Research on cutting performance in high-speed milling of TC11 titanium alloy using self-propelled rotary milling cutters

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Abstract
Titanium alloys are widely used in many areas, such as aerospace, biomedical, and automotive industries, due to their excellent chemical and physical properties. However, its difficult-to-machine characteristic causes various problems in the machining process, such as serious tool wear and elastic deformation of workpieces. To achieve high efficiency and quality of machining titanium alloy materials, this paper conducted an experimental research on the high-speed milling of TC11 titanium alloy with self-propelled rotary milling cutters. In this paper, the wear mechanism of self-propelled rotary milling cutters was explored; the influence of milling velocity was analyzed on cutting process, and the variation laws with the change in milling length were obtained of milling forces, chip morphology, and machined surface quality. The calculation method of self-propelled rotary velocity was proposed, based on the experimental research. The results showed that in the early and middle stages of milling, the insert coating peeled off evenly under the joint action of abrasive and adhesive wear mechanisms. As the milling length increased, the dense notches occurred on the cutting edge of the cutter, the wear mechanism converted gradually into fatigue wear, and furthermore, coating started peeling off the cutting edge with the occurrence of thermal fatigue cracks on the insert. As the milling length was further extended, the milling forces tended to intensify, the chip deformation worsened, and the obvious cracks occurred at the bottom of chips. The increase in milling velocity intensified the friction between chips and self-propelled rotary milling cutters, and decreased the ratio of self-propelled rotary velocity to milling velocity. This caused the drop in cutting performance of cutters and the growth in tool wear rate.

Keywords TC11 titanium alloy · Self-propelled rotary cutter · Wear morphology · Wear mechanism · Surface quality

1 Introduction

With excellent physical and chemical properties, titanium alloys are widely used in the aerospace, chemical, and automobile industries [1–3]. However, the characteristics of poor thermal conductivity, strong chemical activity at high temperatures, and low elastic modulus, cause widespread problems in machining, such as low machining efficiency, poor surface quality, and severe tool wear [4–6]. These shortcomings badly restrict the application and promotion of titanium alloy materials. The PCD and PCBN, novel cemented carbide cutting tools, can improve the machining performance of titanium alloy, but its high cost and high demand for the machine tool rigidity limit the promotion of cemented carbide cutting tools. Therefore, it is necessary and urgent to explore a novel cutting tool with excellent cutting performance, low cost, and good suitability to machine titanium alloy materials. Moreover, it is of great theoretical and practical significance for solution to the difficulty in machining titanium alloy and improvement in machining quality to conduct researches on the cutting performance of the novel cutting tools.

In research on cutting titanium alloy with conventional cutters, Sun et al. [7] carried out single-factor experiments on milling titanium alloy with indexable coated carbide inserts, and obtained the relationship of feed per tooth with cutting force and cutting power. Rashid et al. [8] investigated all possible tool wear mechanisms in dry machining of titanium alloy with uncoated carbide cutting tools, and found that the mechanisms of adhesion, diffusion, attrition, and abrasion were associated with cratering of the rake surface. Koseki et al. [9] researched the coated cutting tool wear during continuous turning of a titanium alloy, and suggested that the
coating wear depended on the interfacial strength between adhesive material and coating as well as on the strength of adhesive material at a high temperature. Daymi et al. [10] evaluated experimentally the influence of different milling conditions on workpiece surface integrity, and concluded that the inclination angle of workpiece, an influential parameter on the surface roughness, showed the best surface finish at a 25° angle, and higher workpiece angle decreased slightly the compressive stress. Yang et al. [11] investigated the cutting performance of the new WC matrix composite tool material by the experiment on machining the titanium alloy, and found the high temperature and mechanical friction were the main causes for tool failure. Tan et al. [12] did experimentally a comparative research on the cutting performance of TiB2-based ceramic cutters and WC-Co composite cutters in the high-speed cutting of titanium alloy, and discovered that the superior cutting performance of the former to the latter was mainly attributed to its better oxidation resistance and high-temperature mechanical properties. Chowdhury et al. [13] investigated comparatively the wear performance of coated and uncoated carbide cutting tools in high-speed turning of TC4 titanium alloy, and the results showed that the tool coating improved significantly tool performance. Wang et al. [14, 15] developed a special revolving cycloid milling cutter for machining the titanium alloy, and experimentally compared it with the ball end milling cutter in the cutting performance. The results revealed that the revolving cycloid milling cutter can significantly reduce the axial and tangential forces, and had better wear resistance and surface quality than the ball end milling cutter. Aiming at the wear mechanism of cutting tools for milling titanium alloy, Niu et al. [16] carried out the experimental research on milling TC11 titanium alloy with coated cutting tools, and found that the crater with chipping and the breakage with flaking were the dominant failure forms of PVD- and CVD-coated inserts. Ji et al. [17] researched the influence of PCD tool geometries on tool wear in milling titanium alloy TC11. The results indicated that the longest tool life can be achieved by selecting suitable radial rake angle (around 1°), axial rake angle (around 5°), and tool nose radius (around 1.6 mm). These studies have provided some good ideas and solutions for the difficulties in machining titanium alloy, but some problems still occur in the machining process, such as the concentration of tool wear and higher cutting temperature in the local area.

