Investigation on wear characteristics of cemented carbide tools in finish turning spherical shells of pure iron

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Abstract
A thin-walled spherical shell made of pure iron material is a key part of precision physical experiments. Tool wear characteristics of freeform surface parts are significantly different from those of single-point turning due to the movement of the contact point between the tool and the workpiece, which affects the form accuracy and surface integrity of workpiece. However, there is lack of a comprehensive understanding of the tool wear characteristics in machining pure iron materials. Therefore, we proposed the mathematical model to investigate the wear characteristics of cemented carbide tool further when spherical shell turning pure iron materials. The results show that uniform flank wear land and notable notch wear occur when turning end face, but notch wear disappears and only flank wear land exists when turning spherical shell. Based on major notch position and minor notch position, a mathematical model is developed to explain formation mechanisms of flank wear land during turning spherical shell of pure iron materials. Theoretical and experimental results show that flank wear land results from the major and minor notch movement. Spherical shell turning and end face turning have the same wear mechanisms, mainly composed of adhesive wear, diffusion wear, and oxidation wear.

Keywords Pure iron · Spherical shell turning · End face turning · Notch wear · Flank wear

1 Introduction
Pure iron materials are widely used in industries such as national defense, energy, and power electronics due to its excellent plasticity, impact resistance, and electromagnetic properties. The thin-walled spherical shell made of pure iron material is a key part of precision physical experiment researches including detonation and shock wave [1–3]. To improve the form accuracy, reliability, and repeatability of the experimental results further, there are higher processing technology requirements for the shape accuracy, position accuracy, and surface quality of the key parts in the experimental device. However, pure iron is a typical difficult-to-machine material due to its high plasticity and toughness [3]. Work hardening and plasticity deformation tend to be serious, and pure iron is easy to be adhered on tool face to form built-up layer (BUL) and built-up edge (BUE), which leads to rapid tool wear. In the process of manufacturing large-size pure iron curved components used in precision physical tests, it is found that the surface quality and contour accuracy of machined workpiece are limited by tool wear [4–7].

At present, some researchers have carried out investigations on tool wear in machining pure iron materials. Kong et al. [8] observed two V-shaped notches located at the major and minor cutting edge, respectively, and uniform flank wear land in the process of turning pure iron materials. The results showed that the formation of notch wear was related to the adhesive wear, diffusion wear, and oxidation wear. Tao et al. [9] found the wear morphology of carbide tools was mainly crater, accompanied by boundary wear on the flank face when cutting pure iron, which resulted from the adhesive wear, abrasive wear, and oxidation wear of carbide tools. Liu et al. [10] revealed that notch dominated the tool life during cutting pure iron after comparing the flank wear,
major notch wear, and minor notch wear under four types of cooling/lubrication conditions. Based on the results of previous researches, we can find that the notch wear is an extremely important part of tool wear when cutting pure iron, nickel-based alloys, low carbon steel, and other materials with strong work hardening tendency. Many researchers have studied the location and formation mechanisms of notch wear. Xiao and He et al. [11, 12] reported that the actual location of DOC notch wear was different from the theoretical one due to the side flow of plastic deformation. They thought that the notch wear resulted from the saw-tooth-shaped chip edge and the side cutting burr on the workpiece. Kong et al. [8] also believed the position of notch wear was outside the cutting area rather than along the depth of the cutting line. They thought the formation mechanisms of notch wear during cutting pure iron material were the comprehensive results of adhesion wear, diffusion wear, and oxidation wear. Bushlya et al. [13] found that major notch was located at the depth-of-cut extremity, and minor notch was related to the defects left on the surface during machining. The results showed that the formation of depth-of-cut (DOC) notch was related to tool stress state, burr formation, and defects of side flow, while plastic flow left on the machined surface resulted in the minor notch wear. Ezugwu et al. [14] revealed the hardened layer beneath the workpiece surface was the key causation of notch wear. Brandt G and Olovsjö et al. [15, 16] observed the notch wear was mainly caused by seizure and pulling out of tool material. Zhuang et al. [17] found notch wear located in the hardened layer of the workpiece and proposed a notch wear model based on the depth of hardening and the notch wear geometry. Kasim et al. [18] thought the location of notch wear was typically near the DOC line and proposed a location prediction model of notch wear during ball nose end milling of Inconel 718.

