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ESTIMATION TOOL FOR OPTIMUM CUTTING CONDITION OF DIFFICULT TO CUT MATERIALS

Titanium alloy and nickel alloy are mainly used for several aeronautical parts due to their high strength and durability at high temperature. However, thermal conductivity of these materials are very low and most of the heat generated during cutting are concentrately conducted into the cutting tool. Therefore, the tool become extremely high temperature resulting shorter tool life. In this paper, a method for calculating the optimum cutting condition for cutting low thermal conductivity materials such as titanium alloy and nickel alloy is developed and evaluated. The temperatures on the cutting tool tip for various combination of tools and work piece materials were calculated by dynamic FEM simulation and the estimation tool for optimum cutting condition is created based on these results. The amount of heat flow and the temperature on the cutting tool were calculated based on cutting theory. Then, optimum cutting conditions for those materials were estimated by newly developed program. The method was finally evaluated by several experiments. It is concluded from the results that (1) The developed program is applicable for estimation of optimum cutting conditions regarding titanium alloy and nickel alloy. (2) Titanium alloy (Ti6Al4V) can be machined with longer tool life using estimated optimum cutting condition.

1. INTRODUCTION

Recently, titanium alloy and nickel alloy materials are being widely used in aeronautic and astronautic parts. The cutting methods with easy application and high accuracy for those materials are also being investigated [1],[2],[3]. However, thermal conductivities of those materials are very low and thus, most of the heat generated during cutting is conducted into cutting tool. Consequently, the tool becomes extremely high temperature and lost its mechanical strength and hardness, resulting shorter tool life. The easy and effective techniques for estimation of optimum cutting condition for cutting these materials are seriously demanded.

Therefore in this research, the cutting simulation using dynamic-explicit FEM is

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operated taking physical properties of work piece, tool types and cutting conditions as input parameters. The temperature at the cutting tool tip during cutting process is very difficult to measure and thus, it is extrapolated using simulation. Finally, the relation between cutting condition and generated heat during cutting of titanium alloy, nickel alloy and some other materials are revealed.

Concretely, the program for calculating the heat generation during cutting and the heat distribution on the whole cutting tool is first developed and evaluated by experiments. And then, the tool tip temperature for various combinations of work, tools and cutting conditions are calculated. The optimum cutting condition can easily be calculated in short time using the developed program. Moreover, the mechanical property of the cutting tool is also investigated by FEM static analysis. In this research, the lathe cutting process is used in experiments for evaluation.

2. INVESTIGATION OF DIFFICULTY FOR CUTTING OF DIFFICULT TO CUT MATERIALS

In this section, the difficulty for cutting of titanium alloy and nickel ally materials is investigated using cutting simulation. Here, dynamic explicit method is used with taking cutting tool types and cutting condition as parameters. The tool tip temperatures for cutting of titanium alloy and nickel alloy materials are calculated and finally the difficulties of cutting those materials are evaluated.

Fig. 1 shows the schematic of the simulation model and the AdvantEdge Ver. 4.5 (dynamic explicit method) software is used in simulation. Three work-piece materials Inconel718 (nickel alloy), Ti6Al4V (titanium alloys) and S45C (carbon steel) are used in calculation. The tool types used are Molybdenum HSS, Carbide P20, Ceramics Al_2O_3, CBN and Diamond. Table 1 shows the analysis conditions used in simulation. Two kinds of cutting conditions, medium cutting for general use and high speed cutting for higher productivity are selected in the simulation.

