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DEVELOPMENT ON AI OPTIMIZING TECHNOLOGY OF NC PROGRAM USING TOOL FREE-CUTTING TEMPERATURE FOR TURNING

In recent years, manufacturing must not only focus on high precision and productivity, but also on saving energy, resources and the environment. At the same time, there are increasing demands for high quality, high grade, wear resistance, heat-resisting property and high rigidity in machining workpieces. Therefore, for example, when creating NC programmes for machining difficult-to-machine materials such as titanium alloys and nickel alloys used in the aerospace industry, it has been very difficult to determine their optimum cutting conditions and create highly productive NC programmes due to lack of experience. Therefore, an AI optimizing technology of NC program using tool free-cutting temperatures for turning was developed and evaluated. The turning was used for this research and neural networks were used for AI optimizing. The algorithm for optimizing NC program using tool free-cutting temperature was firstly developed. Then the AI optimizing program for NC program was developed by C programming language. Previous NC program can rewrite for optimum condition by using the AI optimizing program. The proposed AI optimizing technology of NC program was evaluated by the several experiments. It is concluded from the results that; (1) The AI optimizing program for NC programmes using tool free-cutting temperatures in turning was developed, (2) The developed program was very useful for high productivity, long tool life and environmentally friendly.

1. INTRODUCTION

The requirements for machining are high accuracy and high productivity. To achieve these goals, it is necessary to take measures against thermal deformation of the machine tool [1, 2, 3] and forced cooling of the cutting heat [4, 5, 6]. In addition, cutting of difficult-to-cut materials such as titanium alloy and nickel alloy, which are materials for aerospace industry parts, requires a large amount of cutting fluid and electrical energy for forced cooling to prevent cutting heat [7, 8]. In recent years, there has been a strong demand for manufacturing that takes global environmental conservation into consideration. In addition, it has been pointed out that wet machining using a large amount of cutting fluid has adverse effects on the health of workers and the global environment [9, 10]. Under these conditions, it is extremely difficult to create an NC program while considering high accuracy, productivity improvement, and optimal machining conditions.

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In this study, a technology was developed to correct NC programs with AI so that machining can be performed under optimal machining conditions based on the free-cutting temperature of the tool.

Specifically, first, a calculation model of tool (tip) tip temperature is constructed by a neural network using training data generated by FEM thermal analysis. Next, using this calculation model, a program was developed in C language to modify the NC program so that the tool tip temperature becomes the free-cutting temperature of the tool. Finally, the industrial applicability of the proposed optimizing program was confirmed through turning experiments. The proposed AI optimizing technology of NC program is meant to be used in an engineering activity at the process planning stage. In addition, the free-cutting temperature is the optimum temperature of a tool during machining for higher accuracy and productivity, taking into account tool temperature and wear at the production site.

2. CONSTRUCTION OF CALCULATION MODEL FOR TOOL TIP TEMPERATURE

After deciphering the NC program, understanding the machining conditions, and calculating the cutting heat generation and chip-tool contact surface specifications, it is possible to create an FEM model and calculate the tool tip temperature accurately by FEM thermal analysis. This can be used as an inverse analysis tool to determine the machining conditions under which the tool tip temperature becomes the tool free-cutting temperature. However, the inverse analysis using FEM thermal analysis requires a long time to complete. Therefore, in this study, a neural network was constructed using the results of FEM thermal analysis as training data, which was then converted into algebraic equations and implemented in the macro program of CNC machine tools to modify the NC program so that the tool tip temperature always reaches the free-cutting temperature. In this chapter, a tool tip temperature calculation model was developed for this purpose.

2.1. CALCULATION MODEL OF TOOL TIP TEMPERATURE USING NEURAL NETWORK

Here, to calculate the tool tip temperature, a neural network was constructed using the results of the FEM thermal analysis as the training data. After deciphering the NC program and calculating the amount of heat flowing into the tool, it is possible to calculate and use the tool tip temperature directly by FEM thermal analysis, however in the optimizing technique proposed in this research, it is necessary to calculate the tool tip temperature until it reaches the tool free-cutting temperature by the successive substitution method. In order to reduce the computational load and enable high-speed calculation, the calculation result of the tool tip temperature by the FEM thermal analysis is used as the training data for constructing the neural network, the coupling function and the offset value are extracted from the neural network after the calculation convergence, and the tool tip temperature calculation model (simple algebraic expression) is reconstructed using them. This model is then used in the sequential substitution method. In particular, the uncertainties of developed program can be raised as the friction coefficient during turning between the insert and the workpiece, the heat transfer coefficient near the insert tip during turning, and the effect of forced cooling. These uncertainties are discussed in the evaluation experiments in section 4.1.

First, the training data for building the neural network was calculated by FEM thermal analysis. As shown in Table 1, four different tools, workpieces, and machining conditions and three types of forced cooling were prepared. The coefficient of friction between the tool rake surface and the chip was set to two boundary conditions of 0.1 and 0.3.

Table 1. Cutting conditions of the turning for calculating the training data of the neural network

<table>
<tr><td colspan="2">Insert material</td><td colspan="2">High speed steel</td><td colspan="2">Carbide</td><td colspan="2">Cermet</td><td colspan="2">Ceramics</td></tr>
<tr><td colspan="2">Workpiece</td><td colspan="2">Al</td><td colspan="2">S45C</td><td colspan="2">SUS304</td><td colspan="2">Ti6Al4V</td></tr>
<tr><td rowspan="3">Cutting condition</td><td>Type</td><td colspan="2">Finish cutting</td><td colspan="2">High speed</td><td colspan="2">Middle cutting</td><td colspan="2">Heavy cutting</td></tr>
<tr><td>Standard cutting condition</td><td colspan="2">V: 200
F: 0.1
D: 0.1</td><td colspan="2">V: 500
F: 0.1
D: 0.3</td><td colspan="2">V: 250
F: 0.2
D: 1.0</td><td colspan="2">V: 130
F: 0.4
D: 5.0</td></tr>
<tr><td>Condition for the training data</td><td colspan="2">V': 100
or
V'': 20
F: 0.1
D: 0.1</td><td colspan="2">V': 250
V'': 50
F: 0.1
D: 0.3</td><td colspan="2">V': 125
V'': 25
F: 0.2
D: 1.0</td><td colspan="2">V': 65
V'': 13
F: 0.4
D: 5.0</td></tr>
<tr><td colspan="2">Forced cooling: Heat transfer coefficient W/m²K</td><td colspan="3">Nothing (Dry): 20</td><td colspan="3">Wet: (Oil): 1000</td><td colspan="2">Strong alkaline water mist: 30000</td></tr>
</table>

