

Article

Five-Axis Finish Milling Machining for an Inconel 718 Alloy Monolithic Blisk

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Abstract: Blisks subjected to rough machining for channel creation must undergo finishing processes, and such processes must achieve the required tolerance limits. A high-quality surface finish and predictable long tool life are critical for the finish milling of blisks. Accordingly, the aim of this study was to optimize parameters for the finish machining of an Inconel 718 alloy monolithic blisk. Ball-cone mills were used to machine the blade surface at a constant depth. A sensory tool holder was used to collect cutting force signals during machining, and a digital microscope was used to examine tool wear. The surface texture measuring instrument was used to measure blisk blade surface roughness to evaluate processing quality. This study manipulated two cutting parameters, namely cutting speed and feed per tooth, and investigated their effects. The relationship between cutting conditions and machining efficiency was analyzed. According to the experimental results, we identified a set of optimal parameters at effective cutting speeds of 46.53 m/min, feed per tooth of 0.1 mm/tooth, and depth of cut of 0.05 mm for marginal tool wear and fast cutting speeds. Then the corresponding tool life was estimated by using the derived parameters.

Keywords: monolithic blisk; five-axis machining; machining parameter; tool wear; optimal parameters



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1. Introduction

A monolithic blisk is a critical component of an aircraft engine (aero engine). In contrast to the traditional fan design, in which multiple removable blades are assembled on an individual disk, the design of a blisk considers the blades and their holder disk as a monolithic construction. This design can reduce weight, improve stability during high-speed revolutions, and improve the performance of engines. Moreover, the design obviates the necessity of assembling the blades and the disk during the production process, which improves manufacturing efficiency. Blisks can be manufactured using various methods; the most common method involves machining from solid material by using machine tools. It must be emphasized that a blisk presents a complex geometry, so the machining costs are pretty high. It operates at high temperatures, thus blisks material must have excellent mechanical properties to ensure its high durability. The requirements for material selection, processing environment, and precision in the manufacturing process are strict. Blisks are usually made from difficult-to-cut materials such as titanium and nickel-based alloys and require the use of multiaxis machine tools and complex toolpath planning equipped with suitable tools that operate on well-chosen cutting parameters.

Inconel 718 has been used frequently as blisk material quality because of its superior mechanical properties. However, the machinability of Inconel 718 is relatively low owing to its extreme performance. This thermal-resistant alloy exhibits high strength and tends to exhibit strain hardening even at high temperatures, resulting in high cutting forces and extreme temperatures during machining. Traditional carbide tools wear quickly during machining, especially uncoated tungsten carbide inserts employed under dry conditions.

Research has focused on improving the machining efficiency of Inconel 718 through the use of tool coatings, the use of coolants, and the optimization of cutting parameters [1]. Liquid coolants, also known as cutting fluids, are used to cool the tool and workpiece by removing the heat generated during machining. Pereira et al. proposed the use of external MQL lubrication (CryoMQL) with CO₂ as an internal coolant for the cryogenic cooling of Inconel 718 during milling [2]. This ambient cooling method was demonstrated to engender increased tool life [3]. Kursuncu et al. conducted cryogenic heat treatment on cemented carbide tools to increase their wear resistance and thus improve their cutting performance [4].

Scholars have extensively discussed the effect of cutting conditions, including the tool material and geometry, feed rates, and radial depth of cuts, on tool life [5]. Different cutting methods with various cutting parameters and machining strategies have been proposed for controlling tool wear [6]. Moreover, a study introduced a laser preheating-assisted system and an ultrasonically assisted system for optimizing cutting parameters and improving cutting performance [7]. The computer-aided engineering (CAE) software with the commercial SOLIDWORKS® 2014 was also used to predict the deformations and stresses of the spindle and cutting tools under external loads to evaluate the rationality of cutting conditions [8,9].

The first step of blisk machining entails rough milling, followed by the establishment of a boundary contour on the free surface of the blade [10] and then the control of the tool axis and cutting path to remove the groove material [11]. Traditional flank mills or barrel cutters are often used for machining [12]. In rough machining, efficiency is essential. Studies have presented a plunge milling strategy or four-axis cycloid path for material removal to improve efficiency [13]. Although most studies on blisk machining have discussed roughing processes [14], the finishing operation is also of increased importance in order to achieve the prescribed geometrical precision and surface roughness. High-quality active cutting surfaces and predictable, long tool life are critical conditions in blisk milling. Selecting the optimal machining parameters to obtain the desired surface quality and tool life is the most critical task in blisk finishing.

The aim of the present study is to optimize parameters for the finish machining of Inconel 718 alloy monolithic blisk blades. AlTiN-coated tapered ball end mills were used to machine the surfaces of the blades at a constant depth. The study also investigated the effects of two manipulated cutting parameters: cutting speed and feed per tooth. Cutting force signals during the machining process were collected using a sensory tool holder, and tool wear was observed under a digital microscope. The relationship between cutting conditions and machining efficiency was analyzed. The study results can serve as a reference in the optimization of parameters for the finish machining of blisk blades.

2. Machining of Blisk Blades

Figure 1 depicts a computer-aided design (CAD) model and a solid model of a typical monolithic blisk. A nickel-based alloy was subjected to rough machining and grooving processes to produce the blisk; subsequently, the finishing path of the blade was planned according to the shape of the machined blisk by using the impeller module in Siemens NX 10 software, as illustrated in Figure 2. The driving method was blade finishing milling. In the multi-axis machining of NX, in order to better control the inclination angle of the tool axis, we can set the lead angle and tilt angle according to the direction of the tool path. Previous studies disclosed that when the inclination angle is 25° in machining, the workpiece will have better surface roughness [15]. After selecting the blade surface, we set the tilt angle of the tool to 0.2° and set the minimum lead angle to −30°. A negative lead angle value indicates that the tool is tilted backward relative to the tool path direction. The tool axis was automatically determined by the NX program. After the toolpath was completed, VERICUT—a virtual cutting program—was used for verification to avoid interference in the toolpath and prevent collisions. Figure 3 presents the relationship between the tool axis and the blade surface in VERICUT. The left figure shows the direction

of the tool axis relative to the blisk, and the right figure shows the simulation of finishing after semi-finishing.