The urgent need for improvement in the machining quality and the service life of cutting tools for machining the titanium alloy promoted the advent of self-propelled rotary cutters with self-cooling characteristic. This has got much attention from many scholars. Lei et al. [18] developed a new driven rotary cutting tool for the high-speed machining of the titanium alloy, and conducted a comparative experiment on the driven rotary tool (DRT) and the stationary cutting tool. The experimental results showed that the DRT can significantly increase tool life. Olgun et al. [19] compared experimentally self-propelled rotary turning (SPRT) tools and actively driven rotary turning (ADRT) tools in terms of the cutting performance, and found that SPRT process yielded better tool life and machined part quality. Kishawy et al. [20–22] presented the models for predicting cutting forces, flank wear, and chip flow to evaluate the cutting performance of self-propelled rotary tools in the machining process, and verified the correctness of predicted values by the experiments on machining the titanium alloy. Kossakowska et al. [23] explored the dependence of the rotational speed of self-propelled rotary tools (SPRT) on cutting parameters and revealed some important drawbacks and limitations of SPRT application. Dessoly et al. [24] developed and verified a thermal model for predicting the distribution of cutting temperatures, and compared self-propelled rotary tools (SPRT) and equivalent fixed tools during machining hardened steels in terms of cutting temperatures. The results showed that the SPRT generated lower cutting temperatures. Ezugwu et al. [25, 26] evaluated the tool wear in turning IMI 318 titanium alloy with self-propelled rotary tools (SPRT), and concluded that SPRT exhibited superior wear resistance and provided other major benefits, including the increase in tool life, lower cutting temperature, and higher metal removal rate.

To sum up, the scholars have done lots of relevant research, mainly focusing on cutting mechanisms and experiments of conventional cutting tools [27, 28], but some problems still remain unsolved well in cutting titanium alloy, such as fast tool wear and severe coating shedding. Self-propelled rotary tools improve the chip removal performance and the heat dissipation in cutting process by the self-propelled insert rotation. Thus, the service life of cutters is prolonged and machined surface defects are inhibited obviously. However, the current research into self-propelled rotary tools concentrates mainly on turning techniques, and less on milling titanium alloy [29]. Therefore, in this paper, the experimental research was performed on high-speed milling of TC11 titanium alloy with self-propelled rotary milling cutters (SPRMC), and the cutting performance of cutters was analyzed, based on milling forces, tool wear morphology, and wear mechanism. This promotes theoretically widespread application of the technique for milling titanium alloy with the SPRMC.

