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Article

Productivity Enhancement of Aircraft Turbine Disk Using a Two-Step Strategy Based on Tool-Path Planning and NC-Code Optimization

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Abstract: Most of the parts of an aircraft require the use of lightweight and high-strength materials. Since aircraft parts mainly use mechanical cutting processes, which are the most suitable material removal mechanism, to minimize changes in material properties, it is necessary to develop an optimal cutting tool and cutting solution for each material. This work aims to enhance productivity and reduce the production cost of an aircraft turbine disk through designing a cutting strategy and optimizing the cutting conditions using a simulation approach. The number of tools was reduced from eight to six compared to the existing process conditions for semi-finishing and finishing of a turbine disk, and a new tool path was proposed through simulation. The cycle time was reduced by about 24%. NC-code optimization was performed through feed-rate optimization considering cutting force and chip thickness. As a result, cycle times were reduced by about 14%. Through tool-path optimization and NC-code optimization, it was confirmed that the total cycle time was reduced by about 54%, and tool wear was significantly improved.

Keywords: turbine disk; nickel-based superalloy; productivity; tool path; machining accuracy

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1. Introduction

In general, an aircraft is composed of numerous parts such as an engine, landing gear, and airframe parts. Most of the parts require the use of lightweight and high-strength materials. Recently, the weight reduction of aircraft body and improvement of engine efficiency are required due to issues related to energy saving and low carbon, so the application of aluminum alloy, titanium alloy, nickel-based alloy, and composite materials is increasing [1,2]. Since aircraft parts mainly use a mechanical cutting process to achieve geometric definition, which is the most suitable material removal process, to minimize changes in material properties, it is necessary to develop an optimal cutting tool and cutting solution for each material. Cutting processes with machine tools aim to reduce cutting times and work processes, with aircraft engine manufacturers typically aiming for time savings of 30% to drive down costs.

Yan et al. [3] investigated a structural optimization for the non-circular vent hole on an aero-engine turbine disk. For the vent hole design, a novel optimization method, namely the surrogate-based optimization method using an improved support vector regression, was proposed. The proposed method was verified to be suitable and valuable as an optimization approach. Song et al. [4] studied the improvement of the modeling efficiency and optimization accuracy for fatigue reliability-based design optimization (FRBDO) of an aero-engine turbine disk. The hierarchical fuzzy-neuro method and multi-level collaboration method were proposed by the authors, and two methods were applied to the FRBDO of a high-pressure turbine disk. The optimization results show that the presented framework holds high computational efficiency and accuracy in the FRBDO of a turbine disk. González et al. [5] performed the machining of integral blade rotors made in Ti6Al4V using CO_2 as cryogenic cooling. They found that if some changes in CAD surfaces are allowed, to convert them from a free-form type into rule type in flank milling, productivity could be increased dramatically. Suárez, Polvorosa and their colleagues [6–8] investigated the tool wear and surface integrity of difficult-to-cut materials used as materials for turbine disks in milling and turning.

To solve the problems of cycle time, accuracy, and productivity, studies on tool-path optimization have been conducted in the cutting process. Lin et al. [9] proposed a new way of planning the space-filling curve type tool path by formulating the planning task as a traveling salesman problem for multi-axis freeform surface finishing. The proposed tool-path generation method shows that the method can automatically find the optimal feed direction, and it can generate a shorter tool path than the traditional method. Pezer [10] verified the efficiency of tool-path optimization using a genetic algorithm in relation to the optimization achieved with a selected CAM software. The problem solution was achieved by using MATLAB software, and the obtained results were compared with the results achieved with a CAM software. Ridwan et al. [11] developed an optimizer for canonical machining commands. Fuzzy adaptive control was used to keep a constant cutting load by adjusting the feed rate automatically to the cutting conditions. The results showed that optimum feed rates can be achieved and controlled during the machining process. The developed optimizer helped achieve machining optimization, shorten machining time, and increase product quality. Xu et al. [12] proposed a feed-rate optimization method of end milling using the internal data of the CNC system based on the controlled elitist non-dominated sorting genetic algorithm. Compared to the traditional method of optimizing the feed rate via the cutting force, the spindle power used in the proposed method was better because it is more convenient to acquire and is cost effective. Hatem et al. [13] developed a new system that combines the open CNC control system and an ant colony optimization algorithm by using LabVIEW software for optimization of a tool-path operation to reduce the non-productive machining time. The system was based on STEP-NC interpretation, optimization, 3D simulation, and automatic document generation modules. The percentage of tool-path improvement was 16.96%. Lukic et al. [14] investigated a multi-criteria selection of the optimal parameters for high-speed machining of mechanical parts. The influence of various cutting parameters, including a tool-path strategy, was examined on machining time and the material removal rate. As a result, the optimal parameters were obtained by selecting the optimal level and rank of alternative levels of machining parameters. Hu and Guo [15] proposed a tool-path optimization algorithm of spatial cam flank milling based on NURBS surface. Combined with the theoretical CNC machining error model, the algorithm validity was proved by numerical calculation of the example and simulation experiment results. Dittrich et al. [16] developed a self-optimizing process planning approach for five-axis milling using a machine learning method. After the shape error was predicted and the tool path adapted automatically, the shape error was reduced by 50%. Similarly, Hatem et al. [17] developed a novel tool-path optimization using an ant colony optimization (ACO) algorithm. The paper dealt with an effective methodology to reduce manufacturing time through the creation of quasi-optimal G command sequences. Han et al. [18] and Liang et al. [19] performed feed-rate scheduling to reduce machining time and improve surface finish in a multi-axis CNC machine tool. The effectiveness and time-optimality of the feed-rate scheduling method were verified by several simulation and experimental results. Park et al. [20] developed a smart machining system for optimizing feed rates to minimize machining time. The algorithm was integrated into an autonomous machining system to modify the NC program to accommodate these new feed-rate values. As a result of the experiment, the machining time was reduced by 26%. However, the simulation results showed that the machining time can be reduced by around 35%. This means that the acceleration and deceleration of the machine tool should be considered.

