Evaluation of cutting edge micro-geometry in milling of 316L stainless steel: A study based on FEM

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Research Article

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Abstract

The objective of this research is to simulate the cutting edge micro-geometry in machining a stainless steel (SUS-316L). The accurate finite element method (FEM) are verified by cutting edge preparation and cutting experiments at solid carbide end mills. The cutting edges are prepared by drag finishing. Utilizing this preparation method, the prepared cutting edges have three kinds of roundness profile with symmetry (K=1) and asymmetry (K=0.5 and K=2), which is considered for the modelling. We explored the chip formation, plastic strain and residual stress, mises stress and distribution of temperature, and also tool-chip contact length and the effective rake angle $\gamma_{\text{eff}}$ with three different symmetry (K=1) and asymmetry (K=0.5 and K=2) also be examined. The simulation results suggest that waterfall tools (K=0.5) can increase stress strain and peak cutting temperature compare with other cutting edge micro-geometry. At the same time, the trumpet tools (K=2) also have a great influence on sub-surface and surface stress distribution. Therefore, the cutting edge segment on the flank face $S\alpha$ has significant the metal cutting process.

1. Introduction

In metal cutting, the finite element method (FEM) can save experimental costs and obtain data that are difficult to measure in the experiment [1]. The simulation model is very important in predicting chip formation, calculating the strain, strain rate, temperature and stress distribution on the cutting edge and working surface, and has been favored by many scholars [2]. The micro-geometry of cutting edge is related not only the size but also the shape determine the process condition [3–4].

The design of cutting edge micro-geometry and its influence on machining performance have been a research topic in metal cutting for a long time. It is known that sharp tools are not withstand high mechanical and thermal stresses, such machining operations, therefore, tool manufacturers introduced different types of tool edge preparations such as symmetrical and asymmetrical rounding edge designs. The reproducible production of tailored cutting edge geometries can be carried out via various processes. Common state of the art preparation methods are brushing [5], dry and wet abrasive jet machining [6] as well as drag finishing [7]. The micro-geometry of the cutting edges were adjusted by using the preparation process, usually based on empirical knowledge or in iterative research steps. Therefore, through a lot of experimental efforts, the performance and accuracy of the applied preparation process have been improved.

And if the cutting edge is not symmetrical, it is impossible to align the cutting edge profile with the fitted circle. A number of methods to characterize cutting edge microgeometries exist in literature. Wyen et al. [8] analyze and compare different ways of characterization cutting edge shape, driven by the aim to reduce measurement uncertainty. Due to these disadvantages, Denkena et al. [9] established the form-factor method (also referred to as K-factor method) that contains additional parameters for a more precise cutting edge description. In particular, the consideration of asymmetric edge shapes is a major advantage due to its high effect on the process behavior of cutting tools [10].
The proper selection of cutting edge micro-geometry can be possible once the behavior of material flow around the cutting edge is well understood. The effect of edge preparation on the mechanics of cutting has been investigated by many researchers by using various methods such as analytical [11, 33], computational [35], and experimental [12] methods. Childs et al. [12] analyzed the influence of material properties, chip/tool friction conditions, and cutting edge radius on the chip formation based on the FEM. At the same time, compared the stress, strain, strain rate and temperature changes in the primary and secondary shear zones. Krebs et al. [14] prepared by pressurized air wet abrasive jet machining and investigated the mechanical tool load an asymmetrical edge shape dependent on the $S_\alpha$ and $S_\gamma$.