### 2 Experimental design

In this paper, the corresponding experiments were designed on high-speed milling of TC11 titanium alloy with the SPRMC, for obtaining the variation laws of tool wear morphology, tool wear mechanism, chip morphology, milling forces, and machined surface quality with change in milling length. The experiments were performed on the VDL-1000E milling center, and the clamped experimental system is shown
The workpiece material was TC11 titanium alloy, whose chemical composition and physical property are shown in Tables 1 and 2. The workpiece of a cuboid block was 150 mm long, 100 mm wide and 50 mm high. The DR07-8 SPRMC manufactured by Hippsc was used in the experiments, shown in Fig. 2. The round insert of the SPRMC was the coated cemented carbide one matched with the handle. The insert was 7 mm in diameter and 2.5 mm thick. The substrate material of the insert coated with TiC was cemented carbide, and the inclination angle was 10°.

For observation of the tool wear morphology, the milling forces, the chip morphology, and the machined surface quality at different milling lengths, the milling velocity was set as 80 m/min, the feed per tooth 0.3 mm/z, the milling depth 0.3 mm, and the milling width 5 mm. Additionally, for exploration of the influence of milling velocity on tool wear, the milling velocity was set respectively as 80 m/min, 100 m/min, 120 m/min, the feed per tooth 0.3 mm/z, the milling depth 0.3 mm, and the milling width 5 mm. The experiments were performed in the down milling.

In the milling experiments, the 9171A Kistler rotary dynamometer was used to collect the data of milling forces. The cutter was removed whenever the milling length reached 3 m. Then the VHX-1000 ultra-depth three-dimensional microscope (UDTDM) manufactured by KEYENCE was used for observation of the rake and flank wear morphology; the HITACHI SU3500 scanning electron microscope (SEM) and the BRUKER XFlash6|30 energy-dispersive spectrometer were used to detect the morphology and elements of the wear area, and the Taylor Hobson CCI profilometer was used for detecting the surface morphology and roughness of the retained workpiece. The experiment was not stopped until the flank wear width reached 300 μm or obvious damage happened to the insert. Moreover, the chips were collected at different milling lengths, and then the denture acrylic and epoxy resin were used for inlaid sample preparation, grinding, and polishing of the collected chips. Finally, the macromorphology and micromorphology of chips were observed respectively by the KEYENCE VHX-1000 UDTDM and the HITACHI SU3500 SEM.

### 3 Experimental results and discussion

#### 3.1 Analysis of tool wear

Figure 3 shows the variation in the rake wear morphology of the SPRMC at different milling lengths. When the milling length reached 9 m, the scratches were observed on the local rake face of the insert. Afterwards, the scratched area was evenly distributed and gradually expanded along the circumference of the cutting edge. As the milling length increased, the coating peeled gradually off and weakened its protection for the insert. Consequently, the friction between insert and chip intensified gradually, and plenty of scratches and grooves in the radial direction occurred on the rake face.

| Table 1 Chemical composition of TC11 titanium alloy (%) |
|-----------------|--------|--------|--------|--------|--------|
| Elements        | Al     | Mo     | Zr     | Si     | Ti     |
| Content         | 5.8~7.0| 2.8~3.8| 0.8~2.0| 0.2~0.35| The rest |

| Table 2 Physical property of TC11 titanium alloy |
|-----------------|--------|--------|--------|--------|--------|
| Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Shrinkage (%) | Density (g·cm⁻³) | Impact value (J·cm⁻²) |
| 1030             | 910    | 8      | 23     | 4.5    | 29.5   |
As the cutting proceeded, under the influence of strong friction and mechanical impact, quantities of gaps appeared on the cutting edge, and the extensive material adhesion occurred on the rake face, accompanied by abrasions to the local substrate material of the insert. The occurrence of gaps damaged the continuous smooth rotation of the SPRMC insert and caused stronger friction and mechanical impact, and thus the cutting stability was reduced. When the milling length reached 411 m, the extensive substrate materials peeled off the rake face, and here the cutter could no longer work.

Figure 4 shows the variation in the flank wear morphology of the SPRMC at different milling lengths. When the milling length reached 9 m, the slight scratches occurred on the flank face of the insert. With the increase of milling length, the...
scratched area expanded constantly in the radial direction, and the obvious radial scratches appeared on the flank face. As the cutting proceeded, the workpiece material adhesion happened evidently to the flank face, and the adhesive area was extended with the increase in milling lengths. With the aggravation of tool wear, the adhesive workpiece material was taken away by chips, and thus stronger friction was generated. Therefore, lots of grooves in different depths emerged on the flank face, and the dense notches formed on the cutting edge. During the long machining, the constant rotation of the insert exerted the cyclical thermal fluctuation and mechanical impact on all parts of the cutting edge, finally resulting in coating peeling.