Tool-path and feed-rate optimization are important aspects of obtaining a shorter cutting time and increasing the potential of efficient machining. However, it is difficult to satisfy productivity improvement, time reduction, and cost reduction by considering tool-path and NC-code optimization at the same time as a method that can be easily applied to the actual field.

Many researchers studied cost reduction and productivity enhancement through structural optimization by a design change and tool-path planning. However, the production site has many limitations, making it difficult to change the structural design or apply a new algorithm. It is necessary to find a method that can be easily applied to the field. This work aims to enhance productivity and reduce the production cost of an aircraft turbine disk through designing a cutting strategy and optimizing the cutting conditions using a simulation method. Two main paths of the research are listed as follows. The first step involves optimizing the cutting conditions, including tool-path planning and NC-code generation, using the CAM simulation. The second step concerns verifying the optimum cutting conditions obtained, considering the simulation results. Therefore, the work performs experiments on turbine disk cutting to analyze and discuss machining characteristics.

2. Materials and Methods

2.1. Cutting Strategy

This work focuses on establishing a strategy for reducing cycle time to reduce cost in the turning process of a turbine disk. A methodology for productivity enhancement of aircraft turbine disk using a two-step strategy is proposed in Figure 1. For this, first, a simulation was performed for reducing the number of tools and generating a tool path using the Siemens NX CAM program (NX for manufacturing, Siemens, München, Germany).

The purpose of the simulation is to obtain conditions that reduce the cycle time and minimize the distortion of the parts compared to the existing process. This was achieved through optimization of the material removal sequence as well as developing tool paths that maximize tooling capability whilst minimizing tool wear. What the existing process means is that the conditions used by company H to fabricate the turbine disk are used in the actual aircraft engine. Based on the simulation results, an experiment was performed in a lathe, and the results were analyzed and discussed.

The information of the existing process for machining of an aircraft turbine disk is summarized in Table 1. The material was Waspaloy, a nickel-based superalloy with excellent strength properties and good corrosion resistance. The cycle time was 58 min and 24 s, and eight cutting tools were used.

Table 1. The process information.

Parameters	Specification
Material	Waspaloy
Cycle time	58 min 24 s
Cutting tool inserts (No.: Product model)	T01: CNMG120408 T02: VBMT160404 T03: VDB125RA T04: VDX009-B-03 T05: CCMT09T308FG T06: VDB005-A-R04 T07: VDX009-B-01 T08: GIP-3.00E-0.4
Platform information for machining	Vertical lathe with Fanuc controller

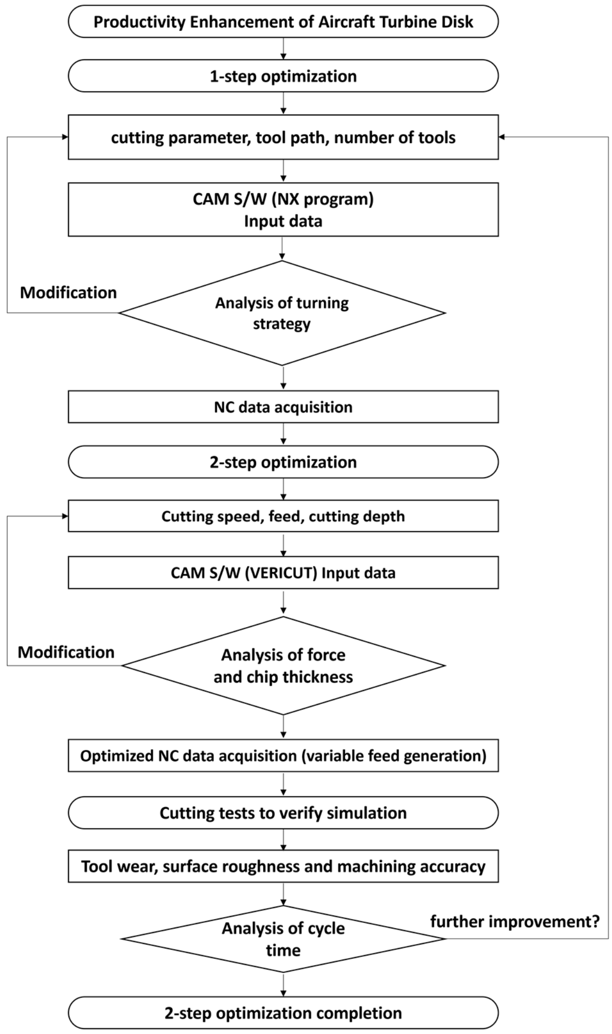


Figure 1. Flow chart of productivity enhancement of aircraft turbine disk using a two-step strategy.