※V: Cutting speed (m/min), F: Feed speed (mm/rev), D: Depth of cut (mm), T: Feed/tooth (mm/tooth), W: Width of cut (mm)

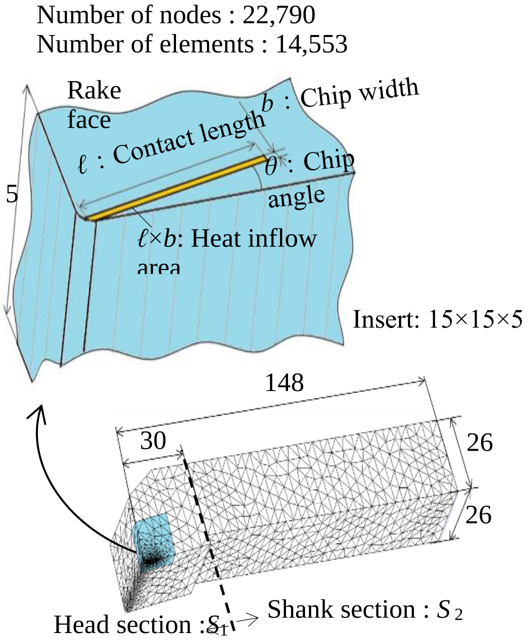


Fig. 1. FEM thermal analysis model of the insert for calculating the training data of the neural network. Heat flow areas and its specifications are shown in the figures

Since only the cutting speed was used as a control parameter for the program optimizing (see details below), three cutting speeds were set in addition to the standard cutting speed V, V' which is 1/2 of the standard speed V, and V'', which is 1/10 of the standard speed V, and a wide range of cutting speeds was adopted as the training data. The FEM model of the tool (insert) shown in Fig. 1 was used for the analysis.

Contact length, chip width and chip angle in Fig. 1 are calculated from basic cutting theory [11, 12]. The coefficient of friction between the uncoated insert and the workpiece was set to 0.3 [12], and the coefficient of friction between the DLC-coated insert and the workpiece was set to 0.1. These conditions are reflected in the FEM model.

As an example, Table 2 shows the FEM thermal analysis conditions [11], [12] when the cutting speed is V and the coefficient of friction between the tool rake surface and the chip is 0.3, and Table 3 shows the FEM thermal analysis results for these conditions. The results where the chip contact length exceeds the tool are marked with an asterisk (*). In this case, the analysis was performed assuming that the heat flowed into only the part of the chip contact length that touched the insert.

Table 2. Calculation conditions for FEM thermal analysis (Steady state condition). There are tool and workpiece materials, these properties, specifications of the heat inflow area, cutting conditions, forced cooling condition and heat generations at coefficient of friction = 0.3 in this table

Tool	Tip material (Insert) and the properties			HS: λ: 24, C: 420, ρ: 8000	CA: λ: 80, C: 210, ρ: 12300	CE1: λ: 25, C: 335, ρ: 6800	CE2: λ: 16, C: 750, ρ: 3400
	Holder & properties			Holder of insert: λ: 43.0, C: 502.0, ρ: 7800			
	Cutting type			Insert			
Workpiece			Material & properties	Al: λ: 237 C: 900, ρ: 2700	S45C: λ: 44.19, C:490, ρ: 7800	SUS304: λ: 20, C: 480, ρ: 7930	Ti6Al4V: λ: 7.1, C: 520, ρ: 4510
Analysis conditions	Heat generation Q W	Type→ Workpiece↓		Finish cutting b = 0.1 mm θ = 0.10°	High speed cutting b = 0.1 mm θ = 0.10°	Middle cutting b = 0.2 mm θ = 0.20°	Heavy cutting b = 0.4 mm θ = 0.40°
		Turning using an insert	Al	ℓ : 0.62 mm HG: 2.78 W, CA:7.34 CE1: 2.88, CE2: 1.93	ℓ : 4.5 mm HG: 9.94 W, CA:27.0 CE1: 10.3, CE2: 6.85	ℓ : 15.1 mm HG: 35.4 W, CA:93.4 CE1: 36.7, CE2: 24.6	ℓ : 57.5 mm HG: 139 W, CA: 353 CE1: 144, CE2: 97.4
			S45C	ℓ : 0.6 mm HG: 5.77 W, CA:14.3 CE1: 5.97, CE2: 4.04	ℓ : 1.7 mm HG: 25.3 W, CA:65.2 CE1: 26.2, CE2: 17.6	ℓ : 5.6 mm HG: 93.0 W, CA: 232 CE1: 96.3, CE2: 65.1	ℓ : 16.7 mm HG: 289 W, CA: 704 CE1: 299, CE2: 204
			SUS304	ℓ : 0.5 mm HG: 6.89 W, CA:15.6 CE1: 7.12, CE2: 4.93	ℓ : 1.7 mm HG: 38.1 W, CA:89.6 CE1: 39.3, CE2: 26.9	ℓ : 5.4 mm HG: 134 W, CA: 305 CE1: 139, CE2: 96.0	ℓ : 22.3 mm HG: 654 W, CA:1402 CE1: 674, CE2: 473
			Ti6Al4V	ℓ : 0.4 mm HG: 11.0 W, CA:20.5 CE1: 11.2, CE2: 8.19	ℓ : 1.0 mm HG: 53.7 W, CA: 107 CE1 55.2, CE2: 39.6	ℓ : 3.5 mm HG: 194 W, CA: 371 CE1: 200, CE2: 145	ℓ : 12.8 mm HG: 806 W, CA:1467 CE1: 827, CE2: 610
	Heat transfer coefficient for forced cooling			Nothing (Dry cutting):20	Wet cutting: 1000 (Conventional)		Wet cutting using strong alkaline water mist: 30000

※λ: Thermal conductivity (W/mK), C: Specific heat (J/kgK), ρ: Density (kg/m^3),
HG: Heat generation time during 1 rotation (s), HS: High speed steel, CA: Carbide, CE1: Cermet, CE2: Ceramics

Table 3. Calculation results (Insert top temperature at steady state) using FEM thermal simulation regarding the forced cooling effects on the tool with some tool materials and cutting conditions at coefficient of friction = 0.3