### 3.2 Analysis of wear mechanism

Figure 5 shows the tool wear morphology of the SPRMC at a milling length of 45 m. The dense scratches in different depths were clearly observed on the rake face. It was found by the energy spectrum analysis that Al and O as well as C and Ti elements existed in the coating material, as shown in Fig. 5b. This indicated that the abrasive wear mechanism acted prominently at a small milling length. The main reason is that the strong friction between insert and workpiece results in the coating shedding, and the scraping effect of hard spots in the shed coating causes the scratches on the tool surface.

Figure 6 presents the tool wear morphology of the SPRMC at a milling length of 120 m. With continuous increase of the milling length, the frequent friction and mechanical impact weakened obviously the adhesive force between coating and substrate, and caused cracks in the area of concentrated loads, otherwise, reducing the adhesive force between coating and substrate, as shown in Fig. 6a. Thus, the coating peeled evenly off the rake face. For further reasons, the coating and substrate material differ in the elastic modulus and thermal expansion coefficient, and the thermodynamic load acts jointly. Therefore, the internal stress is generated between coating and substrate. When the internal stress exceeds the adhesive force between coating and substrate, the coating will peel partially and the cemented carbide substrate will be exposed.

The tool wear morphology of the SPRMC at a milling length of 210 m is shown in Fig. 7. It was found by observing the wear area of the cutting edge that the regular adhesive areas appeared on both rake and flank faces of the insert. As the cutting proceeded, the adhesive areas were taken away by chips, and thus the insert substrate was exposed, as shown in Fig. 7a. Based on the energy spectrum analysis, quantities of
elements contained in the workpiece, such as Ti, Al, Mo, and Zr, were observed in adhesive Zone B, as shown in Fig. 7c. Then the further energy spectrum analysis was made of worn Zone C on the flank face and unworn Zone A, as shown in Fig. 7d, b. Only the elements contained in the coating material (Ti, C, etc.) were found in unworn Zone A, while plenty of elements contained in the substrate material (W, Co, etc.) were found in worn Zone C, but the elements contained in the workpiece (Ti, Al, Mo, Zr, etc.) were not observed. Thus, the adhesive wear occurred obviously on the insert.

Figure 8 shows the tool wear morphology of the SPRMC at a milling length of 330 m. The thermal fatigue cracks in the radial direction were observed clearly on the insert. The reason is that in milling TC11 titanium alloy with the SPRMC, the constant rotation of the self-propelled insert involved alternately all parts of the cutting edge in cutting, so the cutting edge experienced regularly heating and cooling, and finally, the cyclical temperature fluctuation caused the radial thermal fatigue cracks on the insert. Here the tool wear mechanism has turned into a fatigue wear mechanism. As the cutting proceeded continuously, the number of cracks rose with increase in the milling length and eventually a crack network formed. Consequently, the cutting performance and the strength of the insert dropped sharply.
Figure 9 displays the tool wear morphology of the SPRMC at a milling length of 411 m. The occurrence of the thermal cracks on the insert largely reduced the bonding strength between the insert materials, and thus the insert material peeled off under the frequent impact of mechanical load. The peeling damaged the continuous rotation of the insert and will result in stronger friction and mechanical impact. Therefore, given the machined surface quality, the cutter can no longer be used.

3.3 Influence of tool wear on milling forces and chips

Figure 10 reveals the variation in the milling forces and the chip morphology at different milling lengths when the SPRMC was used for milling TC11 titanium alloy. It can clearly be observed from the figure that with continuous increase of the milling length, the milling forces all showed a similar tendency to rise constantly. Among them, the tangential force was the largest and the radial force the smallest. In the early and middle stages of milling, the milling forces grew relatively slow. This has something to do with the improvement in the tool wear resistance made by rotation of the self-propelled insert. The milling forces increased significantly after the milling length reached 330 m. This is because the severe tool wear caused the cutting performance and stability to drop off.