The number of cutting tools was reduced from eight to six for reducing the cycle time in this work. Six tools with an appropriate nose radius were proposed by considering the product shape. Table 2 represents the information on cutting tools.

Table 2. Cutting tool inserts and their details.

No.	Insert	Nose Radius
T01	DNMG150408	0.8 mm
T02	N123F2-0300-RO	1.5 mm
T03	N123F2-0300-RO	1.5 mm
T04	N123G2-0300-0004-GF	0.4 mm
T05	N123H1-0200-RO (L)	1.0 mm
T06	N123F2-0300-RO	1.5 mm

2.2. Tool-Path Planning Using CAM Simulation

Turning process simulation was performed using the proposed six cutting tools. Siemens NX CAM program was used for the simulation, and it was performed in the order of semi-finishing and finishing.

Cutting parameters were selected based on the existing cutting conditions, the conditions recommended by the cutting tool manufacturer, and transferable experience from similar materials.

The cutting sequence was defined by the simulation results, and the 2D simulation model was shown in Figure 2. The sample part geometry and stock to be machined were represented in 2D. Table 3 shows the information on cutting conditions, and machining time for semi-finishing and finishing. The information on the tool paths is shown in Figure 3.

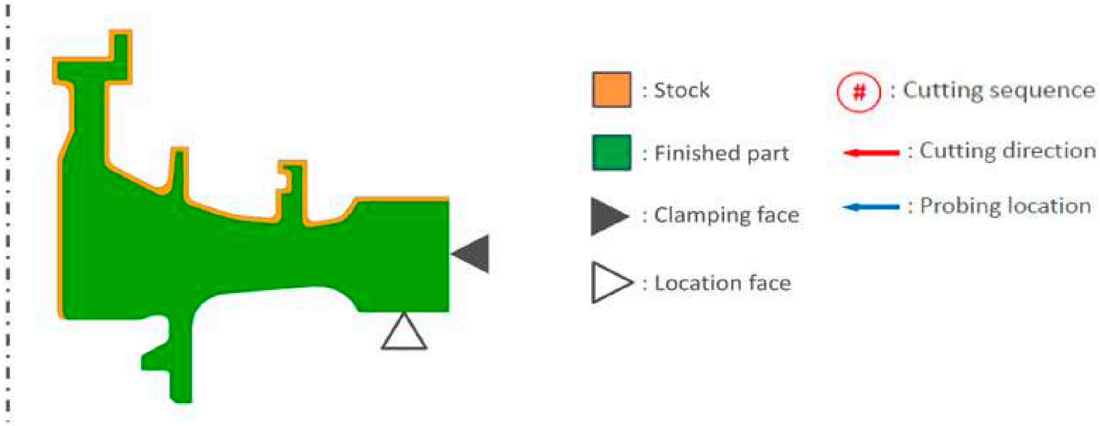


Figure 2. The sample part geometry and stock to be machined.

Table 3. The information on cutting conditions and machining time. (**a**) Semi-finishing; (**b**) finishing.

(**a**)

Stage	No. of Tool	V_c (m/min)	f_n (mm/rev)	a_p (mm)	Time (mm:ss)
A	T01	60	0.15	0.5	02:24
B	T02	50	0.08	0.5	02:37
C	T03	50	0.15	0.5	01:24
D	T04	55	0.15	0.5	02:50
E	T05	50	0.15	0.5	04:05
F	T03	50	0.15	0.5	00:30
G	T01	60	0.15	0.5	01:08
H	T06	55	0.15	0.5	00:37

(**b**)

Stage	No. of Tool	V_c (m/min)	f_n (mm/rev)	a_p (mm)	Time (mm:ss)
I	T01	65	0.12	0.25	01:52
J	T03	50	0.12	0.25	02:49
K	T04	55	0.12	0.25	06:27
L	T02	50	0.08	0.25	03:05
M	T05	50	0.12	0.25	07:53
N	T03	50	0.12	0.25	00:56
O	T06	55	0.12	0.25	01:35
P	T01	65	0.12	0.25	02:22
Q	T01	65	0.12	0.25	02:04

The simi-finishing strategy consisted of 8 steps from A to H, and the total machining time was 15 min 35 s. The finishing strategy has 9 steps from I to Q, and the total machining time was 29 min 5 s. As a result of reducing the number of tools and applying new tool paths, the total machining time including semi-finishing and finishing was 44 min and 40 s, which was reduced by about 24% compared to the previous cycle time.