Bernard et al. [13] comprehensively studied the influence of asymmetrical and symmetrical cutting edge roundness affects the process forces, stagnation zone and ploughing effect by FEM and the reliability of the model is verified by cutting temperature experiment. Maiss et al. [15] established the law of the influence of the asymmetric cutting edge roundness on the machined surface. When $K < 1$, the increased contact between the flank and the machined surface will lead to greater underground normal stress, plastic deformation of the material and improve the quality of the machined surface. When $K > 1$, the minimum undeformed cutting thickness increases, reducing the normal stress caused by material rebound. Schulze et al. [16] studied the cutting edge micro-geometries significantly influence the physical cutting effects on the workpiece surface residual stress and strongly influence of thermal strains localized plastic deformation in the surface layer by Orthogonal cutting (FEM). Shen et al. [17] analyzed the significant influence of $K = 0.5$ and $K = 2$ in machining nickel-based 718. The surface and subsurface residual stress obtained by combining experiment and numerical simulation. For asymmetric rounding cutting edge with $K = 0.5$, the contact area between the tool-chip much longer, thus the friction and tensile residual stress tend to be higher. And for $K = 2$, the between tool and machined surface, higher ploughing depth leads to higher compression stress delaying crack initiation. Recently, Liu et al. [18] used numerical simulation to analyze the roundness of three different cutting edges. For larger honing radius tools, the excessive compression ploughing effect and the surface residual stress are more tensile.

In this paper, the design of three kinds of cutting edge micro-geometry ($K = 0.5$, $K = 1$, $K = 2$) is to understand the mechanics of complex material flow in orthogonal cutting SUS-316L stainless steel. This paper focuses on the experimental and FEM study on the effects of tool edge micro-geometry in terms of chip flows, temperature, and stress distributions. This paper explains the cutting deformation mechanism of different structures of cutting edge, and provides reliable data support for customizing the cutting edge shape. Among them, $K = 0.5$ and $K = 2$ have significant advantages in the actual cutting application process.
2 Materials And Methods

In this section, the design of the cutting edge micro-geometry was shaped to $K = 0.5$ (waterfall edge), $K = 1$ (rounded edge) and $K = 2$ (trumpet edge). The slip field theory, friction and stress theory analysis were proposed to analyze the cutting edge micro-geometry.

2.1 Micro-geometry edge preparation

There is no doubt that the design of the micro geometry of the cutting edge has become important for achieving high performance in machining using cutting tools. The cutting edge microgeometry describes the transition between the rake and the flank face of a cutting wedge. In normal, cutting edge microgeometry is commonly described as an ideal arc with radius $r_e$. Cutting edge radius $r_e$ is determined by a circle formed by the rake flank face of the tool. Limited measuring points, there are many circles with uncertain radius, so many measuring points are needed to fit the micro-shape of the cutting edge to characterize the micro-geometry of the cutting edge.

There are many uncertain characterization data from limited measurement points. Therefore, many measuring points are required to comprehensively characterize the micro-shape of cutting edge. Only one parameter $r_e$ is not enough to completely characterize the complex geometry of cutting edge, as can be seen in Fig. 1.

Denkena et al. [19] developed the form-factor method, which describes not only symmetrical but also asymmetrical cutting edges with the parameters $S_\alpha, S_\gamma, S, \Delta r, K$ and $\varphi$. The tool macro-and microgeometry can be effectively distinguished by the effective rake angle $\gamma_{\text{eff}}$ of the tool [20]. The $\gamma_{\text{eff}}$ is determined by the actual rake angle at a contact point when the workpiece and the tool contact during the cutting process.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>From-factor</td>
</tr>
<tr>
<td>$A$</td>
<td>Plastic equivalent strain in (JC) (MPa)</td>
</tr>
<tr>
<td>$S_\gamma$</td>
<td>Cutting edge segment on the rake face</td>
</tr>
<tr>
<td>$B$</td>
<td>Strain related constant in (JC) (MPa)</td>
</tr>
<tr>
<td>$S_\alpha$</td>
<td>Cutting edge segment on the flank face</td>
</tr>
<tr>
<td>$C$</td>
<td>Strain-rate sensitivity constant in (JC)</td>
</tr>
<tr>
<td>$A_\gamma$</td>
<td>Rake face</td>
</tr>
<tr>
<td>$m$</td>
<td>Thermal softening exponent in (JC)</td>
</tr>
<tr>
<td>$A_\alpha$</td>
<td>Flank face</td>
</tr>
<tr>
<td>$n$</td>
<td>Strain-hardening parameter in (JC)</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Apex angle</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Melting temperature of the work material (JC)</td>
</tr>
<tr>
<td>$r_e$</td>
<td>Edge radius of the tool (μm)</td>
</tr>
</tbody>
</table>
The main objective of cutting edge treatments is to shape the cutting edge into a consistent geometry. Accordingly, possible chipping after grinding or burrs after sintering operations can be removed. Dragging finish machining technology is a relatively suitable technology for preparing the micro-geometry of the cutting edge of the solid carbide end mills, which only involves simple process kinematics. Through drag finishing technology, the micro-geometry of symmetric and asymmetric cutting edges is characterized by K factor and tailored three kinds of cutting edge shapes, as shown in Fig. 2. The reproducible production cutting edge geometries with three different K values tailored via drag finishing on the solid carbide end mills. Figure 2 demonstrates the cutting edge preparation process and cutting edge geometries. In order to study the specific influence of each one of the parameters $S_{\alpha}$, $S_{\gamma}$, and K the following methodical variation of the cutting edge designs is conducted. Symmetrically honed cutting edges with $S_{\alpha} = S_{\gamma}$ and $r_{\varepsilon}=0.01\mu m$ is the basis for designing asymmetric edge structures $K = 0.5$ (waterfall edge) and $K = 2$ (trumpet edge). The adapted preparation process parameters to produce all of the presented three hone designs. The abrasive medium has been preconditioned before a new microgeometry has been produced, in order to determine the preparation process parameter without any influence of abrasives wear. For each of the required microgeometries three tools of each micro-geometry edges have been produced. The microgeometry of a cutting edge can be measured by optical measurement systems.