As the milling length increased, the curling degree of chips diminished gradually, and the folds on the free chip surface became increasingly irregular, meanwhile accompanied by obvious cracks. Furthermore, the burrs on both sides of the chip grew gradually inconsistent in the morphology, and the interface between insert and chip turned less and less smooth and showed obvious scratches. Moreover, the obvious cracks occurred at the bottom of the chip; the number of cracks was directly proportional to the milling length; the sawteeth of the chip were well distributed. This is because the tool wear aggravation resulting from the increase in the milling length reduced the cutting stability. Meanwhile, this decreased the shear effect of the insert on the workpiece and intensified the extrusion effect, and thus the chip deformation further worsened.

3.4 Influence of tool wear on surface quality

When the SPRMC was used to mill TC11 titanium alloy, the machined surface roughness varied with the milling length, as shown in Fig. 11. In the early and middle stages of milling, as
the milling length increased constantly, there was a tendency for the machined surface roughness to worsen slowly, but it was found by observing its 3D morphology that the machined surface still remained regular and smooth. However, when the milling length increased to 330 m, the machined surface became gradually uneven, being accompanied by some damage on it. The main reason for the obvious decrease in the surface quality is that the tool wear grows severe, the notches occur on the cutting edge, and the insert substrate peels off.

### 3.5 Analysis of the influence of milling velocity on milling process

Figure 12 shows the tool wear curves of the SPRMC at different milling velocities. In milling TC11 titanium alloy with the SPRMC at the different milling velocities of 80 m/min, 100 m/min, and 120 m/min, the flank wear presented an approximately linear increase with extension of the milling length. Additionally, the acceleration of milling velocity worsened gradually the tool wear, and particularly when the milling velocity accelerated to 120 m/min, the insert started peeling and even failing prematurely. The reason for accelerating the insert failure is that too high milling velocity makes each part of the edge involved in cutting comes into more frequent contact with the workpiece, and thus the thermal and mechanical impacts are more frequently exerted on the insert.

Figure 13 presents the comparison of milling forces and the comparison of surface roughness at different milling lengths when the SPRMC was used for milling TC11 titanium alloy. In the same milling stroke, all milling forces at the milling velocity of 120 m/min were a little larger than the ones at 80 m/min. As the milling length was extended, both milling
forces and surface roughness were on the less and slower increase at the milling velocity of 80 m/min. This is mainly because in milling TC11 titanium alloy with the SPRMC at the velocity of 80 m/min, the tool is slowly worn to a lesser degree, the milling process is relatively stable, and the milling forces and surface roughness both remain at a lower level.

Figure 14 shows the high-speed milling of TC11 titanium alloy with the SPRMC. It can be seen from the figure that the SPRMC movement consisted of the cutter rotation and the self-propelled insert rotation. Here $V_t$ stands for the rotary velocity of the self-propelled insert, $V$ the milling velocity, $\alpha_n$ the normal rake angle, $\eta_c$ the chip flow angle formed when the insert is fixed, and $\phi_n$ the chip flow angle formed when the insert is in self-propelled rotation.

For research into the influence of milling velocity on self-propelled rotary velocity, C is defined as the ratio of self-propelled rotary velocity $V_t$ to milling velocity $V$:

$$C = \frac{V_t}{V} = \frac{\cos \theta_n \sin \phi_n}{\cos \eta_c \cos (\theta_n - \alpha_n)}$$

In the equation, $\phi_n$ stands for the shear angle. Here $\eta_c$ and $\phi_n$ can be derived from the following formulae.

$$\eta_c' = \arctan \left( \tan \alpha_n \right) + \frac{\tan \cos (\theta_n - \alpha_n)}{\cos \sin \phi_n}$$  \hspace{1cm} (2)

$$\phi_n = \arctan \left( \frac{\cos \alpha_n}{\eta_c' \sin \alpha_n} \right) - \arctan \left( \frac{F_x \tan \alpha_n + F_y}{F_z - F_y \tan \alpha_n} \right)$$  \hspace{1cm} (3)