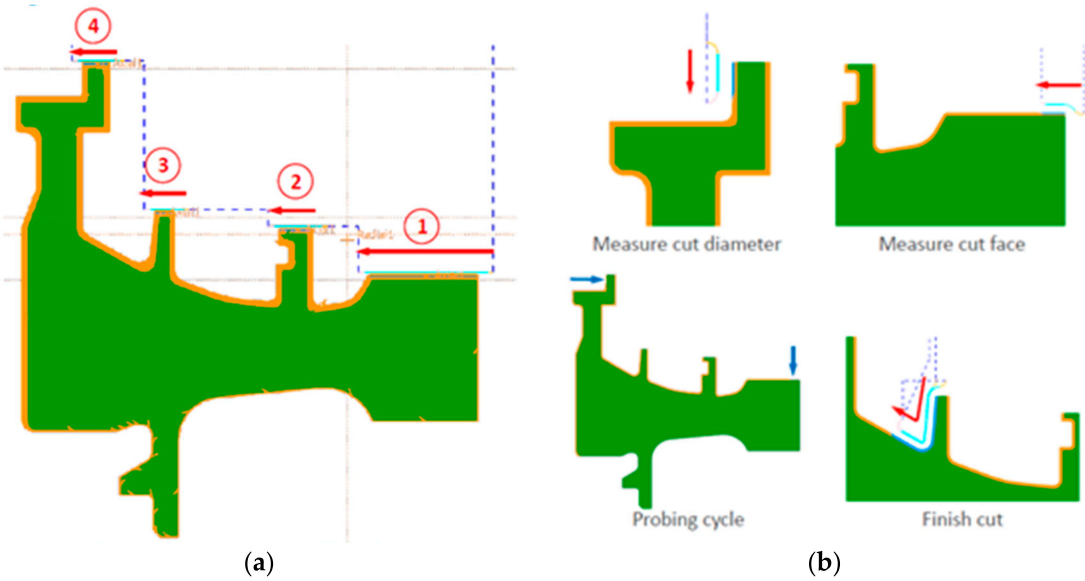


Figure 3. The tool paths by simulation results: (**a**) stage A at semi-finishing; (**b**) stage J at finishing.

2.3. NC-Code Generation and Optimization

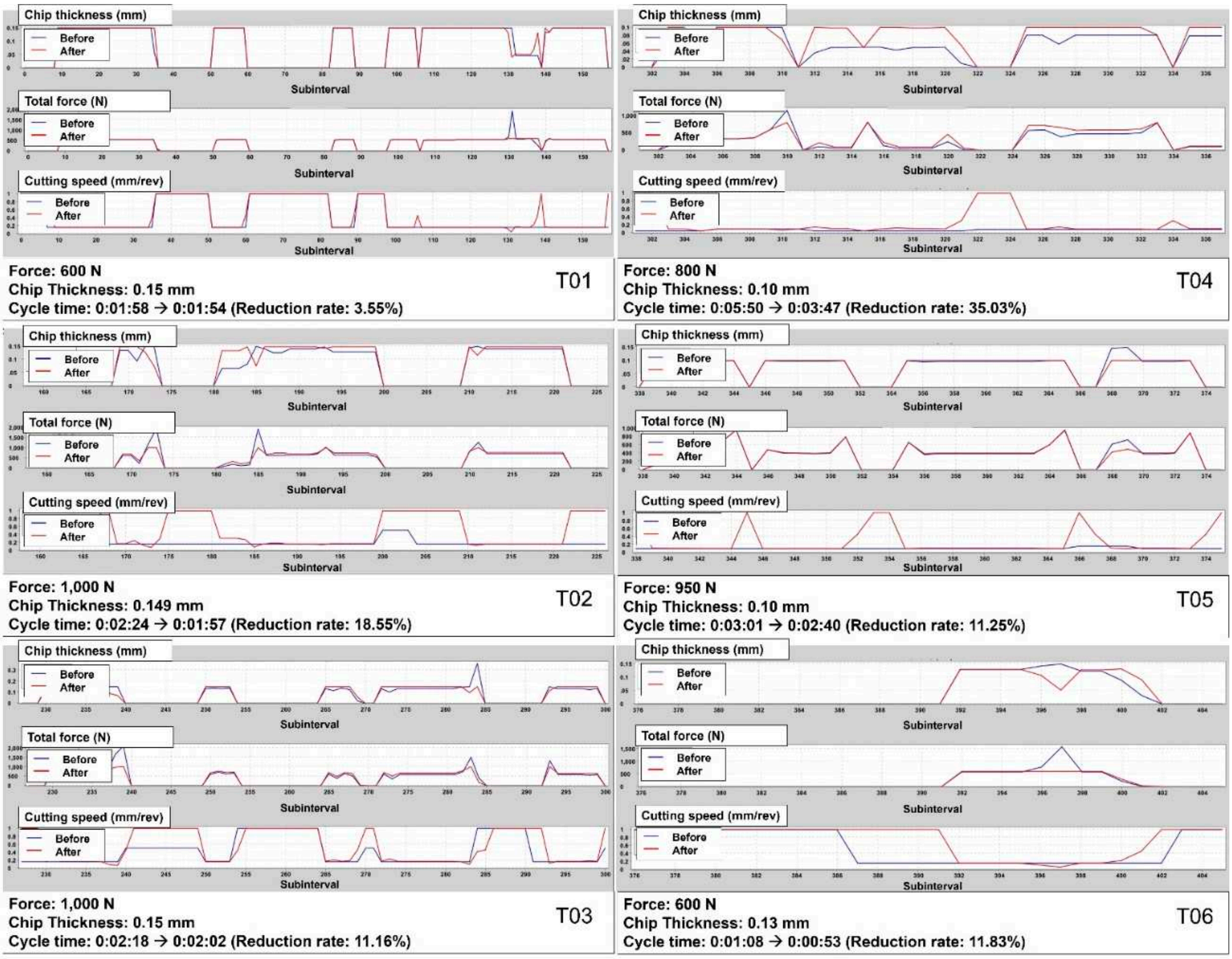
Based on the cutting conditions and tool path generated by Siemens NX CAM program, NC code was generated and verified using CGTech Vericut software (v9.1, CGTech, Irvine, CA, USA), and variable feed was created through the Vericut Force function to shorten cycle time. With the Vericut Force function, cutting conditions can be optimized by adding variable feed to control the cutting load and chip thickness. Keeping maximum chip thickness steady is the key to cut effectively, thin chips adversely affect low productivity and tool wear, while chips that are too thick can cause tool overload and risk breakage. The object functions consist of constant chip thickness and cutting force. Effects such as improvement of machining quality, reduction of tool wear, and reduction of cycle time can be achieved by selecting the optimal feed in the tool path and improving the feed in the air cut section.