The single-point cutting tests were widely carried out to investigate the tool wear mechanisms [19]. Ensuring the unchanged contact point between the tool and workpiece contributes to obtaining accurate tool wear modes and investigating the influence of machining parameters on tool wear. Since the relative position of the tool with respect to the contact area on the workpiece varies continuously, it can be inferred that the notch wear position will also change at the same time. Subsequently, the simulation molding and law of tool wear during machining free from surface parts are significantly different from those during single-point cutting. However, there is lack of a comprehensive understanding of tool wear characteristics in cutting high-plasticity and high-toughness pure iron curved parts.

Therefore, this paper aims to investigate the tool wear characteristics and wear mechanisms in depth by comparing the tool wear characteristics of cutting pure iron end faces and cutting pure iron spherical shells. Subsequently, the evolutionary laws for flank wear, cutting edge radius, cutting edge retraction, and tool nose radius were also obtained. Based on notch wear position of turning pure iron end faces, the formation mechanism of flank wear land was analyzed during turning spherical shells. Furthermore, reducing tool wear rate was a possible way for improving tool life, machining surface quality, and machining accuracy during cutting pure iron curved surface parts.

### 2 Materials and experimental methods

Pure iron materials adopted in the experiments were forged at room temperature and then treated at 700 °C for 2 h. Table 1 shows the chemical compositions of pure iron. Pure iron end faces (diameter 160 mm, thickness 20 mm) and pure iron spherical shells (SR 100 mm, wall thickness 10 mm) are two types of test workpieces for tool wear experiments.

Turning tests were carried out in CNC lathe CK6150S/1000 (made in China) with a maximum spindle speed of 1600 r/min. The types of insert and holder were Kennametal DCGT11T302 HP KC5010 (with TiAlN coating) and SDJCL2020K11 respectively in the present work. The clearance angle is 7°. Machining tests were performed under the same cutting parameters on the pure iron end face and pure iron spherical shell. Cutting parameters were as follows: spindle speed \( n = 200 \text{ r/min} \), feed rate \( f = 0.08 \text{ mm/r} \), and depth of cut \( a_p = 0.1 \text{ mm} \).

Flank wear VB was usually adopted to represent the wear of cutting edge. To fully understand the wear of cutting edge, this work focused on flank wear, cutting edge radius(CER), tool nose radius, and cutting edge retraction of cutting pure iron spherical shells. Flank wear and notch wear were used to evaluate tool wear during pure iron end face cutting. In the experiment, cutting edge wear was periodically examined off-line on the Keyence microscope. At first, the 3D profile of the cutting edge was obtained by using the depth composition function of the microscope. Then, 2D profile of the cutting edge was extracted by the microscope’s internal software based on the 3D profile and CER was measured, as shown in Fig. 1. In Fig. 2(a), the intersection point of flank face and rake face is ideal tool tip (a). \( x_1 \) is the distance between the ideal tool tip and new tool tip, and \( x \) is the distance between the ideal tool tip and worn tool tip. Cutting

| Table 1 the chemical compositions of pure iron. |
| Fe | C | Si | Mn | Ni | S | Cr | Cu | P | Al |
|---|---|---|---|---|---|---|---|---|---|
| > 99.8 | 0.013 | 0.028 | 0.029 | 0.035 | 0.02 | 0.02 | 0.034 | 0.0072 | 0.0023 |

[Springer]
edge retraction is the difference between $x$ and $x_1$. The value of $x$ and $x_1$ is got by 2D profile of the cutting edge extracted by Keyence microscope, as shown in Fig. 2(b). Tool nose radius on rake face, flank wear VB, and notch wear are also measured with the microscope. The adherent pure iron materials on the cutting tools are corroded by using a 10% dilute nitric acid ($\text{HNO}_3$) before tool wear is measured. Tool wear mechanisms are analyzed using a scanning electron microscopy (SEM) equipped with an energy-dispersive spectrometer (EDS) instrument.