		Forced cooling : Nothing (Dry cut) α : 20 W/m^{2}K				Forced cooling : Wet cutting α : 1000 W/m^{2}K				Forced cooling : Strong alkaline water mist cutting α : 30000 W/m^{2}K			
		FC	HSC	MC	HC	FC	HSC	MC	HC	FC	HSC	MC	HC
Al	HS	140	277	419※	461※	116	205	233※	221※	60	93	104※	90※
	CA	136	160	635※	786※	102	197	246※	332※	65	107	113※	142※
	CE1	140	191	424※	467※	116	205	234※	222※	61	93	105※	91※
	CE2	140	197	373※	413※	116	198	220※	210※	55	84	98※	85※
S45C	HS	538	1438	1991	2394	482	1214	1391	1531	295	646	572	643
	CA	449	1336	2279	2543	381	1033	1270	1425	282	679	650	655
	CE1	531	1436	2000	2399	476	1212	1392	1484	294	650	577	646
	CE2	561	1452	1906	2338	494	1218	1349	1533	280	595	511	614
SUS304	HS	645	1654	2742	4310	578	1335	1835	2526	342	608	704	820
	CA	492	1477	2912	4305	418	1065	1567	2156	309	633	727	847
	CE1	641	1647	2759	4310	575	1328	1842	2524	343	612	711	825
	CE2	678	1678	2688	4259	604	1346	1821	2473	320	546	648	753
Ti6Al4V	HS	1154	4147	5754	8103	1046	3637	4342	5439	676	2053	1914	2309
	CA	719	2852	4537	6105	623	2347	2884	3698	474	1648	1604	1758
	CE1	1141	4109	5721	8045	1034	3604	4309	5402	672	2053	1916	2300
	CE2	1276	4475	6008	8613	1149	3894	4534	5694	697	2001	1819	2366

※Conditions that the contact length exceeds the insert length. HS: High speed steel, CA: Carbide, CE1: Cermet, CE2: Ceramics, FC: Finish cutting, HS: High speed cutting, MC: Middle cutting and HC: Heavy cutting,
The values filled in grey were not used to generate a model of the neural network

A limit temperature of 2000°C was set as the temperature at which each tool material softens and becomes difficult to machine, and 144 pieces of data were used as training data, omitting the grey shaded areas (data with steady-state values of 2000°C or higher).

The results of FEM thermal analysis for cutting speeds V and a friction coefficient of 0.1 between the tool rake surface and the chip, and for cutting speeds V' and V" are omitted. These FEM thermal analysis results were processed in the same way as in Table 3, and 895 data were added to the training data, for a total of 1039 data as training data.

Figure 2 shows the neural network model for calculating the steady-state value of the tool tip temperature, and Table 4 shows the details of the input layers. The input layer consists of 10 units； cutting condition {I_1: feed speed f, ($\fallingdotseq$cutting width b)}, workpiece physical properties{I_2:tensile strength k, I_3:thermal conductivity k_w), tool physical properties { I_4: thermal conductivity k_t, I_5: friction coefficient μ between the tool and chip}, I_6: average temperature rise of the tool tip T_t calculated by Reference [13], I_7: chip contact length l, I_8:area on the rake surface of the contacting chips A, I_9:heat flowing into the tool per unit time Q_t, I_{10}:heat transfer coefficient α of the forced cooling. I_6 to I_9 in Table 4 are calculated from basic cutting theory [11, 12]. In particular, the average temperature rise I_6 of the tool was entered as a reference value because the effect of heat transfer was not taken into account. Tool temperature rise D_{xp}(t) at output is the temperature rise at the tool tip considering heat transfer.

The number of units in the intermediate layer is 30. And the number of units in the output layer is one unit at the steady-state value of the tool tip temperature. A sigmoid function and a linear function are used for the intermediate layer and the output layer, respectively. In the input layer, the variables used in Reference [13], the average temperature at near the tool tip calculated in Reference [12], and the information on forced cooling are input as described above.

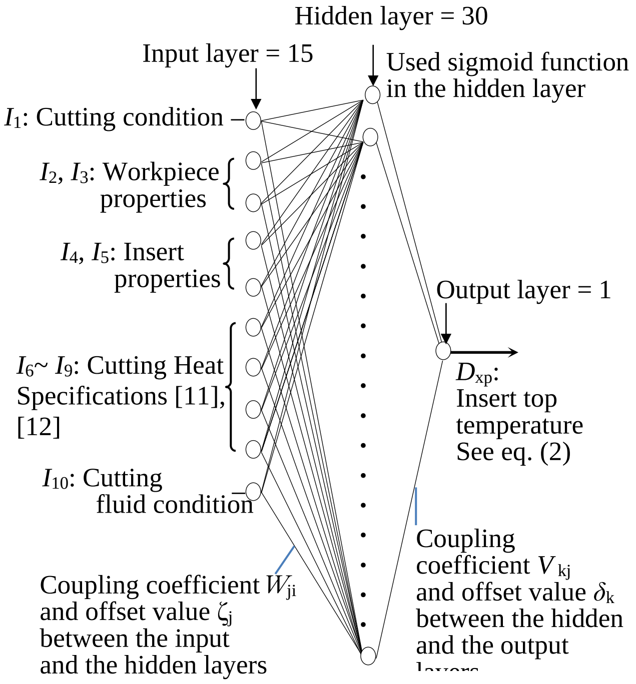


Fig. 2. Neural network model for calculating the insert top temp. in a turning during the forced cooling

Table 4. Input data in the neural network model used for calculating the insert top temperature in a turning

No.	Specification of the input data	Kinds
I_1	Feed speed f = cutting width b	Cutting condition
I_2	Tensile strength k	Workpiece
I_3	Thermal conductivity k_w	
I_4	Thermal conductivity k_I	Tool
I_5	Coefficient of friction μ	
I_6	Tool tip temperature T_t (For reference)	Cutting heat Specifications [11], [12]
I_7	Tool-chip contact length l	
I_8	Tool-chip contact area A	
I_9	Receiving heat quantity of insert Q_I	
I_{10}	Heat transfer coefficient α	Forced cooling

※ Chip property is same to workpiece property

The neural network is trained by successively modifying the coupling functions W_{ji} and V_{kj} between the units and the offsets ζ_j and δ_k between the units in the program by the steepest descent method so that the sum of the squares of the differences between the training data and the output data is minimized. Here, W_{ji} is the coupling function between the input layer and the hidden layer, V_{kj} is the coupling function between the hidden layer and the output layer, ζ_j is the offset value given to the hidden layer, and δ_k is the offset value given to the output layer. The back-propagation method was used here. The error function E_p of the training pattern p is shown in Equation (1).

$$E_p = \frac{1}{2}\sum_k (T_{kp} - D_{kp})^2 \tag{1}$$

where T_{kp} is the training data of unit k for training pattern p and D_{kp} is the output data of unit k for training pattern p.