Since the tool path generated in this work was the result obtained by considering only the cutting tool insert without considering the tool holder and equipment, it is therefore necessary to verify the interference and collision. Based on the tool path and cutting conditions created by the program, NC code was generated to check the interference and collision, considering the tool holder. As a result, it was confirmed that over-cutting, under-cutting, tool holder interference, and the collision occurred in T1, T3, and T4, and the tool holder and cutting tool were changed to smoothly implement the generated tool path. Table 4 shows the cutting tool and tool holder information to be applied to the final cutting test.

Feed optimization was performed using the final selected cutting tool and cutting conditions. Based on the cutting force and chip thickness shown in the simulation results, the cutting conditions for improving productivity while maintaining the cutting force and chip thickness constant were selected. Figure 4 shows the comparison results and cycle times before and after feed optimization for each cutting tool. Within the figure, you will see three plots covering chip thickness, total force, and cutting speed, respectively. Dual optimization was applied to both chip thickness and total force with the resulting change to cutting speed shown in the final plot.

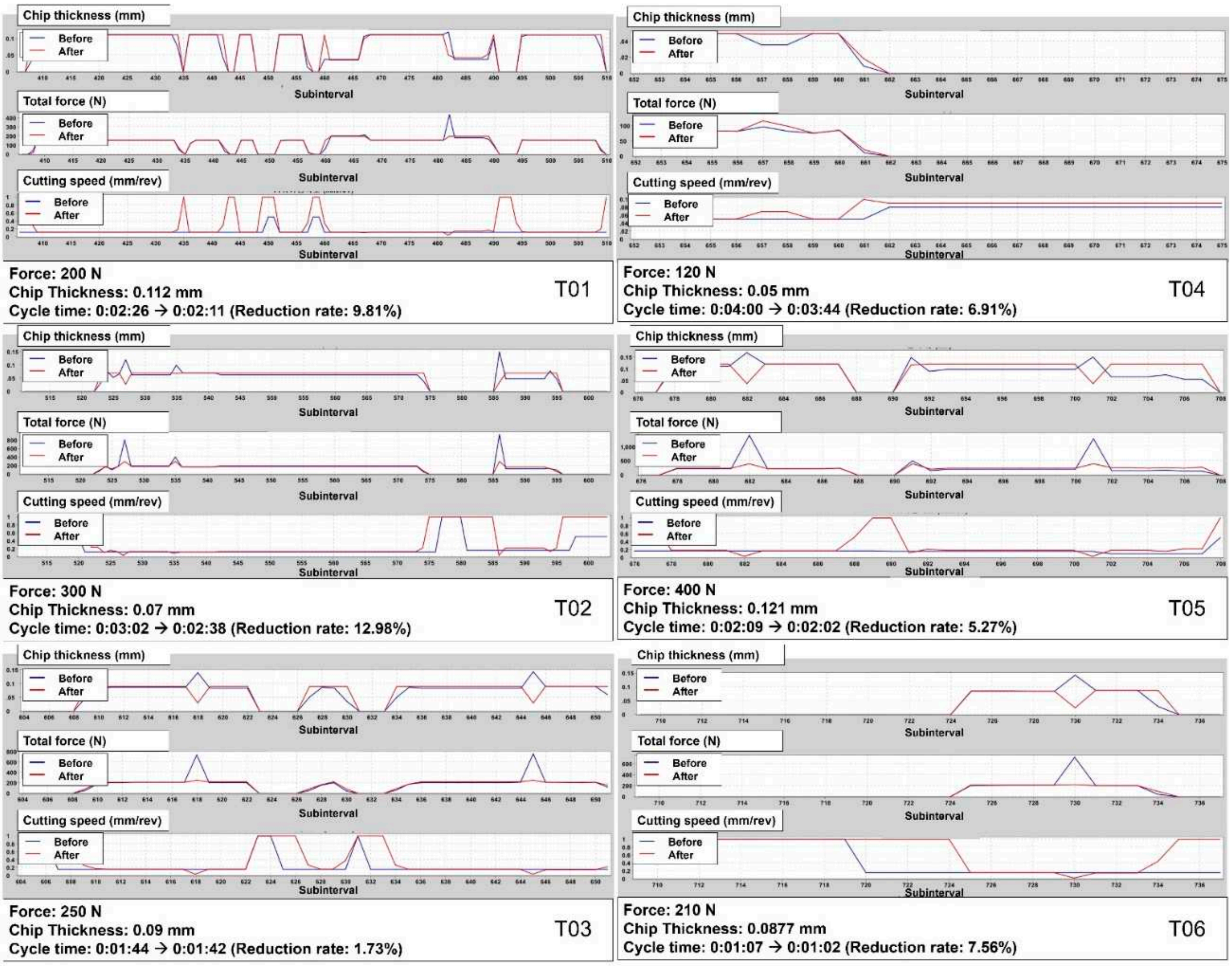
Table 4. Cutting tool inserts and tool holders for final test.