3 Results and discussion

3.1 Tool wear modes

The comparison of tool wear modes in the cutting tools is shown in Fig. 3 when turning pure iron end faces and pure iron spherical shells at the same magnification of the microscope. These images are tool wear morphology after removing adherent materials by dilute nitric acid, and demonstrate the difference of wear modes. In Fig. 3(a), major notch, minor notch, and flank wear on flank face are observed significantly with increasing cutting time during turning end face of pure iron materials, and major notch wear is less than minor notch wear. Because of its larger values, two narrow V-shaped notches are the principal wear modes in turning end face of pure iron. Minor notch wear not only plays a significant role in reaching tool failure but also determines the machined surface integrity. However, only wear land occurs on the flank face and conspicuous notch wear disappears in Fig. 3(b) during turning spherical shell. The size of flank wear land is used as a tool life criterion for turning spherical shell of pure iron materials.

The area of the tool involved in cutting process remains unchanged when cutting the end face. Figure 4(a) shows points A and B on the tool are the theoretical locations of major notch and minor notch respectively. Points A and B at the tool-workpiece contact boundary are always fixed in cutting process. As shown in Fig. 4(b), points C and D at the tool-workpiece contact boundary also travel around the tool nose during cutting the spherical shell. Points C and D are also theoretical notch wear positions, so major notch and minor notch also move simultaneously. Therefore, the difference in wear modes resulted from the tool movement.

3.2 Contact area of tool nose area and workpiece in finish turning pure iron curved surface

The cutting contact area remains unchanged within the feed per revolution, so turning spherical shell can be regarded as several end face turning. The notch wear at the cutting boundary is a key wear mode when cutting pure iron end face, but notch wear disappears in cutting the spherical shell due to tool movement. It can be assumed that major notch and minor notch move along the cutting edge in turning the spherical shell. Coordinate diagrams are developed to solve the mathematical model of major notch movement and minor notch movement along flank face, as shown in Fig. 5. Major notch and minor notch occur at the contact boundary of tool-workpiece.
According to Fig. 5, point M is the theoretical position of major notch. It is derived as follows:

Coordinate transformation formula between $xoy$ coordinate system and $x'$ $y'$ coordinate system is as follows:

$$
\begin{align*}
  x &= x' - R \cos \theta \\
  y &= y' - R \sin \theta
\end{align*}
$$

(1)

where $r_0$ is the original corner radius, and $R$ is the radius of spherical shell outer circle after cutting. $\theta$ is the angle between the straight line passing through the center of the tool nose arc and the coordinate origin and $X$ axis.

Equation of spherical shell outer circle and the tool nose arc in $xoy$ coordinate system can be expressed as follows respectively:

$$
(x + \cos \theta \cdot R')^2 + (y + \sin \theta \cdot R')^2 = R_1^2
$$

(2)

$$
\begin{align*}
  x^2 + y^2 &= r_0^2
\end{align*}
$$

(3)

where $R_1$ is the radius of original spherical shell outer circle. Combining Eq. (2) and Eq. (3), major notch position can be calculated as:
Fig. 3 Comparison of tool wear under different cutting methods: (a) end face turning, (b) spherical shell turning

Equation of the tool nose arc in $x' o' y'$ coordinate system is as follows:

$$\begin{align*}
x_1 &= \frac{T \cos \theta - \sqrt{(T \cos \theta)^2 - T - (2r_0 R \cdot \sin \theta)^2}}{2R} \\
y_1 &= \sqrt{r_0^2 - \frac{T \cos \theta - \sqrt{(T \cos \theta)^2 - T - (2r_0 R \cdot \sin \theta)^2}}{2R}}
\end{align*}$$

Equation (4)

$(x_1, y_1)$ is the theoretical position of the major notch in the $xoy$ coordinate system. It can be seen that the position of the major notch changes with the angle $\theta$.