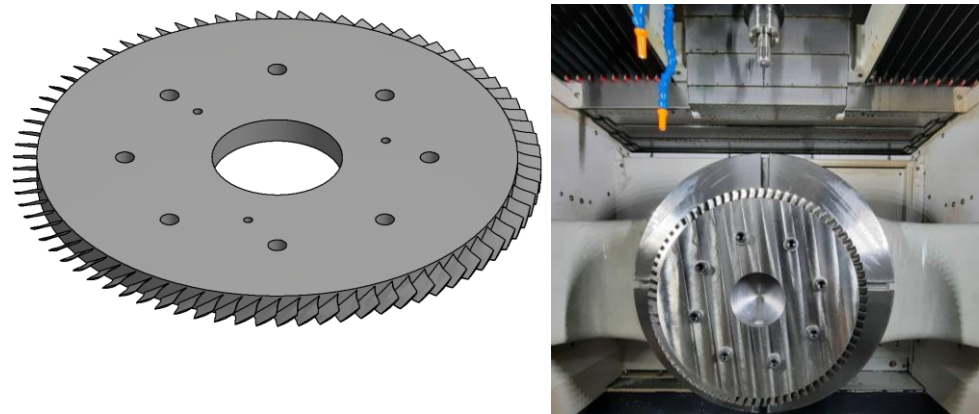


Figure 1. CAD model and solid model of monolithic blisk.

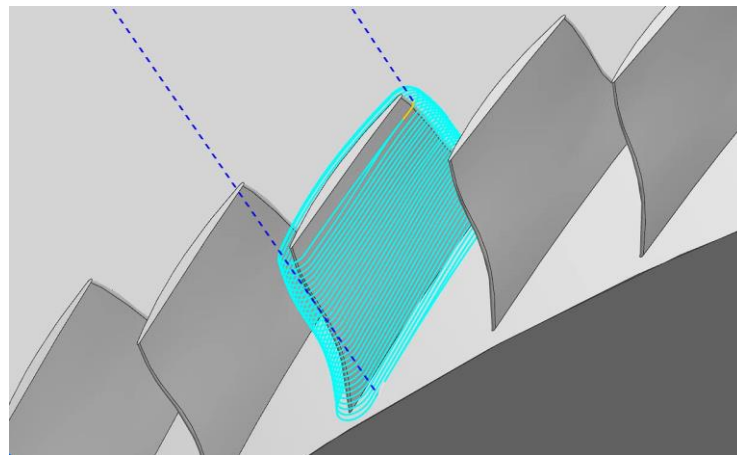


Figure 2. Blade finishing tool path on NX. (The depth of cut has been adjusted to display the tool path clearly. The dark blue dotted lines are the engage and retract of the tool path).

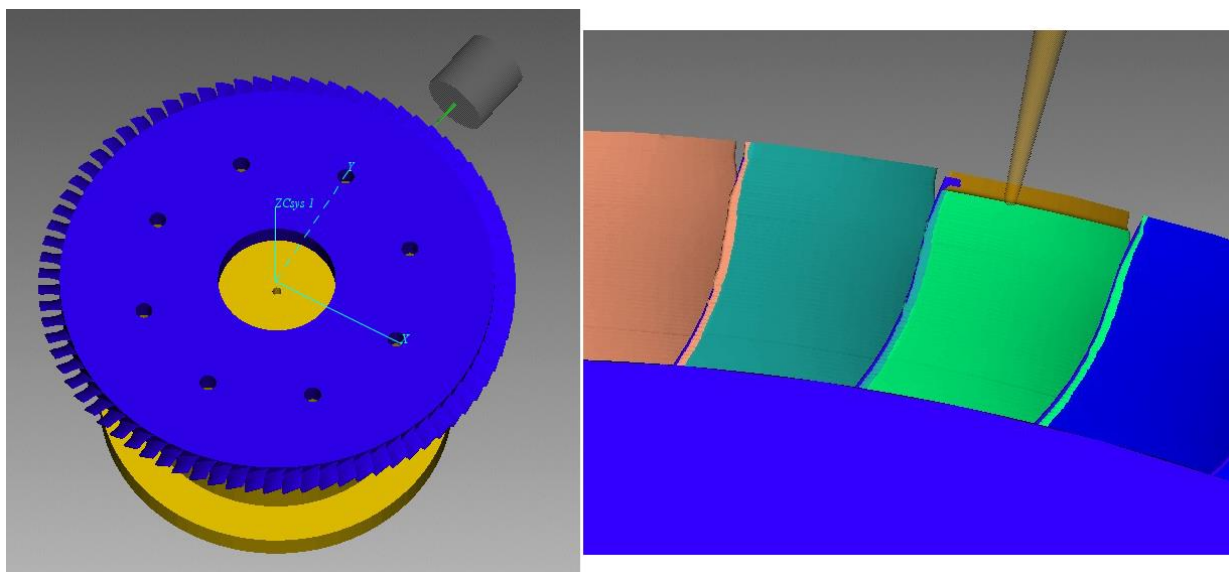


Figure 3. Tool axis in VERICUT. (Each blade used a separate tool path, so the colors are different).

2.1. The Geometrical Parameters of the Blisk

The geometric dimensions of the blisk are shown in Table 1. The primary dimensions are presented in Figure 4.

Table 1. Blisk geometry.

Property	Values
Outer diameter of the blisk (mm)	364
Outer diameter of the hub (mm)	331.5
Length of the blade (mm)	16.25
Thinnest part of the blade (mm)	0.23
Thickest part of the blade (mm)	1.59
Groove width (mm)	6.46
Number of blades	78

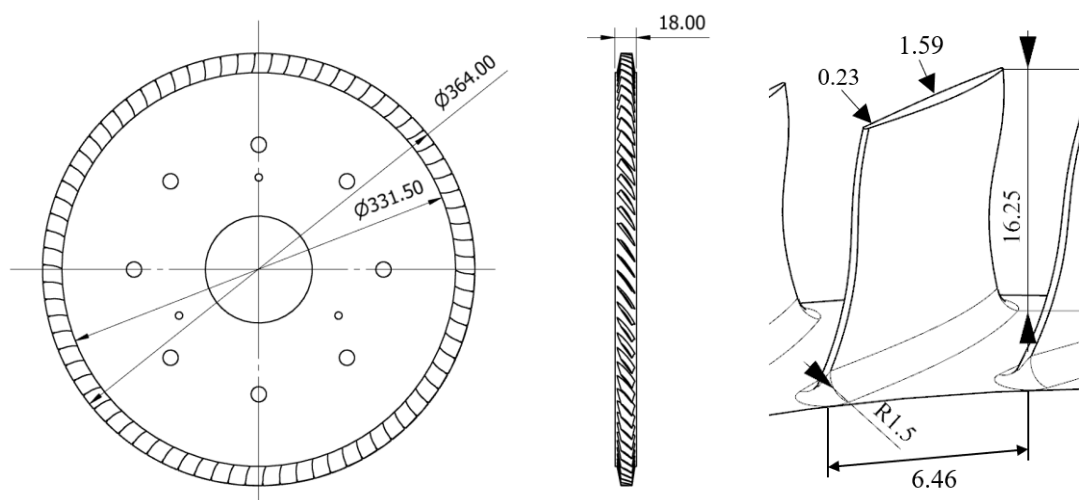


Figure 4. Dimensions of monolithic blisk (unit: mm).