No.	Cutting Tool Insert		Tool Holder
	Before	After	
T01	DNMG150408	DCMT32.51 MT TT5080 (TaeguTec, Daegu, Korea)	S25R-SDQCL-11
T02	N123F2-0300-RO	N123F2-0300-RO (SANDVIK, Stockholm, Sweden)	RG123G07-2525C
T03	N123F2-0300-RO	TDT 3E-1.5-RU (TaeguTec, Daegu, Korea)	TTFR25-70-3RN
T04	N123G2-0300-0004-GF	GEDI 3.00-0.20 (ISCAR, Migdal, Israel)	GEHIR 12-15-3-T6
T05	N123H1-0200-RO (L)	N123H1-0200-RO (L) (SANDVIK, Stockholm, Sweden)	RF123F10-2525B
T06	N123F2-0300-RO	N123F2-0300-RO (SANDVIK, Stockholm, Sweden)	TGEUL2525-3S



(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. Comparison results and cycle times before and after feed optimization. (**a**) Semi-finishing; (**b**) finishing.

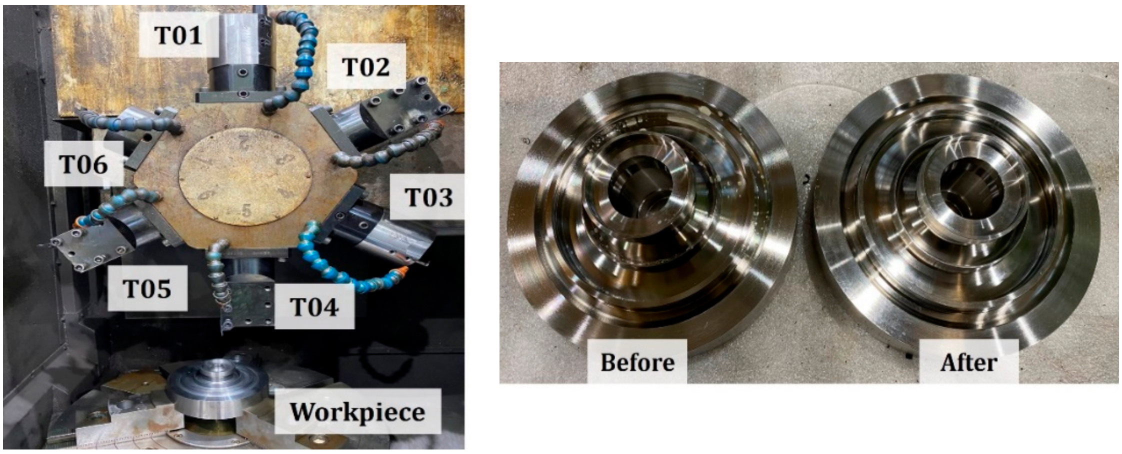
The cycle time decreased the most in the cutting section using the T04 in the semi-finishing process. This is because the cutting speed is improved to maintain the cutting force and chip thickness constant. An average cycle time reduction of 15.2% was obtained in the semi-finishing, and an average cycle time reduction of 7.4% was obtained in the finishing. The cycle time before optimization was 30 min and 58 s, and the time after optimization was reduced by about 14.2% to 26 min and 34 s. The time before feed optimization is different from the simulation optimization result (44 min 40 s). The reason for this is that the time generated by Vericut differs from that of the Siemens NX simulation because it relies heavily on the control files used by Vericut to define the machine simulation. While Vericut simulates real NC code, Siemens NX is taken directly from the NX environment, which contains only the cutting tool path. Figure 5 shows the NC code for semi-finishing T04. It can be confirmed that the variable feed condition was performed.

```
N40T0400
G50S50(MAX RPM.)
/M08(FLOOD COOLAT ON)
(STAGE E FOR SEMI-FISHING-1)
G96S60M3
G00X121.757Z50.0T0404M08
Z-31.632
G1X123.693F1.
X125.628F0.1
X126.596F0.046
G0X122.
Z-33.032
G1X125.677F0.1
X126.596F0.069
X126.316Z-32.892F0.1
G0X122.757
G0Z-30.
X123.05
Z-33.536
G1X123.757Z-33.182F0.139
X125.716F0.101
X126.696F0.049
F0.05
G2X127.396Z-32.832R.35
G1Z-32.332F0.1
G0X123.
Z-31.128
G1X124.157Z-31.482F0.116
X125.85F0.101
X126.696F0.1
F0.05
G3X127.396Z-31.832R.35
G1Z-32.332
G0X123.05
G00Z10.0M05
(STAGE E FOR SEMI-FISHING-1)
G97S40M4
G00X-68.383M08
Z-12.291
G1X-65.383F1.
X-64.383F0.1
X-64.213
X-63.813Z-12.491F0.139
F0.08
G2X-63.53Z-12.55R.2
G1X-58.226Z-12.549F0.1
X-56.105Z-12.549F0.081
F0.08
G3X-55.385Z-12.91R.36
G01Z-14.21F0.101
G00X-69.0
G00Z100.0M09
G97G28U0.W0.M05
T0400
M01
```

Figure 5. Generated NC code for T04.