The experiments were conducted under various combinations of three cutting edge rounding radius $r_{\varepsilon} =0.01\ mm$ and asymmetrical rounding $K = 0.5$, $K = 2$. The cutting tool, which is produced by the Guohong tool system (Wuxi) Co., Ltd (solid carbide end mills Type-D6R1), is integral straight shank R-type end mill with four cutting edges. The tool parameters are from reference [7]. In the drag finishing process, the three kinds of micro-geometries used to prepare. The abrasive medium and process parameters required for the preparation of cutting edges are from the literature [26].

By parameter $r_{\varepsilon}$ And K values, comprehensive definition the micro-geometry of the cutting edge for the following research.

To reduce uncertainties in the cutting edge characterization, we used a fitting algorithm developed by Wyen [21]. In the algorithm, the fitting area was defined iteratively as a function of edge flattening and wedge angle $\beta$ of the cutting edge. Making the fitting area user independent increases repeatability. The mathematical determination of the fitting area can be accomplished using the following algorithm. The steps described are illustrated in Fig. 3 with the indicated numbers. Following this algorithm the symmetry and asymmetry rounded cutting edge further parameters have to be used, e.g. distances between cutting edge profile and an auxiliary horizontal straight line left and right to the wedge angle bisector. For an ideal radius of $r_{\varepsilon} = 10 \mu m$, 100 evenly distributed measurement points and a measurement uncertainty for one point of $U = 0.5 \mu m$, the resulting radius uncertainty is 2% of the diameter, based on an uncertainty range of $P = 95\%$ ($k = 2$).
Table 1
Cutting edge preparation groups with measured K and \( r_\varepsilon \) values

<table>
<thead>
<tr>
<th>Tool group</th>
<th>Theoretical K-value</th>
<th>Measured 1#</th>
<th>Measured 2#</th>
<th>Measured 3#</th>
<th>Cutting edge radius ( r_\varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.5</td>
<td>0.453</td>
<td>0.58</td>
<td>0.532</td>
<td>10 ± 1µm</td>
</tr>
<tr>
<td>Group 2</td>
<td>1</td>
<td>0.987</td>
<td>1.157</td>
<td>1.078</td>
<td>10 ± 1µm</td>
</tr>
<tr>
<td>Group 3</td>
<td>2</td>
<td>1.83</td>
<td>1.75</td>
<td>1.865</td>
<td>10 ± 1µm</td>
</tr>
</tbody>
</table>

Subsequently, images using a scanning electron microscope SEM were made and the tools were measured with an optical measurement device Infinite Focus of the company ALICONA IMAGING GMBH, Graz, Austria and the measured data repeated three times.