Minor notch occurs at point N. According to Fig. 3, the theoretical position of minor notch is derived as follows:

$$\begin{align*}
(x' - \cos \theta \cdot R)^2 + (y' - \sin \theta \cdot R)^2 &= r_0^2 \\
y' &= \tan \left(\theta - \frac{f}{2R}\right) \cdot x'
\end{align*}$$

Equation (5)

The straight line through point N and the origin of the coordinates in $x' o' y'$ coordinate system can be expressed as follows:

$$y' = \tan \left(\theta - \frac{f}{2R}\right) \cdot x'$$

Equation (6)

Fig. 4 Schematic of turning end face (a) and turning spherical shell (b)
Fig. 5 Theoretical position of major notch and minor notch in the coordinate system

Combining Eq. (5) and Eq. (6), we obtain

\[
x' = \frac{2R' \tan \left( \frac{\theta - f}{2R'} \right) \sin \theta + 2R' \cos \theta}{2 \left(1 + \tan^2 \left( \frac{\theta - f}{2R'} \right) \right)}
\]

\[
y' = \tan \left( \theta - \frac{f}{2R'} \right) \cdot \frac{2R' \tan \left( \frac{\theta - f}{2R'} \right) \sin \theta + 2R' \cos \theta}{2 \left(1 + \tan^2 \left( \frac{\theta - f}{2R'} \right) \right)}
\]

\[
\begin{align*}
\left( x', y' \right) & \text{ is the theoretical position of the minor notch in the } \bar{x}'\bar{y}' \text{ coordinate system.} \\
\text{To simplify the equation, } A = \tan(\theta - \frac{f}{2R'}) \text{ is brought into Eq. (7). Then, according to Eq. (1), the theoretical position of minor notch in } xoy \text{ coordinate system is derived as follows:}
\end{align*}
\]

\[
x = \frac{R' \left( A \sin \theta + \cos \theta \right)}{R' \left( A \sin \theta + \cos \theta \right)^2 - \left( 1 + A^2 \right) \left( R'^2 - r_0^2 \right)} - R' \cos \theta
\]

\[
y = \frac{\lambda \left( R'^2 - r_0^2 \right)}{R' \left( A \sin \theta + \cos \theta \right)^2 - \left( 1 + A^2 \right) \left( R'^2 - r_0^2 \right)} - R' \sin \theta
\]

By replacing the theoretical position movement model of major notch and minor notch, and the relevant parameters \((r_0 = 0.2 \text{ mm}; R_1 = 100 \text{ mm}; R = 99.9 \text{ mm})\) into MATLAB, it can be shown that major notch and minor notch pass along tool nose arc and have an overlap area, as shown in Fig. 6. Notch wear is the key factor resulting in tool failure, so the overlap area is the maximum wear area of carbide tools when turning the spherical shell. According to the wear characteristics of the turning spherical shell in Fig. 3, it can be found that the wear in the middle of the flank wear band is relatively larger, which is consistent with this model. This model also illustrates the flank wear land formation mechanism when turning the spherical shell. The wear land across the entire cutting edge occurs due to the movement of major notch and minor notch.

Fig. 6 Theoretical position trajectory of major notch and minor notch

Fig. 7 Notch wear and flank wear during turning end face and spherical shell
Actually, the tool wear is mostly characterized by the average flank wear. To better understand the law of tool degradation, the tool wear is comprehensively characterized by the cutting edge radius (CER), the flank wear (VB), and tool nose deterioration and corner radius. The tool edge degradation laws provide guidance on the effect of tool wear on surface accuracy during turning pure iron curved surface.