The training pattern is the result of tool tip temperature calculation for cutting conditions. The neural network model was trained using 1039 training patterns created from the previous training data with standardization. After 6800 trials, the value of the error function E_p was reduced to 1.4×10^{-29}, which is considered to be converged.

Using the above neural network model, we obtain an algebraic expression. Using the coupling functions W_{ji} and V_{kj}, which are known values at this point, and the offset values between units ζ_j and δ_k, the relationship between the input and output layers is shown in Equation (2).

$$\begin{aligned} D_{kp} &= f\left\{W_{ij}, V_{ij}, \zeta_j, \delta_{k,}\ Input\ data\ (x = 1,2,\cdots 17)\right\} \\ &= \sum_{p=1}^{Hidden\ layer\ no.} \frac{V_{kp}}{1 + \exp\left\{-\sum_{q=1}^{Input\ layer\ no.}\left(W_{pg}\cdot I_q + \zeta_q\right)\right\}} + \delta_k \end{aligned} \tag{2}$$

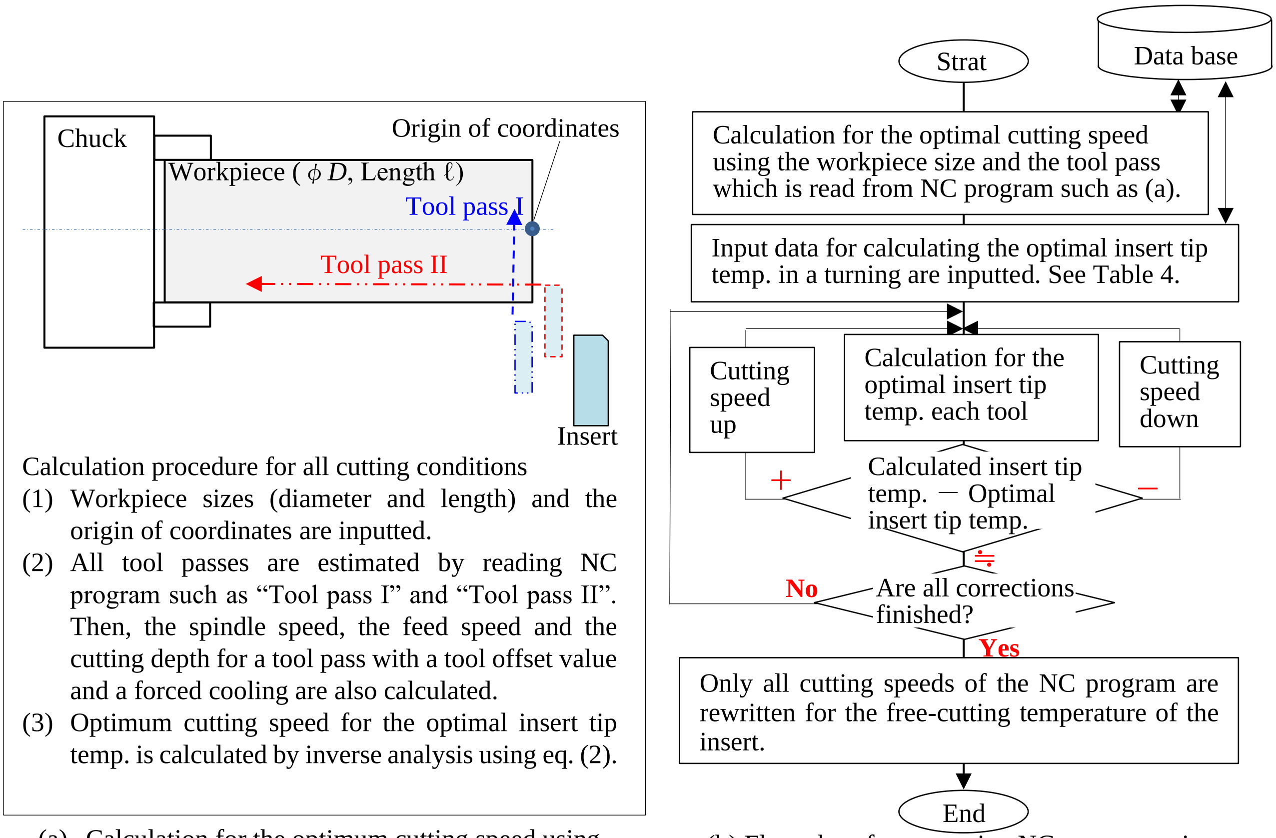
The steady-state value of the tool tip temperature can now be calculated using an algebraic equation (2) by entering the tool material, workpiece material, machining conditions, and the presence or absence of forced cooling. Equation (2) is an important calculation model used in optmizing NC programs that use tool free-cutting temperature as a criterion.

2.2. CONSIDERATION OF TOOL FREE-CUTTING TEMPERATURE USED AS A CRITERION

The tool free-cutting temperatures for cemented carbide and cermet tools were used 940°C for cemented carbide and 1210°C for cermet tools respectively. These values are 10 % larger than the crater wear temperatures of 850°C for cemented carbide and 1100°C for cermet tools, respectively [13]. This 10 % larger value was subjectively determined by considering machining accuracy, tool life, and productivity. In addition, Narutaki et al.'s tool surface temperature of 1600°C [14] was used as the tool free-cutting temperature for the normal use of ceramic tools. In the program to be developed, these values were set in the database and used as offset values so that they could be changed as necessary.

3. ALGORITHM FOR OPTMIZING NC PROGRAMS AND THE OPTMIZING PROCIDURE USING IT

Figure 3 shows the algorithm and working procedure for optimizing the NC program. First, as shown in Fig. 3(a), the NC program is automatically decoded and the tool paths for all processes in the program are obtained. At that time, the feed speed, spindle speed, tool number, and forced cooling ON/OFF of each tool path are also captured and recorded. The operator is then asked to input the workpiece size (diameter and length or coordinate input) and the origin coordinate. The cutting conditions (cutting speed, feed speed and depth of cut) for all toolpaths are calculated and recorded from the workpiece position in NC coordinates and the toolpath, feed speed and spindle speed in the NC program. Then, as shown in the flowchart in Fig. 3(b), the operator is asked to input the data necessary to calculate the steady-state value of the tool tip temperature (Equation (2), see Table 4). At that time, the operator is asked to enter the tool information, including the type of tool used in each toolpath and the specification of its (right-hand, left-hand, or reverse byte). The physical properties of the tool and workpiece, as well as the heat transfer coefficient of the forced cooling medium, are stored in a database and are available for use. This database is accessible at all times and can be deleted, added, or rewritten as necessary. The steady-state value of the tool tip temperature is then calculated for each tool



Calculation procedure for all cutting conditions

(1) Workpiece sizes (diameter and length) and the origin of coordinates are inputted.