2.2 Modelling and simulations

Finite Element simulations are performed by using the Third Wave AdvantEdge and the ALE formulation. Specifications related to the ALE formulation at the boundaries of the workpiece and of the chip Orthogonal cutting model was shown in Fig. 4a. Chip geometrical parameters are defined in. Figure 4b. The cutting tool was modeled as a rigid body with described geometry in previous section (rake angle 2°, clearance angle 8°, and edge radius 0.01µm with K = 0.5, K = 1 and K = 2) and fixed in all directions except the cutting direction.

It is assumed that the workpiece material is elastic-viscoplastic material, and the tool material is initially set as rigid, so as to simulate the physical characteristics of the process in the best way. The Johnson–Cook constitutive model developed by Johnson and Cook [22] is applied to include the strain-hardening, strain-rate, and thermal softening effects on the flow stress of the material in the primary shear zone, which is expressed as: Eqs. (1)

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

1

Experimental work was carried out in order to obtain the friction coefficient to use as an input in the FEM simulation [23]. The friction coefficient was calculated using the Coulomb model through the Eqs. (2)

\[
\mu = \frac{F_f + F_c \times \tan \gamma}{F_c - F_f \times \tan \gamma}
\]

2

where \( F_f \) represents the feed force, \( F_c \) the cutting force and \( \gamma \) is the tool rake angle. Both cutting forces were obtained experimentally [25].
The parameters in this Eq. (1) for SUS-316L is given in Table 2 [24]. The workpiece grid division is shown in Table 3. All the simulations were cutting length 3mm and the chip formation, cutting force and cutting temperature are in the stable state, where the stresses on the tool can also reach steady state, which corresponded to approximately. Analysis of cutting simulation data, select a stable cutting state, which is about half of the cutting length and cutting time between 0.0005s to 0.001s.

### Table 2
The material properties and Johnson-Cook parameters in simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Notation</th>
<th>SUS-316L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature(℃)</td>
<td>T_{room}</td>
<td>20</td>
</tr>
<tr>
<td>Melting temperature(℃)</td>
<td>T_{melt}</td>
<td>1398</td>
</tr>
<tr>
<td>Thermal softening coefficient</td>
<td>m</td>
<td>0.533</td>
</tr>
<tr>
<td>Work-hardening exponent</td>
<td>n</td>
<td>0.508</td>
</tr>
<tr>
<td>Reference strain rate</td>
<td>\varepsilon_0</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>Initial yield stress(MPa)</td>
<td>A</td>
<td>514</td>
</tr>
<tr>
<td>Hardening modulus(MPa)</td>
<td>B</td>
<td>514</td>
</tr>
<tr>
<td>Strain rate dependency coefficient</td>
<td>C</td>
<td>0.042</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>\mu</td>
<td>0.68</td>
</tr>
</tbody>
</table>

### Table 3
workpiece meshing parameters

<table>
<thead>
<tr>
<th>Simulation options</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum element size(mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Minimum element size(mm)</td>
<td>0.01</td>
</tr>
<tr>
<td>Mesh refinement factor</td>
<td>8</td>
</tr>
<tr>
<td>Mesh coarsen factor</td>
<td>3</td>
</tr>
</tbody>
</table>

A series of cutting simulation is usually used to study the cutting process of cutting edge micro-geometry: Cutting speed of 100 m/min and 150 m/min, cut set depth of 0.05 mm and 0.1mm, and immersion cooling with three types of cutting edge rounding of 0.01 mm and asymmetrical rounding $K = 0.5$, $K = 2$ in Fig. 2. SUS-316L and solid carbide end mills are selected to be the materials of the workpiece and cutting tool.