The measured tool wear working as a function of cutting time is shown in Figs. 7 and 8. Major notch wear and minor notch wear increase with the cutting time when turning the end face, and major notch wear and minor notch wear are larger than the average flank wear. By turning spherical shell, the notch wear disappears, but the flank wear is about twice that by turning the end face, which verifies that the aforementioned mathematical model is reasonable. As the contact position of the tool-workpiece moves constantly while turning spherical shell, notch wear at the cutting boundary may travel along tool nose arc as well. Therefore, flank wear of turning spherical shell is larger than that of turning end face. Tool flank often rubbed with the contact boundary of the tool-workpiece when turning pure iron end face and tool materials are pulled out easily due to tool strength descent. The cutting contact area does not move only within the feed per revolution when turning spherical shell, which makes tool wear at contact boundary of the tool-workpiece smaller. Therefore, flank wear of turning spherical shell is smaller than notch wear of turning end face.

Variation of flank wear affects cutting edge radius (CER), cutting edge retraction, and tool nose radius. It has been known that cutting edge radius represents the tool’s sharpness and directly influences cutting force and cutting temperature [20, 21]. CER variations in the cutting process are depicted in Fig. 10(a). At the early stage of cutting, the cutting edge of the new tool is sharp and low in strength. The contact area between the cutting edge and workpiece is very small. Therefore, the cutting edge is subject to heavy loads, which results in a large initial wear rate. Tool materials

![Fig. 8 Flank wear during turning end face and spherical shell](image)

**3.3 Tool wear evolution in turning curved surface of pure iron**

![Fig. 9 Evolution of the cutting edge profile](image)

![Fig. 10 Variation of CER (a), cutting edge retraction (b), and tool nose radius (c) during turning spherical shell](image)
may fall away because of attrition. The cutting edge gradually becomes dull. CER tends to increase before cutting for 50 min. $S_\alpha$ is related to flank wear, and $S_\alpha$ can influence the size of material stagnation zone and the material separation point. The more material that flows under the flank face, the greater the friction between the flank face and the machined surface [22]. The flank face is squeezed and rubbed by the elastic–plastic deformation layer, causing the flank face to rapid wear. As shown in Fig. 9, the profile of cutting edge shows a great loss of flank face material, and serious flank wear results in the edge tip moving toward the rake face. The edge profile indicates that the flank wear acts as the grinding tool and re-sharpening the cutting edge tip [23]. Therefore, CER tends to decrease after cutting for 50 min.

Cutting edge retraction significantly affects the precision of curved components. Obtaining the values of cutting edge retraction can facilitate tool compensation when cutting curved parts, which can improve the machining accuracy of the parts. Cutting edge retraction gradually increases with cutting time in Figs. 9 and 10(b). Cutting edge retraction indicates a significant increase in turning for 10 min due to the very sharp edge of the instrument and low strength. What’s more, Fig. 11 indicates that the flank face wear gradually increases, causing the tool nose to continuously retract along the radial direction of the tool nose arc. According to the relationship between flank wear and cutting edge retraction [24], severe flank wear of cutting spherical shell made cutting edge retraction better.

According to tool imprinting, tool nose radius is an important factor influencing the surface roughness. A bigger tool nose radius of worn cutting edge on the machined surface will lead to a smaller surface roughness [24]. Tool nose still maintains a circular arc shape due to notch wear disappearance as shown in Fig. 12. Tool nose radius fluctuates around 215 µm when cutting the spherical shell, as shown in Fig. 9(c). However, cutting edge retraction is continuously increasing, so tool nose arc is continuously degrading in the radial direction in turning spherical shell.