(2) All tool passes are estimated by reading NC program such as “Tool pass I” and “Tool pass II”. Then, the spindle speed, the feed speed and the cutting depth for a tool pass with a tool offset value and a forced cooling are also calculated.

(3) Optimum cutting speed for the optimal insert tip temp. is calculated by inverse analysis using eq. (2).

(a) Calculation for the optimum cutting speed using the workpiece size and the NC program

(b) Flow chart for correcting NC program using the optimal insert tip temp. regarding turning

Fig. 3. Working procedure for correcting NC program using the optimal insert tip temp. regarding turning (See Section 2.2 for the optimal insert tip temp)

pass and compared to the tool free-cutting temperature used in that tool pass. If the tool tip temperature is higher than the tool free-cutting temperature, the cutting speed is reduced and the same trial is performed again. This is done using the successive substitution method and the cutting speed at which the steady-state tool tip temperature falls below the tool free-cutting temperature is recorded as the optimum cutting speed for that tool path. The same procedure is carried out for all toolpaths. At this time, the tool free-cutting temperature is also stored in the database and can be used. In the determination of the tool free-cutting temperature, the allowable value is an offset value of ±5°C, which can be rewritten at any time. When the calculation of the optimum cutting speed for all tool paths is completed, the program is terminated by rewriting the cutting speed of all machining processes in the NC program to the optimum cutting speed that was calculated and recorded earlier. This program was created in the C language (C++ builder). When the cutting speed, feed speed, and depth of cut are individually reduced to reduce tool temperature, the reduction in workpiece removal (productivity) is the smallest for the cutting speed, so the program was modified to change only the cutting speed to raise productivity.

4. EVALUATION FOR REVISION TECHNOLOGY OF NC PROGRAM

4.1. EVALUATION OF CUTTINNG PROPERTIES (TOOL TEMERATURE, TOOL LIFE AND WORKPIECE SURFACE ROUGHNESS)

A NC program for turning a cylindrical workpiece (material: Ti6Al4V) with a diameter of ϕ 19 mm into a diameter of ϕ 18 mm × length of 75 mm and a surface roughness of Ra 1.6 μm or less was cut. And the effects on cutting properties (tool temperature, tool life, and workpiece surface roughness) were clarified experimentally. This was done in order to reliably evaluate tool tip temperature and tool life in the experiments. As shown in Table 5, NC program I was created for turning under medium cutting conditions (cutting speed V=150 m/min, feed rate 0.2 mm/rev, depth of cut 0.5 mm, dry), using S45C as workpiece and carbide with a free cutting temperature of 850°C as tool, respectively. The first revision was to rewrite NC program I to NC program II using the proposed method for "dry turning of workpiece Ti6Al4V (difficult-to-cut material) at a free-cutting temperature of 650°C for carbide tools. As a result, the cutting speed V = 150 m/min was corrected to V = 28 m/min. The second revision was to rewrite NC program I to NC program III using the proposed method for wet turning by forced cooling with a strong alkaline water mist with a heat transfer coefficient of 14000 W/m^{2}K, using a workpiece Ti6Al4V (difficult-to-machine material) and a carbide (DLC-coated) tool with a free cutting temperature of 480°C. NC program I was rewritten to NC program III using the proposed method. This modified the cutting speed V = 150 m/min to V = 58 m/min.

Figure 4 shows a comparison of steady-state values of tool tip temperature. The data of experimental temperatures at two locations near the tool tip is firstly measured with thermocouples, then the steady-state values of the tool tip temperature in Fig. 4 are calculated for interpolating the data by FEM simulation [5].

Table 5. Cutting condition for measuring the insert tip temperature regarding the DLC coating insert with the small through hole and the communicating tube during the turning for difficult-to-machine material

Cutting conditions		
Cutting speed *V* 150, 58, 28 m/min	Feed speed 0.2 mm/rev	Depth of cut 0.5 mm
Workpiece		
Material: Ti6Al4V		
Tools (Insert) &Cutting type		
Carbide, CNGG120408R-P TH10 by Tungaloy		
Experimental parameters		
I: Dry (*V*=150 m/min) using NC program I		
II: Wet (Type A2×20 Dilution) (*V*=150 m/min) using NC program I		
III: Dry (*V*=28 m/min) using NC program II		
IV: SAWM with DLC coating insert (*V*=58 m/min) using NC program III		

※SAWM: Strong alkaline water mist (Heat transfer coefficient 14000 W/m^{2}K)

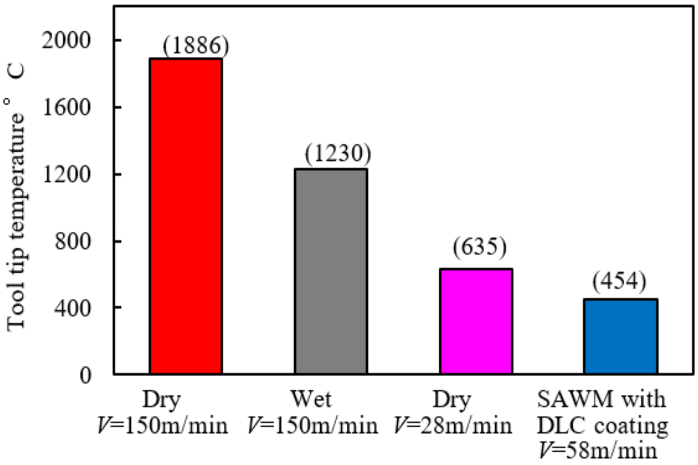


Fig. 4. Experimental results for the tool tip temp. Countermeasure using the proposed program was a success. Because the optimum cutting speeds for the free-cutting temperature of the insert. were calculated by the program

When turning the workpiece Ti6Al4V in NC Program I before revision, the tool tip temperature was 1886°C in the dry cutting and 1230°C in the wet cutting (using water-soluble cutting fluid), which were inappropriate temperatures for the carbide tools used. In contrast, in the corrected NC program II and NC program III, the tool tip temperatures corresponded well to the free-cutting temperatures entered, respectively, and the "program to correct the NC program" functioned effectively. Uncertainties in developed program include the friction coefficient during turning between the insert and workpiece, the heat transfer coefficient near the tip of the insert during turning, and the effect of forced cooling, however the calculated and experimental results corresponded to this degree; for example, when the calculated vale was 650°C, experimental temp. was 635°C, and when the calculated vale was 480°C, experimental temp. was 454°C.

