum cutting temperature

4. Conclusions

AdvantEdge FEM is used to simulate orthogonal dry cutting of Ti6Al4V Alloy using cemented carbide tools to investigate the effect of tool edge radius on residual stress, it can be concluded that:

(1) The residual stress at the machined surface is residual compressive stress and become more tensile than compressive beneath the machined surface for five radii.

(2) Tool-edge radius affects the magnitude and distribution of residual stress significantly, the magnitude of residual compressive stress, the thickness of compressive layer and the magnitude of residual tensile stress increase with the increase of tool-edge radius.

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