2.2. Material

Inconel 718 has high strength and oxidation/corrosion resistance at elevated temperatures, rendering it suitable for high kinetic-energy and corrosion-resistant environments in the aerospace industry. Inconel 718 is primarily composed of nickel and chromium. Nickel can improve heat resistance and corrosion resistance, and chromium can improve oxidation resistance and sulfur resistance. Table 2 lists the mechanical properties of Inconel 718, which were provided by the material supplier Xitron Innovation [16].

Table 2. Mechanical properties of Inconel 718.

Property	Values
Density (g/cm ³)	8.19
Poisson's ratio	0.29
Young's modulus (GPa)	200
Ultimate stress (MPa)	860
Yield stress (MPa)	551
Elongation (%)	51.7
Hardness (HRB)	97.7
Thermal conductivity (W/m·K)	11.2

2.3. Experimental Equipment

The milling machine was a five-axis machining center CT-630 (Tongtai, Kaohsiung, Taiwan) equipped with a Siemens 840Dsl CNC controller.

The material of a cutting tool considerably influences the machining of Inconel 718 alloy blisks. The tool must have high thermal hardness, good ductility, high wear resistance, and high impact resistance. In this study, a tapered ball-nose end mill (Jen Wu Cheng Shun Turning Tools, Kaohsiung, Taiwan) was used for machining, as displayed in Figure 5. Several studies on the machining of nickel-base alloys have shown that TiAlN-coated tools have better tool life in high-speed milling than other coatings, such as TiN and TiCN [17]. Therefore, this study used TiAlN-coated. The specifications of the tool are presented in Table 3 [18]. We used water-soluble cutting fluids during the cutting process.



Figure 5. Tapered ball nose end mill.

Table 3. Specification of tapered ball nose end mill.

Property/Composition	Values
Shank diameter (mm)	6
Tool nose radius (mm)	1.5
Over length (mm)	75
Cutting length (mm)	20
Taper angel (degree)	3
Rake angle (degree)	2
Flute helix angle (degree)	30
Flutes	2
Material	Tungsten Carbide
Coating	AlTiN

A sensory tool holder (pro-micron, Kaufbeuren, Germany) was used to measure cutting force signals [19]. The sensory tool holder collected the axial cutting force, cutting torque, and X-axis and Y-axis bending moment during the finish machining of the blisk blades and wirelessly sent the collected data to a computer. The X-axis and Y-axis bending moments are defined as the bending moments in the XZ plane and YZ plane, respectively, where the Z-axis is the axial direction of the spindle. Because the tool axis was set to side milling during the cutting process, the bending moment was selected as the primary observation parameter. Polar diagrams of the bending moment in the X-Y direction were used to observe the force in real time [20]. The specifications of the sensory tool holder are presented in Table 4.

Table 4. Specification of sensory tool holder.

Property	Values
Measuring frequency (Hz)	2500
Maximum allowable speed (rpm)	18,000
Operating temperature (°C)	0–50
Collet size	ER20
Spindle taper	BBT-40
Total length (mm)	155

A digital microscope (VHX900F, Keyence, Osaka, Japan) with depth-of-field synthesis and multiple illumination functions was used to examine the milling cutters during the experiments. The microscope was used to examine the wear of the cutting edge and the

side edge after machining. The magnification of the microscope ranges from $20\times$ to $1000\times$; we set the magnification to $100\times$ to examine the tools.

3. Finish Machining Strategy and Method

The machining strategy first involved rough machining on the blank and grooving using a torus milling cutter with a diameter of 5.0 mm and a corner radius of 0.5 mm. The thickest part of the blade was machined to a thickness of 2.18 mm. To ensure the surface quality, a ball-end mill with R2.0 was used for semi-finish machining. Processed the thickest part of the blade to 1.78 mm with the machining allowance set to 0.1 mm. Finally, the tapered ball-nose end mill was used for finishing to the required dimensions of 1.59 mm. The machining process is displayed in Figure 6. During the machining process, we set different parameters for the cutting speed and feed per tooth to observe the cutting bending moment and tool wear.

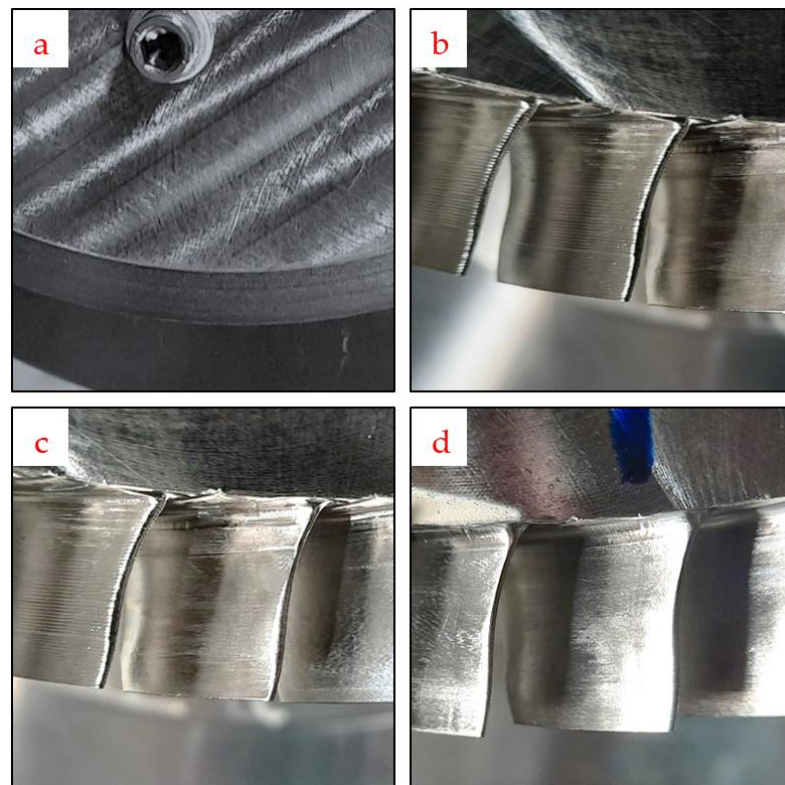


Figure 6. The machining process: (a) Blank, (b) Roughing, (c) Semi-Finishing, (d) Finishing.