### 2.3 Experimental validation
Machining experiments using prepared cutting tools are conducted to validate the FEM simulation. The milling trials are conducted a three axis vertical machining Center (α-D14MiB). The machining system setup is schematically shown in Fig. 5. Chips are collected and cutting tools are examined using an optical microscope. The workpiece material used in the experiments is SUS-316L. The workpiece size is 100 mm× 100 mm × 50 mm. The machining conditions are the same as in the simulation. Chip size, shape, microstructure and mechanical properties are important components of the overall characterization of chips through actual end milling. Chips obtained after milling were made into a specimen. After polishing and etching the chip specimen, optical microscope was used to observe the chip morphology, and obtained the chip microscopic morphology. In cutting tests, cutting speeds was selected as \( V_c = 100 \text{ m/min} \), \( f_z = 0.1 \text{mm/z} \) with three kinds of cutting edge preparation. Experiments are replicated two times.

The physical assumptions and the numerical framework adopted for the modeling of orthogonal cutting are presented in this section.

3 Results And Discussions

3.1 Calibration of FEM simulations via chip geometry based experiments

The results of simulations were validated with corresponding experiments to check reliability of the identified model. Figure 6 shows the comparison of chip morphology obtained in simulation and experiment process under the same cutting conditions \( (V_c=100\text{m/min}), \ f_z = 0.1 \text{mm/z} \) at (three conditions \( K = 0.5, \ K = 1 \) and \( r_{β} = 10 \text{µm}, \ K = 2 \)). A detailed comparison of simulated serrated chips with microscopic chip images is shown in Fig. 6. It is observed that almost all simulated chip geometries investigated depict periodic formation of serrated and uniform sized chip segments after a large single segment. The maximum serrated chip of tooth height, pitch and valley. measured serrated chip geometry was reached. The results of measured and simulated serrated of maximum serrated chip parameters are given in Fig. 7. In addition, close agreements between the simulated and captured serrated chip shapes and morphologies are observed. The results showed that relative error of tooth height is 15.38%, 7.1%, 4% and the relative error of tooth pitch in 6.7%, 11.1%, 8.3% and in the the relative error of tooth valley in 5.9%, 16.7% 9.1% at condition of \( (K = 0.5, \ K = 1 \) and \( r_{β} = 10 \text{µm}, \ K = 2 \)), respectively. Therefore, it can be said that the simulation of different cutting edge micro-geometry and cutting parameters in this paper provides an efficient uniformity to identify other cutting characteristics which is desirable for modeling of cutting processes.

3.2 Analytical model for tool-chip interface

As shown in the Fig. 8 the honed cutting edge parameters have been defined. The quantitative parameters of cutting process vary greatly with cutting edges micro-geometry, such as effective rake
angle $\gamma_{\text{eff}}$, undeformed chip thickness $h$, contact length of rake and flank face of the tool, etc. With the increase of K value, the effective rake angle $\gamma_{\text{eff}}$ becomes growth gradually, resulting in the intensified extrusion deformation between the cutting edge and the machined surface, thus affecting the quality of the surface quality. The result of the simulation in Fig. 9 (a) (b) (c). The contact length of chip and tool, the stagnation point $S$ position and $\gamma_{\text{eff}}$ variation are simulated and analyzed. The position of the stagnation point is defined when the simulation parameter $V_c = 100$ m/min and $f = 0.1$mm/r. The contact length $l_\gamma$ between $P_\gamma$ and $S$ has a great influence on the chip flow due to the high negative effective rake angle. The result of the simulation in Fig. 9 (d) (e) (f), the sticking contact length of $l_p$ was analysed, reference [30]. The length $l_c$ of slip zone is the point of chip and rake face. With the increase of K value, the stagnation point $S$ gradually shifts to the rake face, and the $\gamma_{\text{eff}}$ at point $S$ measured $\gamma_{\text{eff}} = -51.73^\circ$ at $K = 0.5$ and $\gamma_{\text{eff}} = -36.45^\circ$, $\gamma_{\text{eff}} = -32.94^\circ$ at $K = 1$ and $K = 2$. The undeformed chip thickness $h$ also increases with the increase of K value, so that the extrusion deformation of the flank face of the machined surface increases. The contact length of chip and tool in rake and flank face at different cutting speeds and feeds were measured in Fig. 10.