In the formula, $\zeta_c$ stands for the ratio of chip thickness $h_{\phi_n}$ to cutting thickness $h_{\phi}$, known as the chip thickness deformation coefficient [30]. Put Eqs. (2) and (3) into Eq. (1), and then the ratio C of self-propelled rotary velocity $V_t$ to milling ve-

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**Fig. 13** Comparison of milling forces and comparison of surface roughness at different milling lengths

**Fig. 14** High-speed milling of TC11 titanium alloy with the SPRMC

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locity $V$ can be derived. Due to the influence of tool wear and other factors, chip thickness and milling forces are not fixed in value. As shown in Fig. 15, the maximum and minimum values of each parameter were selected at different milling lengths for calculation, and consequently the varying curves of self-propelled rotary velocity with milling lengths were obtained.

Figure 15 shows that the increase in milling length reduced gradually the self-propelled rotary velocity and the ratio $C$ of self-propelled rotary velocity to milling velocity under the aggravating action of tool wear and chip friction. At the milling velocity of 120 m/min, cracks, tool tipping, and substrate peeling occurred sequentially on the tool surface. The reason is that with the decrease in self-propelled rotary velocity, the contact between insert and workpiece was less frequent, and it was more difficult to dissipate heat in the milling area, and thus the tool wear was worsened. This reduced the insert integrity and caused further decrease in self-propelled rotary velocity.

4 Conclusion

In this paper, an experimental study was conducted on high-speed milling of TC11 titanium alloy with the SPRMC, and the influence of milling velocity on tool wear and milling forces was analyzed. Consequently, the laws of milling forces, chip morphology, and machined surface quality varying with milling lengths have been obtained. The conclusions are drawn as follows.

1. In the early and middle stages of milling, under the joint action of abrasive and adhesive wear mechanisms, both rake and flank coatings of the SPRMC peel evenly, and are simultaneously accompanied by the obvious scratches, grooves, and adhesion.
2. Due to the cyclical thermodynamic impact, the tool wear of the SPRMC worsens and develops gradually to the breakage stage, despite being dominated by the fatigue wear mechanism. Meanwhile, the dense notches and thermal fatigue cracks occur on the cutting edge, and thus the insert starts peeling and failing evidently.
3. There is a tendency for all milling forces to rise as the milling length is extended, and the acceleration of milling velocity causes obvious increase in all milling forces. The chip deformation deteriorates gradually with increase in milling length, and the folds on the free chip surface turn irregular. Moreover, the interface between tool and chip gets unsmooth with obvious scratches, and the evident cracks form at the bottom of chips, accompanied by ill-distributed saw-teeth.
4. The continuous increase of milling length causes stronger friction and mechanical impact, and thus the smooth surface machined by the SPRMC grows gradually rough. As a result, the machined surface quality declines clearly. Additionally, the acceleration in milling velocity increases both the tool wear rate and the machined surface roughness evidently.
5. Based on the experimental results, the calculation method for self-propelled rotary velocity was proposed. It is found through analysis of the tool wear morphology that the ratio of self-propelled rotary velocity to milling velocity gradually decreased with increase in milling lengths under the effect of tool wear. This increased the time when the tool and workpiece were in contact, further accelerating the tool wear.
Authors' contribution Lu Yujiang has designed the experiments, conducted the experiments, collected and analyzed data, and written the manuscript; Chen Tao has organized the project, designed the experiments, and written the manuscript.

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Data availability The raw/processed data required to reproduce these findings cannot be shared for the time being. Data will be made available upon request.

Declarations

Ethics approval and consent to participate The research does not involve human participants or animals, and the authors warrant that the paper fulfills the ethical standards of the journal. It is confirmed that all the authors are aware and satisfied of the authorship order and correspondence of the paper.

Consent for publication All the authors are satisfied that the last revised version of the paper is published without any change.

Competing interests The authors declare no competing interests.

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