3.1. Cutting Speed

3.1.1. Processing Conditions and Parameters

It was reported that feed has no significant effect on carbide cutter milling Inconel 718 [17]. Nevertheless, cutting speed V_c is related closely to cutting force and tool wear. An appropriate range of cutting speed for side milling has been proposed in the literature. Hence, in our experiments, the depth of cut A_p and feed per tooth F_z were fixed, and different cutting speeds were set (ranging from 26 to 96 m/min). The effective cutting speed V_e during the cutting process is very important. It is calculated based on the effective diameter D_e , as shown in Figure 7 [21].

$$D_e = D_c \sin(\varphi + \theta) \quad (1)$$

$$\cos \theta = 1 - \frac{2A_p}{D_c} \quad (2)$$

where D_c is the ball nose diameter. φ is the inclination angle of the tool. Because the lead angle is set to -30° in the NX program, the maximum tool inclination angle is 30° . The maximum effective diameter D_e can be calculated to be 2.115 mm. When the cutting depth is tiny, the effective cutting speed is much lower than the setting speed, and the tool cutting conditions will be lower than its application range. Therefore, this study recalculated the effective cutting speed V_e .

$$V_e = V_c \frac{D_e}{D_c} \quad (3)$$

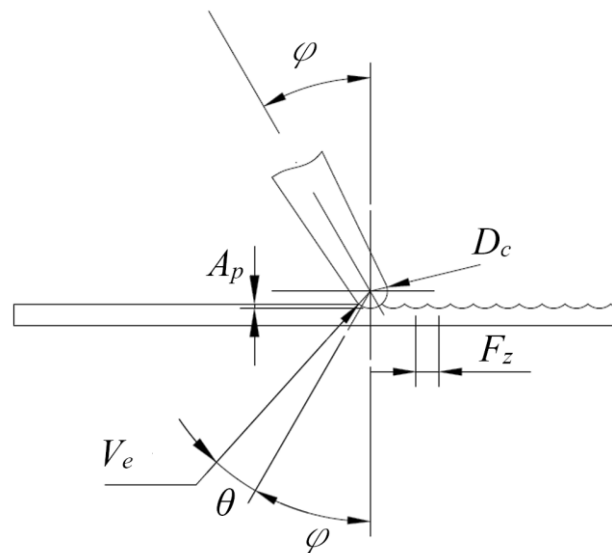


Figure 7. The effective cutting speed V_e for inclined milling.

Thus, eight experiments were performed. The effective cutting speeds after recalculation are listed in Table 5. Each experiment was a complete process in which a new tool was used for blade cutting. In Experiment 7, the cutting speed was originally set to 86 m/min, and the spindle speed was set to 9125 RPM, which resonated with the machine. Therefore, the cutting speed was increased to 91 m/min in this experiment. Under the fixed feed per tooth, an increase in the cutting speed also engendered an increase in feed, which reduced the time required for processing.

Table 5. Machining parameters I.

	Cutting Speed V_c (m/min)	Effective Cutting Speed V_e (m/min)	Feed per Tooth F_z (mm/tooth)	Depth of Cut A_p (mm)	Time (min/s)
Exp. 1	26	18.33	0.05	0.05	56:25
Exp. 2	36	25.38	0.05	0.05	40:53
Exp. 3	46	32.43	0.05	0.05	32:08
Exp. 4	56	39.48	0.05	0.05	26:26
Exp. 5	66	46.53	0.05	0.05	22:30
Exp. 6	76	53.59	0.05	0.05	19:43
Exp. 7	91	64.16	0.05	0.05	16:48
Exp. 8	96	67.69	0.05	0.05	16:06

3.1.2. Cutting Signal Capture and Analysis

During the machining process, cutting force signals were captured by the sensory tool holder. Because the toolpath involved side milling using a side rake, the tool was mainly subjected to lateral forces. The bending moment was thus used as the basis for evaluating

the cutting condition. The toolpath progressed from the periphery of the blade to the hub on a layer-by-layer basis along the blade surface, as illustrated in Figure 2. The bending moment signals captured in each experiment were recorded on the basis of the cutting layer, as shown in Figure 8. The bending moments in Experiments 1–3 and 5–6 were stable, while the value raised in Experiment 4 and continued to rise in Experiments 7 and 8. It is mentioned in the literature that cutting speed and cutting force are not linearly related [17]. At medium cutting speeds, because of the material properties of Inconel 718, the cutting force will first decrease, then increase slightly as the cutting speed changes, and become stable. But when the cutting speed exceeds the critical value, the cutting temperature will increase. The tool edge will be welded, and the front edge will be seriously worn. The cutting force will increase significantly. It can be speculated that the cutting speed in Experiment 7 exceeded the critical value, indicating that the cutting conditions were inappropriate. The abnormal increase in Experiment 4 may come from machine vibration or cutting chatter.

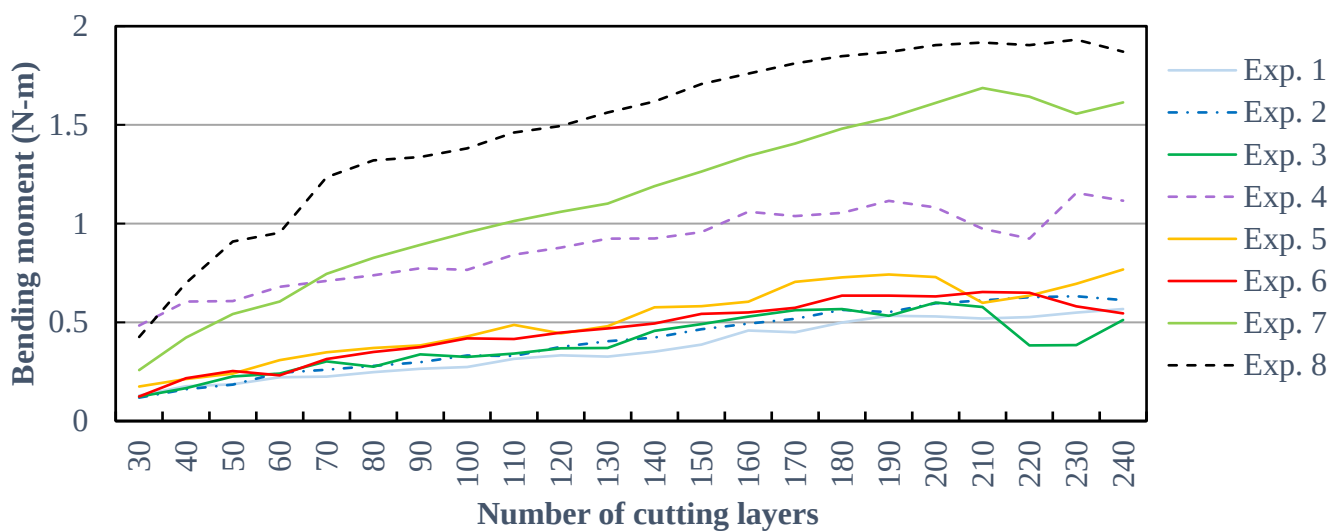


Figure 8. Bending moments at different cutting speeds.