Figure 5 shows the results of the tool life test. In Fig. 5, flank wear of 0.3 mm is used to compare tool life for each machining condition. The horizontal axis is shown in cutting volume, and the machining time for each cutting speed is also shown in parentheses. For example, the machining time at a cutting speed of 150 m/min and the cutting volume of 500000 mm3 is 33.3 min. In the tool life test, the tool life was determined when the flank wear amount reached 0.3 mm. Compared to NC program I before revision, the tool life of NC program II was 9 times longer and that of NC program III was 29 times longer. Thus, the developed program to modify the NC program was effective in extending tool life.

Figure 6 shows the measurement results of workpiece surface roughness Ra. The workpiece surface roughness of the dry cutting and wet cutting operations using NC program I before modification reached a surface roughness Ra of 1.6 μm or more soon after the start of the experiment, indicating that the desired surface roughness in this section could not be maintained. On the other hand, in NC program II and NC program III after modification, the workpiece surface roughness remained at around Ra 1.6 µm until the end of the tool life, and the NC programs were modified to enable turning of good workpieces until the end.

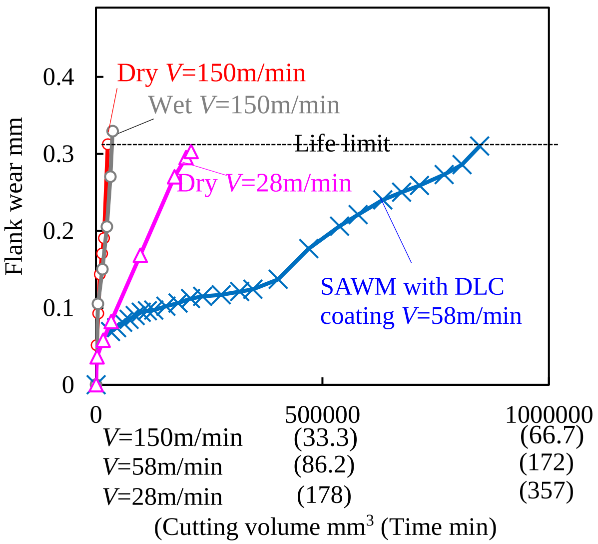


Fig. 5. Experimental results for tool life for evaluation of the proposed program. The tool lives of the turning using the countermeasures III and IV were longer than the other turnings I and II

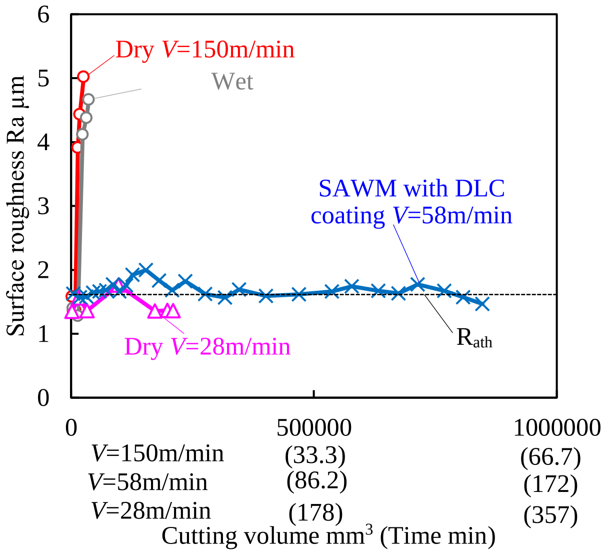
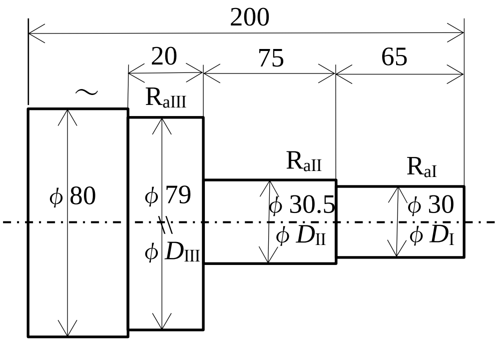


Fig. 6. Experimental results for surface roughness on workpiece for evaluation of the proposed program. The surface roughness of the turning using the countermeasures III and IV were smaller than the other turnings I and II because of small thermal influence

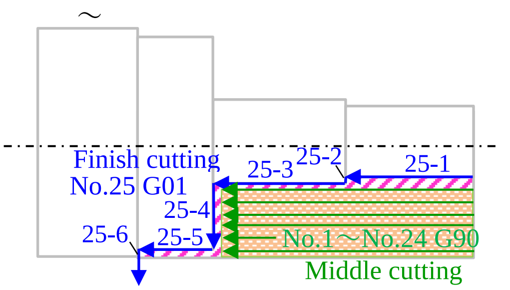
4.2. EVALUATION OF MACHINING ACCURACY AFTER REVISION OF NC PROGRAM FOR MULTILE PROCESSE

In order to perform dry turning of the S45C part (stepped round bar) shown in Fig. 7, NC program A was created to achieve the medium finishing conditions shown in Table 6. The program was created in a very simple manner by a novice machinist and roughing and finishing operations were performed without tool change at a constant spindle speed of 1200 min^{-1}. Therefore, NC program A is an unrealistic program by beginners and needs to be corrected. In this section, the tool free-cutting temperature of the carbide tool to be used at 850°C was firstly set, corrected NC program A to NC program B using the proposed optimizing NC program and observed and evaluated the machining properties (dimensional accuracy and surface roughness), tool life, and tool wear. Furthermore, in order to increase productivity (NC program C was made to further improve NC program B with the goal of increasing productivity), forced cooling with water-soluble cutting fluid Type A2 (diluted 20 times) was applied, and NC program A was corrected to NC program C in order to achieve the same tool free-cutting temperature as the previous optimizing, and the same evaluation was performed.