3.3. Influence of variable micro-geometry on strain fields

Figure 11 indicates that the effect of micro-geometry edge design on the plastic strain and adiabatic shear zone induced on the workpiece. In metal cutting, severe deformations take place in the shearing zones and in the vicinity of the cutting edge where high strain-rates and temperatures are observed. Work material deformation behavior in primary and secondary zones is highly sensitive to the cutting conditions. As shown in Fig. 11 (plastic strain analysis) (a, b, c). In addition, the max-plastic strain zone is mainly concentrated on the rake face and the symmetric cutting edge ($K = 1$) has higher shear extrusion deformation than asymmetric cutting edge. However, with increase $S_\alpha$, the plastic strain decreases near the flank. This is due to the plowing effect, the contact area between the flank and the machined surface increases, and the material undergoes uniform plastic deformation [26].

As shown in Fig. 11 (d, e, f) (strain rate analysis), the distributions of the strain rate variables with mainly concentrated in the primary and secondary deformation zones. The FE results were observed that the strain rate focused on the adiabatic shear zone according to the cutting edge micro-geometry. The increase of strain rate gives two corollaries: (i) As $S_\alpha$ increase subface residual stress increases [27]; (ii) More strain energy is converted into heat in this area. This is the same as along the side $l_\alpha$ is related to the increase of contact length.

However, in FE simulation, the strain at the tool-chip interface and around the cutting edge is converted into temperature, as shown in Fig. 11 (h, i, g), which is consistent with [28]. Therefore, the use of finite element (FE) simulation to accurately predict the distribution of process variables (such as stress and temperature) is critical to determine the optimal cutting conditions, tool materials, edge geometry and coating to help improve the quality of the machined surface and overall productivity.
3.4. Stagnation zone and ploughing effect

In Fig. 12, the stagnation point S of the tool and the sliding speed of the material analyze the temperature distribution of the symmetrical and asymmetrical cutting edge rounding. In front of the cutting edge, there is a relatively slow material flow area, where chips and machined surfaces are formed. And this area defined the dead metal zone (DMZ). This stagnation zone was also observed by Denkena et al. [20]. On the rake face, due to the friction between the chip and the tool, the chip is extruded and deformed, and the material flow reaches the lowest level of cutting speed. The cutting temperature produces the highest temperature change here. In contrast, the tool temperatures of the three cutting edges shown are different. The maximum temperature of the symmetric tool \( K = 1 \) can reach 525 °C, while the maximum temperature of the asymmetric cutting edge (\( K = 0.5 \) and \( K = 2 \)) is around 480 °C. The maximum temperature of the tool is significantly affected by the friction heat and the heat transfer from the chip and workpiece to the tool. Through the dotted line in the figure, when \( K \) values decreases from 2 to 0.5, the contact length of flank \( l_\alpha \) until the point \( P_\alpha \) increases, the cutting temperature is gradually transferred from the rake face to the flank face. Below the stagnation point, the metal dead zone (DMZ) was forming, as shown in the white area. The temperature of the DMZ will increase with the increase of the thickness of the uncut chip, which is greatly affected by the micro-geometry of the cutting edge [4, 29, 34]. Therefore, compared with the symmetrical cutting edge, the heat transferred to the tool is less when the asymmetrical cutting edge with proper design is used. Due to the thermal softening characteristics of SUS-316L, it becomes more advantageous to process under these conditions.

3.5 Temperature distribution

The cutting temperature condition is an important parameter for studying the cutting edge micro-geometry, which has a great influence on tool wear, tool life, surface quality, machining efficiency and part accuracy. As is shown in Fig. 13, the temperature distribution is mainly concentrated in the first deformation zone, and extends to the second and third deformation zones according to the cutting edge micro-geometry. Because the cooling conditions are set in the whole simulation environment, most of the cutting temperature is taken away by the chip. With the increase of feed parameters (undeformed cutting thickness), the cutting temperature increases. However, with the same feed parameter \( f = 0.1 \text{mm}/\text{Z} \), the cutting temperature increases about 10% as the cutting speed increases from \( v_c = 100 \text{m/min} \) to \( 150 \text{m/min} \), in Fig. 14.