3.1.3. Tool Wear and Cutting Moment

The captured bending moment signals during processing in the x direction and y direction were plotted on the x- and y-axes, respectively, and a polar diagram of the bending moment signals was generated, as displayed in Figure 9. The size and distribution of the plots on the polar diagram were examined to determine the cutting force and damage to the tool holder. According to the distribution of the plots, Experiments 1–3 exhibited the most concentrated and uniform distributions, indicating that the force in the cutting process was average and stable. The graphs of Experiments 7 and 8 were relatively scattered and revealed that the number of flutes was two. The data revealed that the bending moment increased. Tool wear was observed under a digital microscope with a magnification of 100×, as depicted in Figure 10. Because of the setting of the tool axis (Figure 3), the contact area between the tool and the blade was on the side cutting edge of the front end of the tool. The most severe wear occurred on the flank of the side edge. Although the bending moment is usually the best representation of tool wear in side milling among cutting forces, it is not necessarily the cause of tool wear. The tool in Experiment 4 can be observed to have more serious wear compared to Experiments 1–3. Severe wear was demonstrated by the tool flank in Experiments 7 and 8. In the machining of difficult-to-cut materials, flank wear mainly comes from the amorphous transformation caused by friction and heat accumulation between the tool and the workpiece. It can be speculated that the temperature generated by the cutting speed under this condition is too high, which has caused welding or plastic deformation on the tool surface [22].

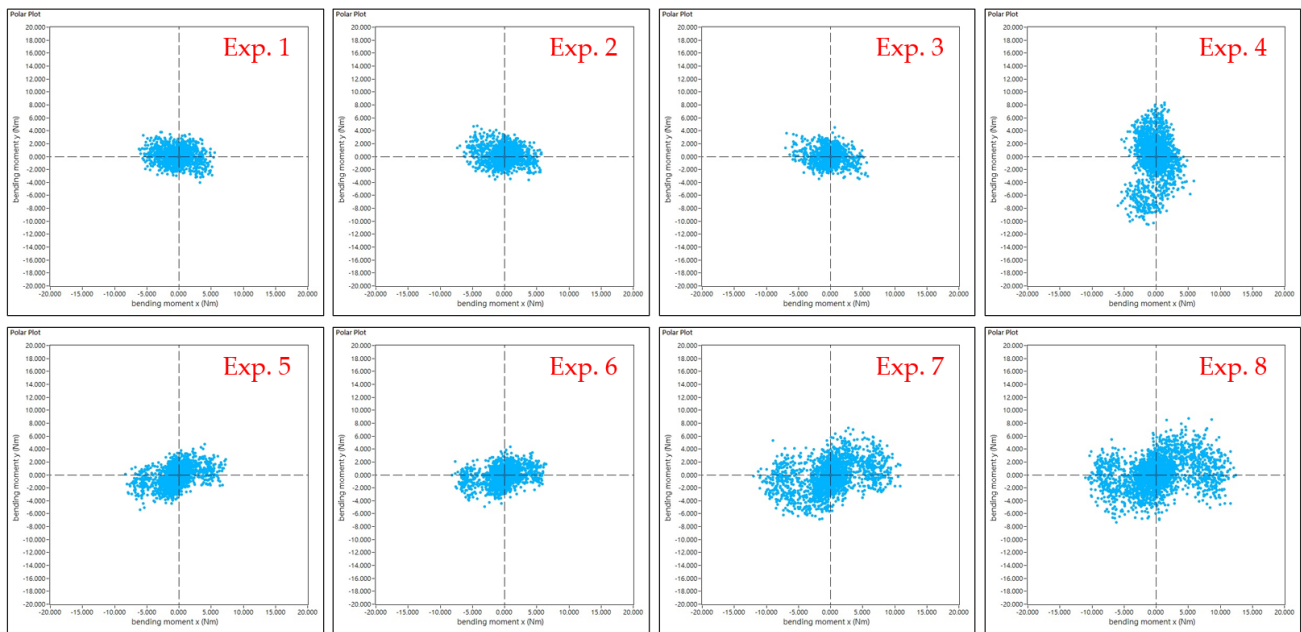


Figure 9. Bending moment in polar coordinates at different cutting speeds.

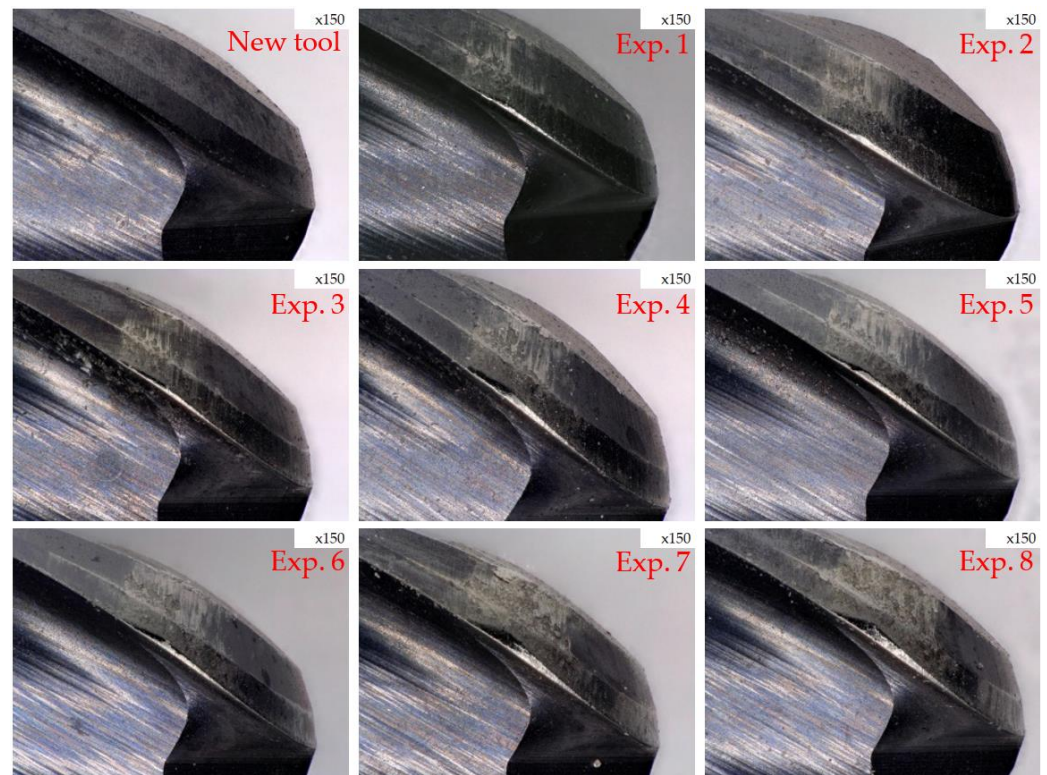


Figure 10. Flank wear at different cutting speeds.

3.2. Feed per Tooth

3.2.1. Processing Conditions and Parameters

According to the experimental results regarding cutting speeds, we also considered tool wear and machining efficiency. Cutting speeds of 66 and 76 m/min were selected as the reference, and the feed per tooth was adjusted. The machining parameters were determined and are presented in Table 6. A new tool was used for each experiment.