3. Results and Discussion

The turning operation was conducted on a vertical lathe (S&T Dynamics Co., Ltd., Changwon, Korea, Type T850VD). The quality evaluation was performed by machining the turbine disk under the cutting conditions before and after feed optimization. Moreover, the effect of feed optimization was verified through tool wear evaluation. The test specimen was manufactured by roughing operation of the Waspaloy cylindrical material. Figure 6a provides the experimental setup with six cutting tool inserts, and Figure 6b shows the final products before and after feed optimization was applied.



(a) (b)

Figure 6. Experimental setup and the photograph of manufactured turbine disks. (**a**) Six cutting tool inserts and workpiece; (**b**) final products before and after feed optimization.

3.1. Tool Wear

The tool wear of the used cutting tools during the semi-finishing and finishing process was measured using a digital microscope. Flank wear, which can be called major wear, was measured, and it was measured from the top of the crater wear to the maximum depth.

Figure 7 shows the tool wear after semi-finishing. In T01 and T03, flank wears were not significantly different before and after optimization. This is because they maintained a constant chip thickness and cutting force in the process even before optimization. In the case of T02, flank wear of 0.2 mm and a fracture of 2 mm occurred before optimization. This is due to the strong cutting force of about 2000 N before optimization. Tool wear was decreased by about 74% after optimization. In the case of T04, flank wear of 0.297 mm and a fracture of 1.615 mm occurred before optimization. It is analyzed that this is due to the non-uniform chip thickness before optimization and the strong cutting force of about 1200 N in a specific area. Tool wear was decreased by about 60% after optimization. In T05, flank wear was decreased by 40% after optimization, and it is considered that tool wear was reduced due to a constant chip thickness. T06 had a very small depth of cut, so significant wear and fracture did not occur.

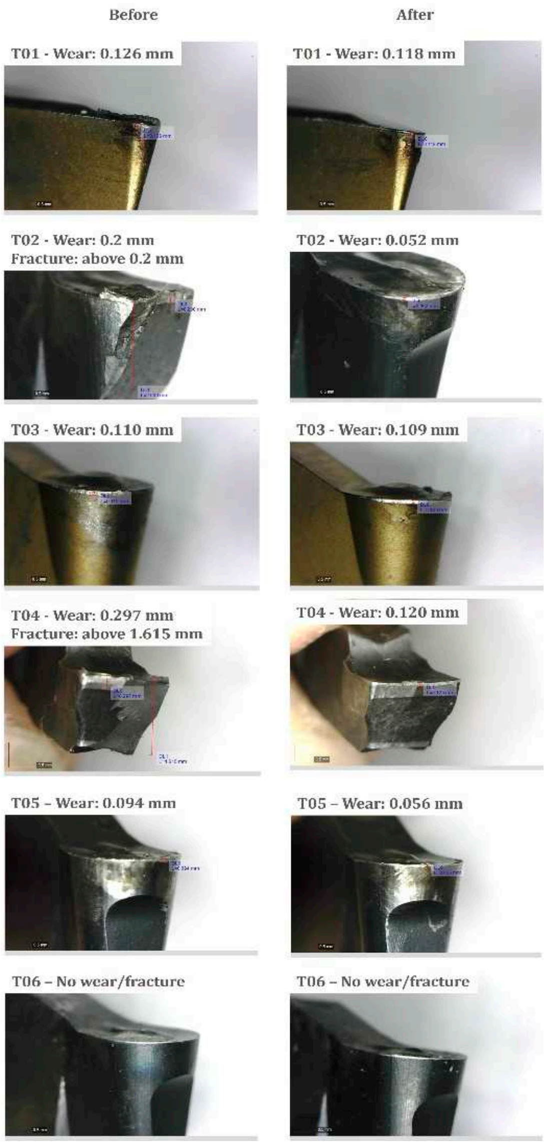


Figure 7. Cutting tool wear at semi-finishing.

Figure 8 shows the tool wear after finishing. In finishing, there was no tool breakage due to the reduced conditions compared to semi-finishing. In T01, it is considered that the difference in flank wear before and after optimization was not significant. This is because a constant chip thickness and cutting force were maintained even before optimization. After optimization, flank wear was decreased by about 54% in T02 because it was machined while maintaining a constant chip thickness and cutting force. In T03, the cutting force and chip thickness increased after optimization compared to before optimization, but there was no significant difference in tool wear. In T04, flank wear decreased by about 29% after optimization, and in T05 and T06, significant wear and fracture did not occur.

Figure 8. Cutting tool wear at finishing.

3.2. Surface Roughness and Machining Accuracy

The surface roughness was represented by the centerline average height (R_a), ten-point median height (R_z), and maximum peak-to-valley roughness height (R_{max}) using surface roughness measurement equipment. The measurement length was 2 mm on the machined surface, and a cut-off value of 0.25 mm was used. Three sections of the disc groove were measured, and the measured average values are shown in Table 5. The average values of three experimental iterations under the same conditions were used for reliable results.