Figure 8 shows the change over time of the steady-state tool tip temperature (calculated values) before and after the optimizing of the NC program (here, the calculated values in the corrected program are used because it was difficult to measure the tool tip temperature due to the setup), the cutting speed and the spindle speed. Each calculation result is machining processes of one part from the beginning of machining. Cutting speed of NC program B, which was corrected so that the tool tip temperature became 850°C, was reduced, and the machining time increased accordingly. Normally, this optimum cutting speed would be obtained by long trial-and-error experiments, but the proposed method was able to calculate it in a very short time of less than one second. When the NC program C was corrected for wet turning, the modified cutting speed was faster than that of NC program B. This resulted in a reduction in machining time and an increase in productivity.



(a) Drawing for the industrial part



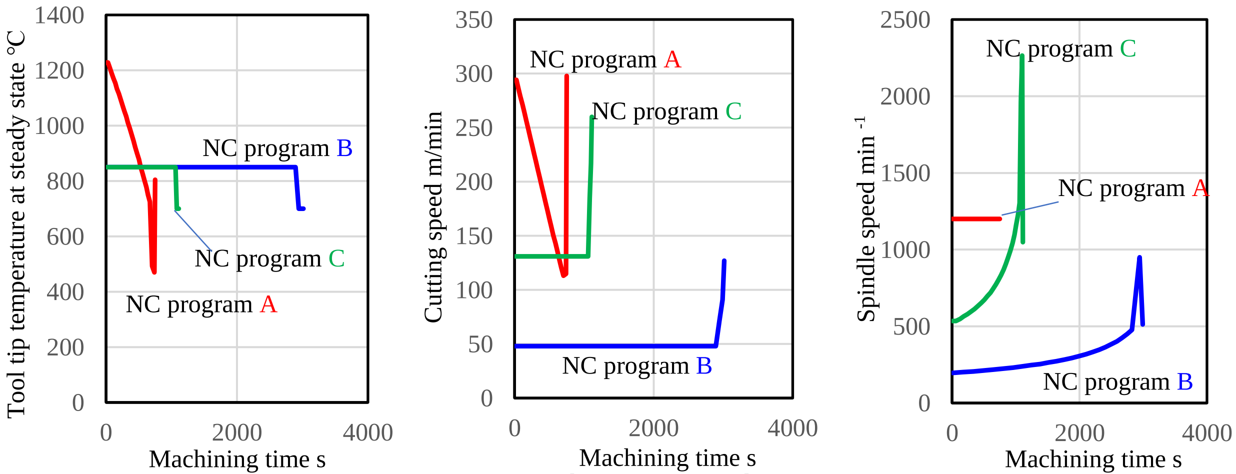
(b) Tool pass for cutting the industrial part

Fig. 7. A drawing and a tool pass of the industrial part for evaluation of the proposed method (Workpiece: S45C, Insert: Carbide)

Table 6. Cutting conditions in the program A of the industrial part with S45C for evaluation of the proposed method. Spindle speed is 1200 min^{-1}constant

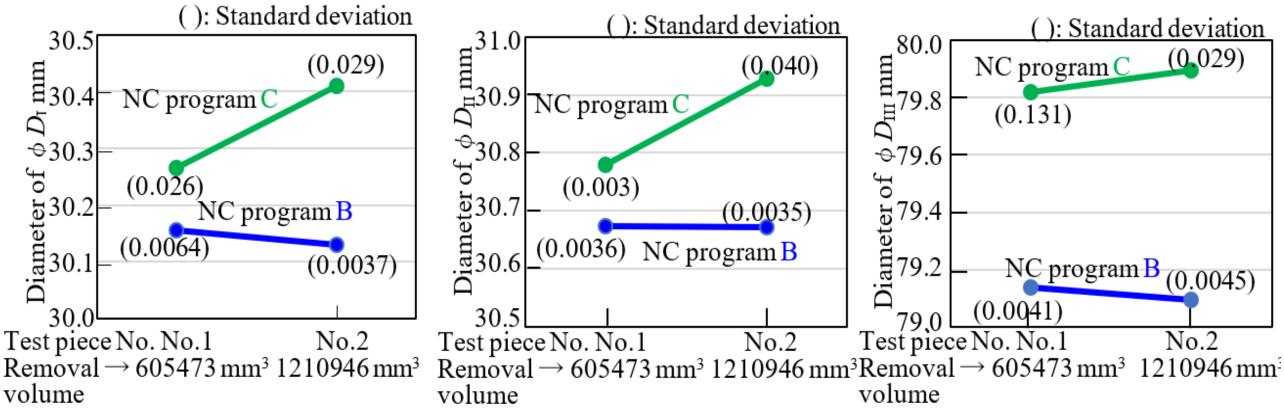
Cutting conditions in the program A					
Kinds of Cutting	Tool pass No.	Used G function	Cutting speed V m/min	Feed speed f mm/rev	Depth of d cut mm
Middle cutting	1～24	G90	121～294	0.25	1.0
Finish cutting	25-1	G01	113	0.1	1.0
	25-2	G01	113	0.1	—
	25-3	G01	115	0.1	0.75
	25-4	G01	115	0.1	—
	25-5	G01	298	0.1	0.5
	25-6	G01	298	0.1	—
Theoretical surface roughness on the finish surfaces Ra-th※1					
R_{aI} on 25-1, R_{aII} on 25-3 and R_{aIII} on 25-5: each 0.39 µm					
Tool (Insert) & Workpiece					
Insert: Carbide, CNMG432-SA KS20 Tungaloy, Nose radius n_r 0.8 Workpiece material: S45C (φ80×200) Coefficient of friction: 0.3					
Experimental parameters					
I: Dry cutting using the program A II: Dry cutting using the corrected program B III: Wet cutting with cutting oil VG68 using the corrected program B (Heat transfer coefficient: 1000 W/(m^{2}K))					

※1 $R_{a\text{-}th} \fallingdotseq (R_{z\text{-}th}) \div 4 = (f^2 / n_r \div 8 \times 1000) \div 4$



(a) Tool tip temperature (b) Cutting speed (c) Spindle speed

Fig. 8. Relationship between the tool tip temp., the cutting speed and the spindle speed and the machining time before and after the corrections (Calculation)



(a) ϕD_I mm on the workpiece (Target value: ϕ 30.0 mm)

(b) ϕD_{II} mm on the workpiece (Target value: ϕ 30.5 mm)

(c) ϕD_{III} mm on the workpiece (Target value: ϕ 79.0 mm)

Fig. 9. Dimensional accuracy on the workpieces (Experiment)

The decrease (green and blue curves) in tool temperature with increasing cutting time is due to the decrease in depth of cut after the finishing condition.