### 3.4 Tool wear mechanisms in turning curved surface of pure iron

As mentioned previously, by turning the spherical shell, the notch wear disappeared, and the flank wear was about twice that by turning the end face, which showed notch wear must participate in the formation of flank wear land. Hence, it could be inferred that the flank wear mechanism of turning spherical shell was basically the same as the notch wear mechanism of turning the end face. According to the EDS analysis results, it could be seen that pure iron materials adhered at the notch (Fig. 13) and flank wear area (Fig. 14). The pure iron materials were easily cold-welded on the tool under the high temperature and high pressure in the cutting area. The pure iron materials bonded on tool surface would be plucked away by the action of chip flow or workpiece travel. As adhered pure iron materials peeled off, tool materials were also pulled out. Xue et al. regarded this process the adhering layer goes through as “formation–stacking–plucking process” [25]. In addition, ambient air was easy to enter the cutting area. O element at tool wear area was observed in Figs. 13 and 14. Serious oxidative wear occurred under promotion of high cutting temperature, especially at the tool-workpiece and tool-chip contact boundaries. W and Co in cemented carbide tools were main
elements that are oxidized [16]. In the early stage of cutting, the TiAlN coating might suppress the adhesion of the workpiece material onto the rake face and flank face, due to its high-temperature hardness and excellent high-temperature chemical stability. However, as the cutting process progresses, the constant friction between the tool and the workpiece causes it to fall off, especially at the high temperature and stress gradient of the contact boundary between the tool and the workpiece. When TiAlN coating layer peeled off, W and Co were prone to be oxidized, which accelerated to the formation of softer oxidations. Fe in the workpiece and Co in the carbide tool matrix are homologous, so they have a strong affinity. Fe and Co could be almost completely dissolved at the high temperature [26, 27], so they diffused easily with each other at the high temperature and pressure in the cutting area. In Figs. 13 and 14, the contents of Co were 5.03% and 3.06%. The Co content was lower than the standard content of new tool. Co was the binder of cemented carbide tools. Diffusion of Co weakened the adhesive strength among the carbide particles (WC), which made tool materials pulled out easily. At the same time, Fe in the adherent layer and the workpiece also diffused into the binder phase (Co) of cutting tool by means of grain boundary diffusion to break tool structure [25–27]. Fe was oxidized easily, which accelerated the formation of oxidation such as Fe$_2$O$_3$ and Co$_2$O$_4$ [26]. Where the iron content was high, the oxygen content was also high, as shown in Figs. 13 and 14. The diffusion and oxidation weakened tool strength, which resulted in tool materials being pulled out under the combined actions of scratching and attrition.

Therefore, flank wear mechanisms of coated carbide tools included adhesive wear, diffusion wear, and oxidation wear when turning spherical shell, which was consistent with notch wear mechanisms. But these factors are not independent, which means the tool wear mechanism is complex and can be triggered off as long as one factor changed [8].

![Fig. 13 EDS analysis results of turning end face](image1)

![Fig. 14 EDS analysis results of turning spherical shell](image2)
4 Conclusions

This research explored tool wear characteristics in finish turning pure iron curved surface. The following conclusions can be drawn.

(1) The main wear modes during end face turning of pure iron material are flank wear and severe major notch wear and minor notch wear. However, severe notch wear disappears and only flank wear land along the tool nose occurs during spherical shell turning of pure iron material. Aforementioned difference of wear modes is caused by the continuous movement of the tool-workpiece contact position during turning curved surface.

(2) A mathematical model is developed to explain formation mechanisms of flank wear characteristics in turning of pure iron spherical shell. The flank wear land results from the movement of major notch position and minor notch position, and the overlap area of major notch position and minor notch position is the maximum wear area.

(3) The flank wear of turning spherical shell is larger than that of turning end face, but smaller than notch wear of turning end face. It verifies that the mathematical model is reasonable. Due to serious flank wear, the cutting edge radius tends to increase first and then decrease. Cutting edge retraction gradually increases, and tool nose radius fluctuates around 215 µm. Therefore, tool tip retracts along the radial direction of tool nose arc.

(4) Flank wear mechanisms are the result of the combined effects of adhesion wear, diffusion wear, and oxidation wear during turning spherical shell of pure iron materials. It is consistent with notch wear mechanisms of turning end face.

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Data availability Data will be made available on request.

Declarations

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