Table 6. Machining parameters II.

	Cutting Speed V_c (m/min)	Effective Cutting Speed V_e (m/min)	Feed per Tooth F_z (mm/tooth)	Depth of Cut A_p (mm)	Time (min/s)
Exp. 9	66	46.53	0.05	0.05	22:30
Exp. 10	66	46.53	0.075	0.05	16:36
Exp. 11	66	46.53	0.1	0.05	13:02
Exp. 12	76	53.59	0.05	0.05	19:43
Exp. 13	76	53.59	0.075	0.05	14:09
Exp. 14	76	53.59	0.1	0.05	12:14

3.2.2. Cutting Signal Capture and Analysis

As presented in Figure 11, Experiments 9 and 12 yielded lower bending moment curves than did the other experiments. When the feed per tooth was set to 0.05 mm, less cutting force was observed. The cutting forces at a feed per tooth of 0.1 and 0.075 mm were similar. The feed per tooth has a significant effect on the cutting force, but the relationship is not linear. In the literature, a second-order nonlinear cutting force model of spindle speed and feed per edge was derived based on experimental data [23]. In experiments, there are also situations where the specific cutting forces of 0.06 and 0.07 mm/tooth are quite close.

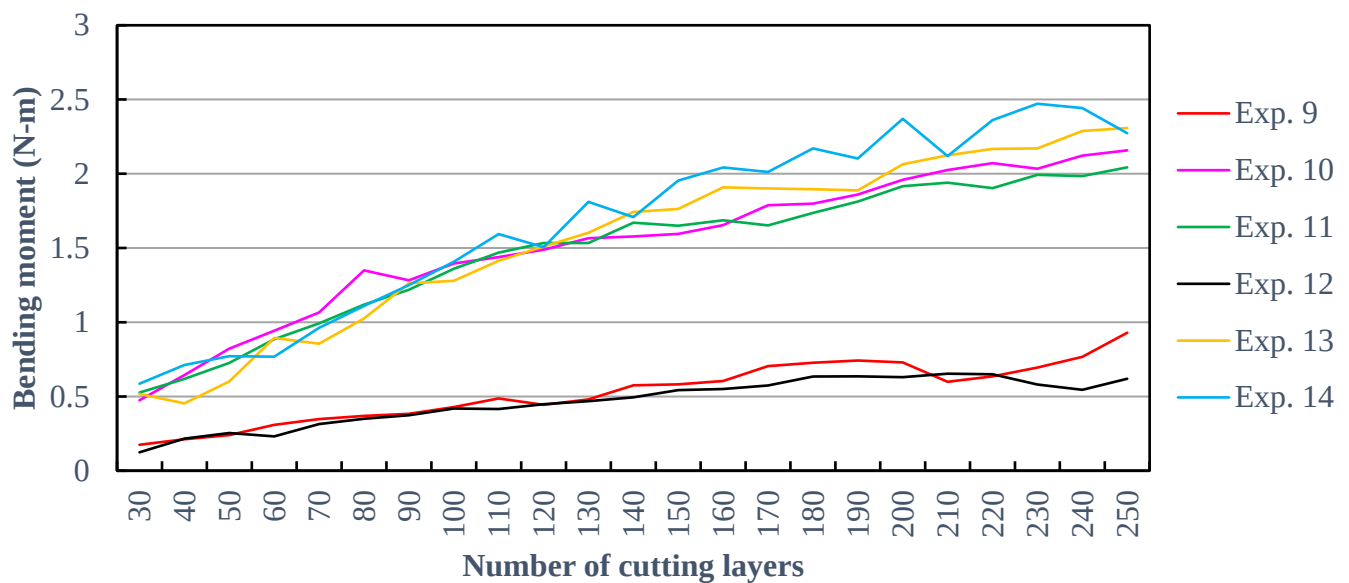


Figure 11. Bending moments at different feeds per tooth.

3.2.3. Tool Wear and Cutting Moment

According to the polar diagram of the bending moment, the distributions observed for Experiments 9 and 12 were more concentrated than those observed for the other experiments (Figure 12). The other diagrams revealed a relatively large cutting force, and the tool may break at dense points. The tool exhibited various degrees of wear under magnification, as illustrated in Figure 13. Experiments 9 and 12 yielded relatively low wear, which is consistent with the smaller bending moments we observed.