Table 5. The measurement results of surface roughness.

Roughness Parameters	Surface Roughness (μm)	
	Before Optimization	After Optimization
R_a	0.806	0.869
R_z	3.827	3.167
R_{max}	4.401	4.782

There was no significant difference in surface roughness before and after optimization. If surface roughness improvement is the main objective, additional feed optimization considering production time will be possible.

Table 6 shows the measurement results of machining accuracy before and after optimization with the level of precision required for design. Measurements were performed at a total of 12 measuring points using a coordinate measuring machine as shown in Figure 9, and all were satisfied within a tolerance of ±0.2 mm.

Table 6. The measurement results of machining accuracy.

Measuring Items	Specification (mm)	Measurement Value (mm)	
		Before Optimization	After Optimization
Circle-1	37.900 ± 0.2	38.002	38.010
Circle-2	55.560 ± 0.2	55.519	55.671
Circle-3	59.700 ± 0.2	59.641	59.648
Circle-4	64.500 ± 0.2	64.690	64.485
Circle-5	83.300 ± 0.2	82.390	83.454
Circle-6	85.940 ± 0.2	86.074	86.096
Circle-7	123.760 ± 0.2	123.808	123.782
Circle-8	124.400 ± 0.2	124.225	124.269
Circle-9	131.500 ± 0.2	131.678	131.832
Distance-1	24.630 ± 0.2	24.619	24.622
Distance-2	27.430 ± 0.2	27.415	27.420
Distance-3	35.050 ± 0.2	35.063	35.042

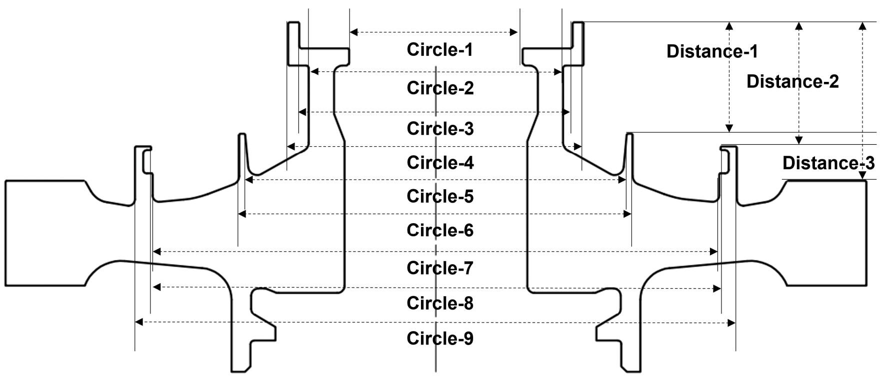


Figure 9. Measurement points.

3.3. *Quantitative Analysis of Cycle Time Improvement*

The number of tools and the tool path were optimized compared to the existing process for the purpose of reducing cycle time in the turbine disk turning operation. In addition, the cycle time was shortened by creating the variable feed based on the generated tool path and cutting conditions. The measurement results were satisfactory within the design tolerance of 0.2 mm. Surface roughness measurement results also showed little difference before and after optimization. In particular, the tool wear decreased by about 40–74% in semi-finishing and 29–54% in finishing. Finally, the cycle time was improved by 54%, as shown in Table 7.

Table 7. Cycle time improvement.

Order	Progress	Cycle Time (mm:ss)		Improvement Rate
		Before	After	
1	No. of tools reduction and tool-path optimization	58:24 (Machine cycle time)	44:40 (NX environment)	24%
2	NC-code optimization with variable feed	30:58 (Vericut environment; same environment as machine cycle time)	26:34 (Machine cycle time)	14%
Total of cycle time		58:24	26:34	54%

4. Conclusions

In this work, the machining cost of an aircraft turbine disk was reduced, and the productivity was improved by establishing a machining strategy and optimizing the cutting conditions using a simulation approach. The number of tools was reduced, and the tool path was optimized with variable feed compared to the existing cutting conditions.

Verification experiments were performed to confirm the optimization strategy. Within the range of cutting parameters selected for this work, certain conclusions can be summarized as follows:

- The number of tools was reduced from eight to six compared to the existing condition for semi-finishing and finishing of a turbine disk, and a new tool path was proposed through simulation. The cycle time was reduced by about 24%.
- NC-code optimization was performed through feed optimization considering cutting force and chip thickness. As a result, cycle times were reduced by about 14%.
- As a result of analyzing tool wear by performing a cutting test, it was confirmed that tool wear was reduced by up to 74% in semi-finishing and up to 54% in finishing. This is because machining was performed while maintaining a constant cutting force and chip thickness.
- Through tool-path optimization and NC-code optimization, it was confirmed that the total cycle time was reduced by about 54% and tool wear was significantly improved.
- The method proposed in this study dramatically enhanced productivity and reduced manufacturing cost.

This work was focused on reducing cycle time to enhance productivity. The cycle time has been significantly reduced, but tool wear, surface roughness, and accuracy were similar before and after optimization. In future research, we plan to perform optimization to improve accuracy. In addition, measurement and evaluation such as product quality, cost analysis, and sensitivity analysis will be considered.

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