We can find that trumpet (\( K = 2 \)) tools can reduce the temperature of flank face compared with other tools, but trumpet tools caused the temperature of the rake face to rise. This is because the trumpet tool has a smaller \( S_\alpha \) of the tool and reduces the contact between the flank and the machined surface, thus reducing the cutting temperature. Bassett et al. [5] analyzed \( S_\alpha \) and \( S_\gamma \) effects on cutting thermal load. By keeping \( S_\gamma \) constant (\( K < 1 \) waterfall) to increase \( S_\alpha \), which increases the friction of the flank, resulting in an increase in the temperature. In addition, FEM simulation shows that the metal dead zone increases leads to more heat generation. Since symmetrical cutting edge micro-geometry tools are used in this study, the cutting temperature in middle is obtained compared with \( K = 0.5 \) and \( K = 2 \).
3.6 Residual stress analysis

In metal cutting, residual stress is the key factor to analyze the integrity of the machined surface, which has two crucial factors: mechanical load and thermal stress and volume change caused by phase transformation [30]. Figure 15 shows the formation process of residual stress in detail. This paper analyzes the influence of thermal-mechanical load on residual stress based on tool edge geometry (symmetry (K = 1) and asymmetry (K = 0.5 and K = 2)). During the cutting process, the workpiece material around and in front of the tool tip (region 1) is severely compressed by the main shear region, resulting in compression plastic deformation. The tensile residual stress is generated in the area below it (profile 1). The workpiece material is separated near the stagnation point S, the material above it generates chips, and the material below it is ploughed into the processing surface. With the advancement of cutting, the new processed material will be partially stretched by the tool behind the stagnation point S, resulting in tensile stress (profile 2). Due to the low thermal conductivity of SUS-316L, the heat energy transferred to the workpiece is trapped in the limited thickness (surface/near surface), and the concentrated heat in the surface/near surface material will make it expand rapidly, so the compressive thermal stress is generated in the surface/near surface layer during the cutting process (section 3).

By comparing the cutting edge micro-geometry of the K values, the workpiece residual stress is analyzed. Through FEM analysis, the maximum mises stress changes from K = 0.5 to K = 2. The stress on the surface of zone 1 decreased from 800MPa to 449MPa and the width of adiabatic shear zone 1 decreases. This phenomenon can be explained as follows: with the increase of K value, the area of DMZ decreases, γ eff increases, and the energy in the cutting process decreases [31]. When K = 0.5, the maximum mises stress on the profile 1 has larger than other cutting edge shapes. Larger negative γ eff will produce high thermal mechanical load, thus the normal/tangential stress on the zone 2 and penetrate into the workpiece expand in zone 3.

With the increase of cutting speed and feed rate, the residual stress increases on the surface and subsurface. In the surface/near-surface layer zone 1, the increase of compression residual stresses generated by deformation with higher plasticity deformation with K values; With the increase of deformation depth, the tensile stress on the sub-surface zone 2 increases [10, 35]. The compress residual stress increased with increasing the cutting and feed speed, the thermal effect and plastic deformation increasing as a whole. However, below the surface, the compressive residual stresses increase with an increase Sα means decreased K value. The stresses could directly affect fatigue life, corrosion resistance and component distortion. As is shown Fig. 17(c, f, i)), we can find that trumpet tools (K = 2) have little influence on residual stress compare with conventional hone edge tools (K = 1) Fig. 17 (b, e, h). Figure 17(a, d, g) with waterfall edge (K = 0.5) can greatly generated compress residual stress near the machined surface zone 1 and the maximum stress is concentrated near the tool tip. We can also get similar conclusions from [32], they found that the application of PCBN wiper inserts leads to reduce surface roughness and higher compressive residual stress. Maiss et al. [15] comprehensively described the influence of asymmetric edges on the machined surface roughness. They found that the edges with
shape factor $K < 1$ would lead to greater thermo-mechanical normal stress, resulting in plastic deformation and minimum elastic recovery, so as to obtain better surface finish. With $K > 1$, cause smaller normal stress. This paper does not validate the analysis of three cutting edge shapes on surface integrity through experiments, and the follow-up research will continue to verify.