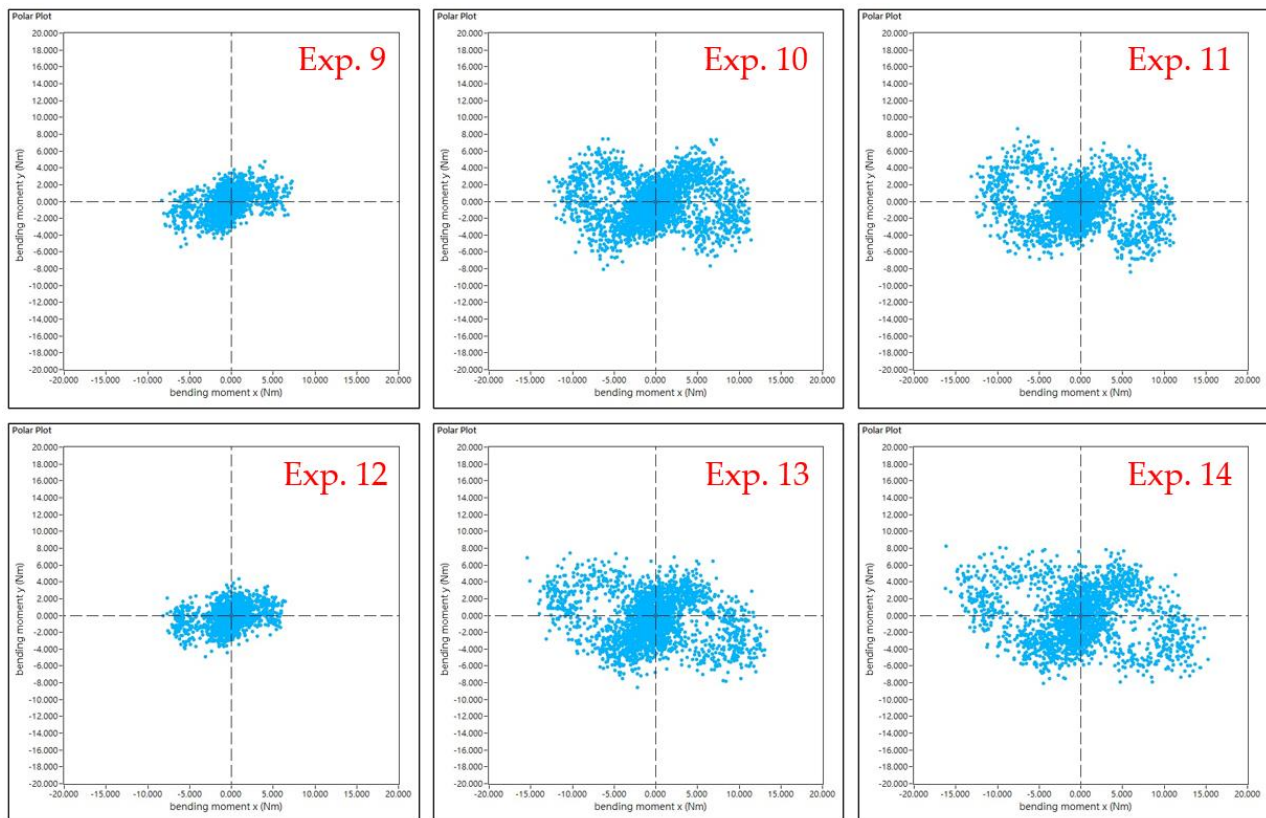


Figure 12. Polar coordinates of bending moment at different feeds per tooth.

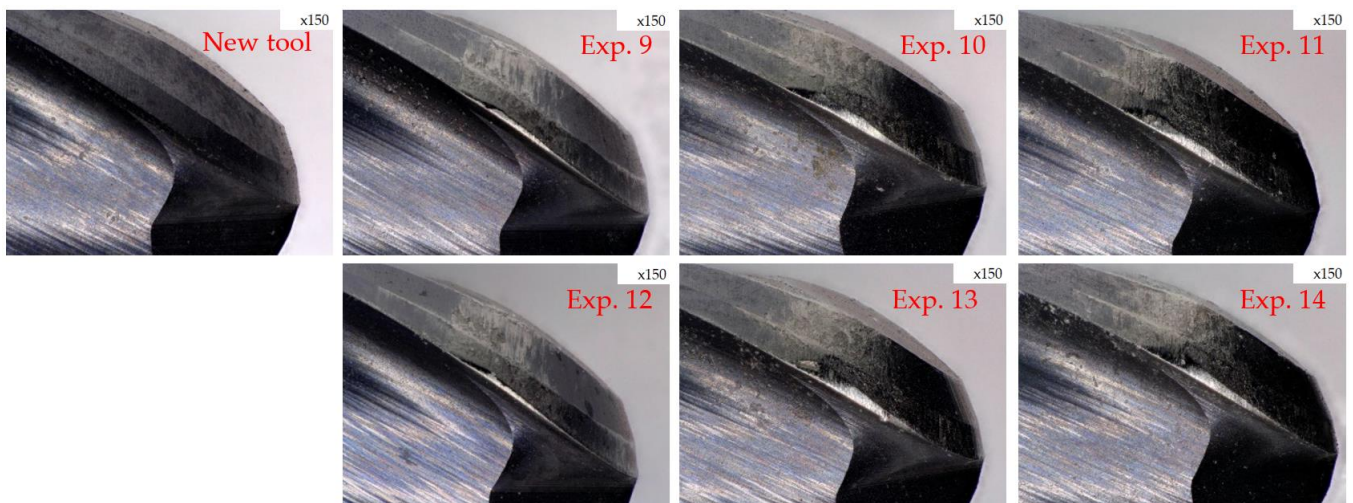


Figure 13. Flank wear at different feeds per tooth.

4. Tool Life Test

Through basic cutting experiments, we determined the relationship between cutting parameters, bending moments, and tool wear. The experimental results could be used to evaluate machining efficiency and surface roughness requirements. For mechanical efficiency considerations, this study expected the blade surface roughness to reach a satin finish, which means the roughness requirement is RZ6.3 (Ra1.6). We measured the finished surface roughness, as shown in Figure 14. According to the measurement results, we explored reasonable machining parameters that could be used to test the tool's life.



Figure 14. Finished blade surface.

4.1. Assessment of Surface Roughness

Currently, two methods are widely used in the aerospace industry to measure surface roughness: contact and noncontact. We used the noncontact method by portable surface texture measuring instrument for online measurement during processing. The instrument was HANDYSURF+35 (TOKYO SEIMITSU, Tokyo, Japan) and its resolution can reach $0.0007\ \mu\text{m}$. Each blade was measured three times to obtain the average. Non-contact 3D white light interferometer microscope Opt-scope (TOKYO SEIMITSU, Tokyo, Japan) with a high vertical resolution of $0.01\ \text{nm}$ was used for offline measurement. We compared the results of the two measurement methods, as shown in Figure 15. The results revealed that all processing results in Experiments 1–14 fulfilled the roughness requirements.

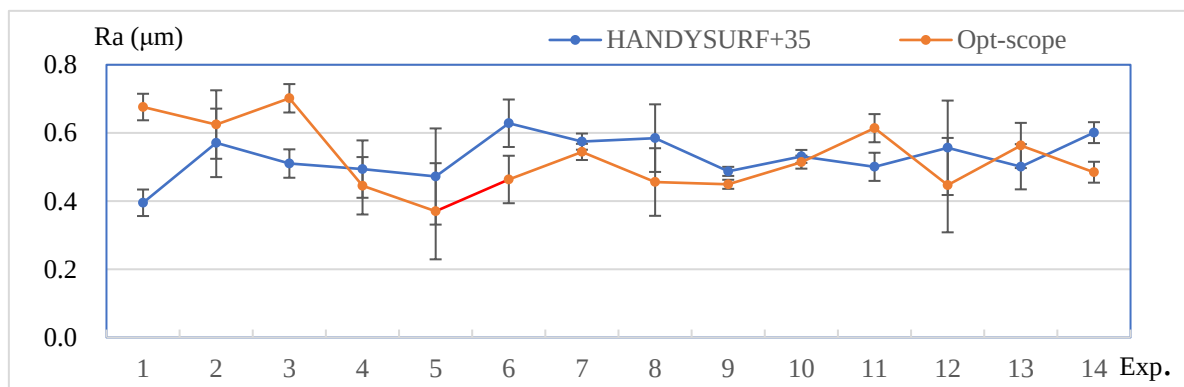


Figure 15. Surface roughness measurement results.

4.2. Repetitive Experiments

The basic cutting experiments revealed optimal machining parameters yielding small and stable cutting forces, which helped improve the surface quality of the blade. However, considering processing efficiency, one can adjust the machining parameters within an acceptable surface quality to shorten the machining time. We selected the parameters of Experiment 11 and performed repeated experiments by using the same tool 12 times (Table 7) for tool life assessment.

Table 7. Machining parameters III.