Figure 9 shows the measurement results of the dimensional accuracy (diameter) of the workpiece after turning. When turning was performed using the NC program A before modification, the machining process became difficult due to tool wear on the machining process No. 3 (diameter ϕ 68.0 mm, machining removal volume 253338 mm^3) during rough machining of the first workpiece (G90), and the measurement results could not be shown in Fig. 9. The finished diameter was programmed to be ϕ 30.0 mm, ϕ 30.5 mm, and ϕ 79.0 mm as shown in Fig. 9a, 9b, and 9c, respectively, however all the finished diameters remained large. This phenomenon is mainly considered to the tool wear and thermal deformations between the workpiece and the tool; in the case of NC Program B, the workpiece diameter of the second run was smaller than that of the first run because of the reduction of the workpiece diameter due to the thermal expansion of the workpiece and the tool. In NC program C, the second workpiece diameter is considered to become larger than the first workpiece diameter because the effect of tool wear was larger than the effect of thermal expansion of the workpiece and tool.

Figure 10 and Fig. 11 show the results of the measurement of tool flank wear and six photographs of tool wear, respectively. Fig. 11a shows a photograph of tool wear at the time of machining process No. 3 (diameter ϕ 68.0 mm, machining removal volume 253338 mm^3) during roughing (G90) of the first workpiece when turning was performed using NC program A before modification. The machining beginner created a program with a constant spindle speed of 1200 min^{-1}, which caused extremely large thermal effects, resulting in severe tool wear during the machining process. Turning with NC program B in Fig. 11b shows that although there is some thermal effect, there is no chipping and general turning can be achieved. When turning was performed using NC program C in Fig. 11c, tool wear at the end of machining the first workpiece was similar to that of NC program B, and the amount of wear was large due to the high spindle speed. However, the tool wear at the end of the machining of the second workpiece was significantly higher. The reason for higher tool wear in the case of Program C is simply because of higher cutting speed.

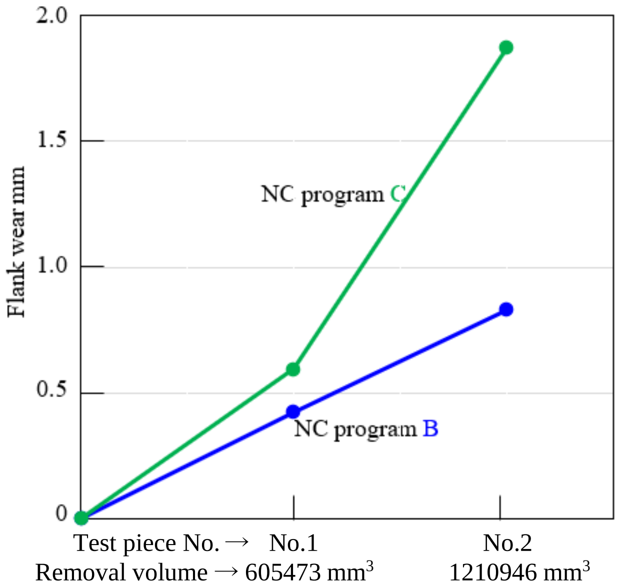
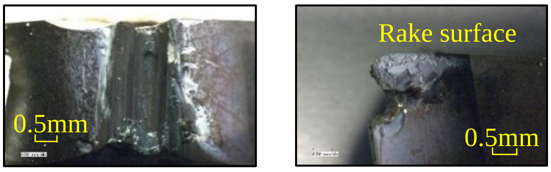
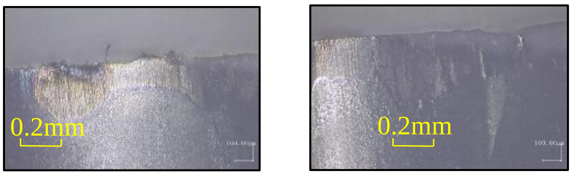


Fig. 10 Tool life test results for experiments using NC program B and C.



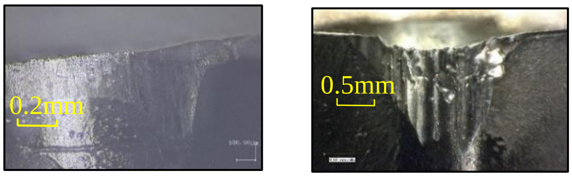
(a) NC program A before correct (Spindle speed 1200 min^{-1}, At workpiece diameter ϕ 68 and removal volume 253338mm^3)



Test piece No.1, Removal volume 605473 mm^3

Test piece No.2, Removal volume 1210946 mm^3

(b) NC program B of dry turning after correction



Test piece No.1, Removal volume 605473 mm^3

Test piece No.2, Removal volume 1210946 mm^3

(c) NC program C of wet turning after correction

Fig. 11. Tool wear photographs after turning for experiments using NC program A, B and C.

As described above, the machining of workpieces was not completed with program A before the revision, but two workpieces were completed with program B and program C after the revision, respectively. Thus, the proposed program to correct the NC program was considered to be industrially effective. In this research, the tool free-cutting temperature was determined by considering the free-cutting performance of the tool only. However, it is necessary to make final revision while taking into consideration the resonance phenomenon and vibration of the machine tool, thermal deformation of the tool, and the generation of the constitutive build-up edge.

The results of this research can be summarized as follows.

(1) The objective of this research is to correct NC programs easily, quickly, and accurately. A program which was used a neural network and the tool free-cutting temperature (as a criterion to revise NC programs for turning) was developed and evaluated.

(2) By using the corrected NC program, it was possible to perform turning with the tool tip temperature used within the tool free-cutting temperature. This enabled, for example, an inappropriate NC program created by a novice to be corrected to an NC program that could perform turning at the tool free-cutting temperature to be used.

(3) By setting an appropriate tool free-cutting temperature in the corrected program, the tool tip temperature, tool life, and workpiece surface roughness could be controlled. Since these machining characteristics are difficult to control constantly and easily in a general factory, the developed program is effective both industrially.

(4) The developed program maintained the tool at the optimum free-cutting temperature and enables normal turning for turning that require the setting of unconventional machining conditions, such as turning of difficult-to-cut materials, forced cooling with strong alkaline water mist, and DLC coated inserts.

(5) Workpiece cutting was not completed by Program A before the optimizing, but by Programs B and C after the optimizing, two workpieces were completed, respectively. Thus, the proposed NC program optimizing technique was industrially effective.

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