4 Conclusions

According to the practical machining requirements, three different cutting edge geometries ($K = 0.5$, $K = 1$ and $K = 2$) are designed in this paper. Through $K$ factors characterization and finite element simulation, the chip formation, thermo-mechanical load stress, plastic strain and residual stress are analyzed in cutting SUS-316L. And verify the correctness of the model through experiments. The main conclusions are summarized as follows:

- In this paper, three cutting edge geometries $K = 0.5$ (waterfall edge), $K = 1$ (rounded edge) and $K = 2$ (trumpet edge) are designed and prepared on solid carbide end mills by drag-finishing. Through cutting experiments, the friction coefficient $\mu = 0.68$ is calculated by the cutting force and rake angle, the chip geometric parameters are analyzed, and verified the finite element model reliability.

- Through finite element analysis, it shows the micro-geometry of the cutting edge on the tool-chip contact and effective rake angle, and the maximum $\gamma_{\text{eff}} = -51.73^\circ$ is obtained when $K = 0.5$ and the longest contact length of stick zone $l_p$ and slip zone $l_c$ is obtained for $K = 2$. With the increase of cutting speed, the contact length raises.

- By analyzing the strain field, the plastic strain about three kinds of cutting edge micro-geometries produced the tool-chip interface mainly concentrated in the primary and secondary deformation zone, and focused on the adiabatic shear zone. More strain energy is converted into heat in this area, and the maximum plastic strain area is mainly concentrated on the rake face.

- The maximum temperature of the symmetric tool $K = 1$ can reach 525 $^\circ$C, while the maximum temperature of the asymmetric cutting edge ($K = 0.5$ and $K = 2$) is around 480 $^\circ$C. When $K$ values decreases from 2 to 0.5, the contact length of flank $l_\alpha$ until the point $P_\alpha$ increases, the cutting temperature is gradually transferred from the rake face to the flank face.

- Through FEM analysis, the maximum mises stress changes from $K = 0.5$ to $K = 2$. The stress on the surface of zone 1 decreased from 800 MPa to 449 MPa and the width of adiabatic shear zone 1 decreases. The trumpet tools ($K = 2$) have minimal impact influence on residual stress and waterfall edge ($K = 0.5$) can greatly generated compress residual stress near the machined surface zone 1 and the maximum stress is concentrated near the tool tip.

Declarations

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References


Figures

Figure 1

Inaccurate description of cutting edge micro-geometry with $r_\varepsilon$.
Figure 2

Solid carbide end mills: cutting edge geometries and drag finishing process
Figure 3

Steps to characterize the rounding of a cutting edge profile by a Gaussian fitted circle with a unique solution.

Figure 4

Schematic of the FE simulation model of the orthogonal cutting process with $r_e = 10$ μm.
Figure 5

(a) Experimental tests (b) Chip geometry characterization parameters

Figure 6

Verification of chip morphology obtained in simulation and experiment process at cutting speed of 100m/min and a feed of 0.1 mm/rev.
Figure 7

Analysis of the difference between experiment and simulation by chip height, pitch and valley.
Figure 8

Tool-chip contact characteristics of cutting edge

Cutting speed: $V_c=100\text{ m/min}$
Uncut chip thickness: $h=0.1\text{ mm}$
Depth of cut: $a_p=0.1\text{ mm}$
Cool condition: Immersion
Figure 9

Simulated tool-chip contact length and the effective rake angle $\gamma_{\text{eff}}$ at $V_C=100\text{m/min}$, $f=0.1\text{mm/r}$

Figure 10

Contact length at tool-chip interface for K Values and different cutting speeds
Figure 11

Influence of cutting edge micro-geometry on subsurface strain

Figure 12

Stagnation point and flow direction on material flow
Figure 13

Temperature distribution at difference cutting parameters
Figure 14

Temperature distribution of the (a) Rake face (b) Peak temperature during turning
Figure 15

Formation mechanism of residual stress

Figure 16

Demonstrates the variation of maximum effective stresses on the tool
Figure 17

Residual stress distribution of workpiece