	Cutting Speed V_c (m/min)	Effective Cutting Speed V_e (m/min)	Feed per Tooth F_z (mm/tooth)	Depth of Cut A_p (mm)	Time (min/s)
Exp. 15~26	66	46.53	0.1	0.05	13:02

4.3. Bending Moment and Tool Wear

The cutting force increased steadily as the experiment progressed, as shown in Figure 16. The bending moment demonstrated a step jump after Experiment 23. We assessed magnified images of the tool and detected a crack on the flank of the tool after Experiment 23 (Figure 17). The cracked part is built-up-edge (BUE) adhesion [24]. After BUE is formed and peeled off, the coating will be taken away and part of the edge will peel off. Therefore, when BUE occurs, the tool wear increases significantly, and the bending moment also increases significantly. These phenomena will cause a decrease in surface roughness and dimensional accuracy, which then often requires tool replacement. On the basis of the evaluation results, we determined that the tool life was approximately eight blades under the selected surface quality and efficiency parameters.

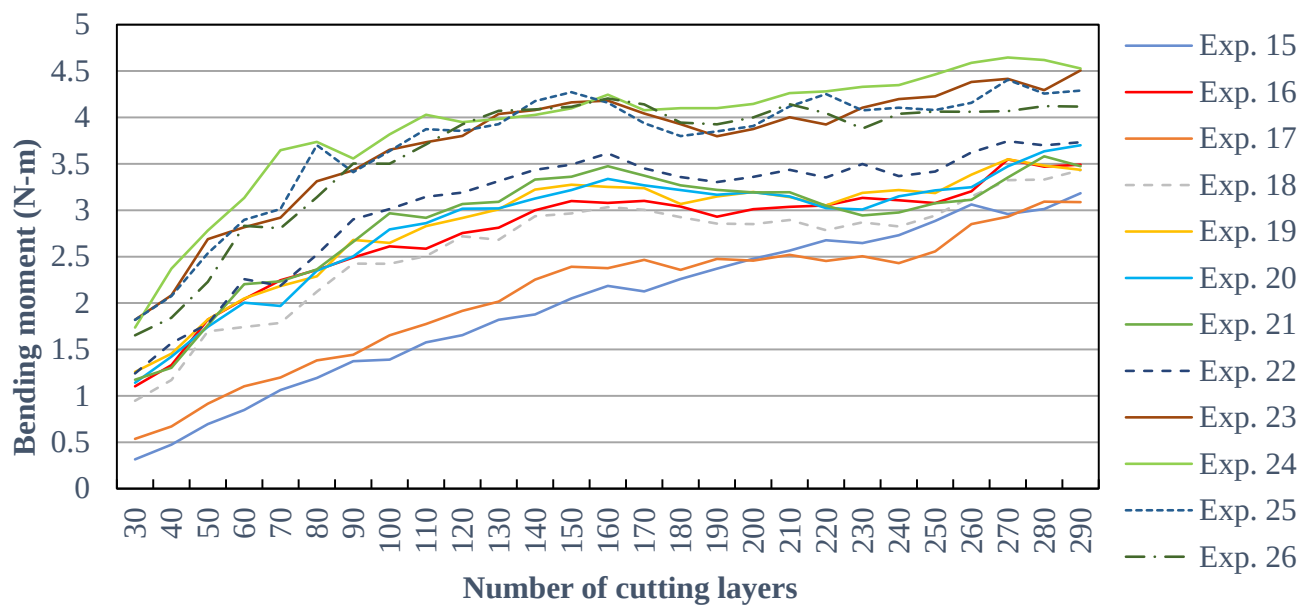


Figure 16. Bending moments in repeated experiments.

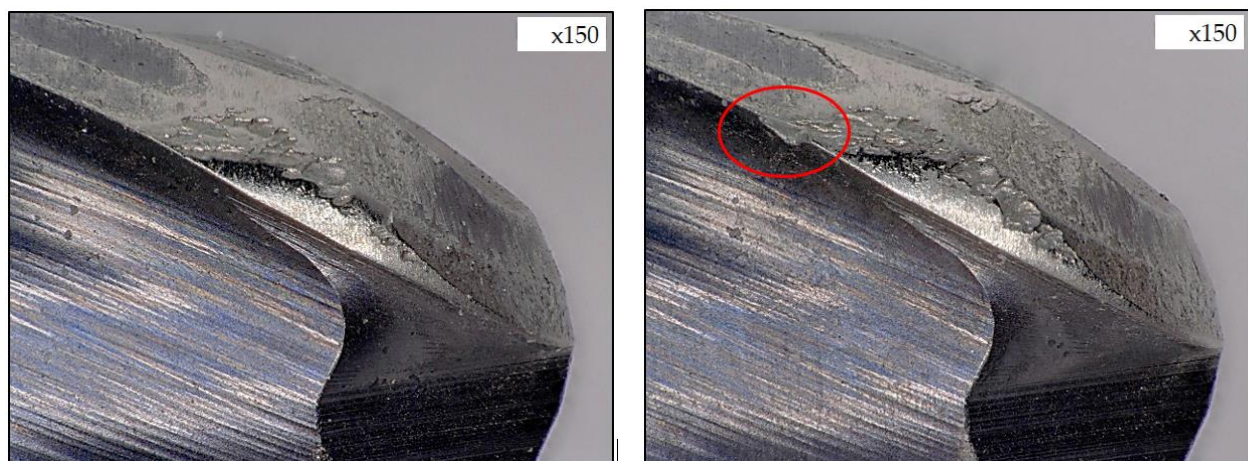


Figure 17. Flank wear after Experiments 22 (Left) and 23 (Right). (The red circle shows the cracked part).

In addition, every time a new blade is cut, the bending moment curve first decreases and then gradually increases. This phenomenon can be speculated that when the end mill is deeper and deeper in the groove, the cutting reaction force of the blade gets bigger and bigger. Chip removal becomes more difficult, resulting in an increasing bending moment in the later stage.

5. Conclusions

In this study, we conducted basic cutting and tool life experiments to analyze cutting conditions in the blisk finishing processes. Force signals collected by a sensory tool holder directly indicated the cutting forces and the influence of machining parameters on the cutting forces was nonlinear; this could thus help us select efficient parameters. The bending moment diagram also accurately indicated tool wear, which could help us estimate the time required to change the tool. On the basis of our findings, we drew the following conclusions:

1. A cutting speed between 66 and 76 m/min (effective cutting speed between 46 and 53 m/min) can provide a relatively low cutting force, which can shorten the machining time and maintain surface quality.
2. A feed per tooth of 0.05 mm can provide a relatively low cutting force, and a feed per tooth of 0.075 and 0.1 mm can provide relatively high cutting forces, and the values are similar.
3. A cutting speed of 66 mm/min (effective cutting speed of 46 m/min) and feed per tooth of 0.1 mm can provide the most stable cutting force and the highest processing efficiency.
4. Under the aforementioned conditions, a tapered ball-nose end mill can process a total of eight blades.

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