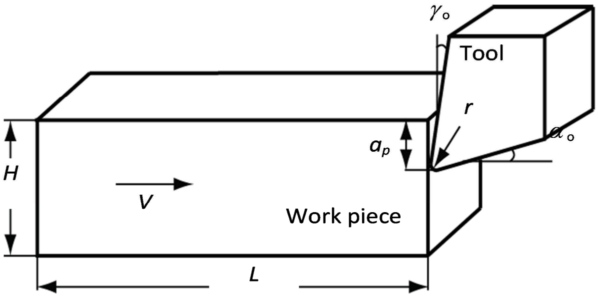

Fig. 1. Cutting simulation model

However, cutting of carbon steel using diamond tool would occur dispersion of carbon atoms from diamond tool to the carbon steel work piece and this will cause extremely large wear and tool damage. Therefore, this combination is omitted in the simulation. Moreover, the cutting tool model is changed into two dimensional model in the simulation.

Table 1. Analysis conditions for cutting simulation

Cutting parameters	Medium cutting	High speed cutting
Cutting depth : a_p	1 mm	0.2 mm
Feed speed : f	0.2 mm/rev	0.1 mm/rev
Cutting speed : V	150 m/min	1000 m/min
Cutting distance : l	9 mm	
Room temperature : Tr	20^{o}C	
Workpiece height : H	2 mm	
Workpiece length : L	10 mm	
Rake angle : γ_0	5^{o}	
Clearance angle : α_o	10^{o}	
Tool tip radius : r	0.02 mm	

Fig. 2 shows one example of the simulation results showing temperature distribution of cutting Ti6Al4V with carbide tool for 9 mm cutting distance. It is observed that steady state thermal condition is reached at this cutting distance. The temperature at the tip of the tool determines tool life and cutting accuracy. Therefore, in this research, the tool tip temperature is investigated by using cutting simulation with taking parameters for work piece materials, types of cutting tools and cutting conditions. Fig. 3 shows the simulation results of the tool tip temperature by cutting simulation at 9 mm from starting. It can be seen that the temperature results for cutting Ti6Al4V and Inconel 718 are comparably higher than S45C This is due to their low thermal conductivities of 7.1W/Mk, 11.4WmK which are very much lower than S45C (49.8W/m.K). Therefore, almost the heat generated between the tool and the chip during cutting is conducted into the cutting tool having higher thermal conductivity. Moreover, in the case of using same cutting condition and work piece, the tool with high thermal conductivity materials CBN (800W/m.K) and diamond (1000W/m.K) exhibit lower tool tip temperature than other types of tool materials. This is due to the effect that the thermal conductivity of the cutting tool material is very high and most of the cutting heat is conducted through the cutting tool and released out with higher heat sink effect. This causes lesser temperature differences throughout the whole cutting tool. Moreover, diamond tool having lower coefficient of friction also assist less heat generation during cutting.

Here, the problems relating to the temperature rise on the cutting tool tip will be considered. Johnson revealed the phenomenon; most of the metals becomes soften and decreases its yield strength when their temperature becomes higher [4]. The relationship between temperature and thermal softening factor, which Johnson discovered is shown in

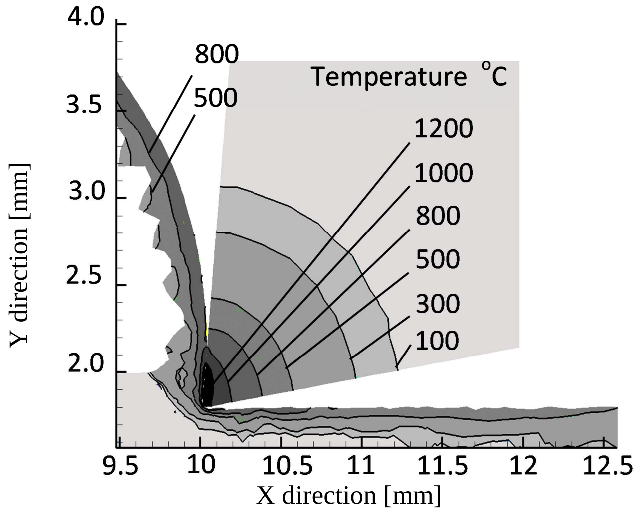

Fig. 2. Example of simulation result

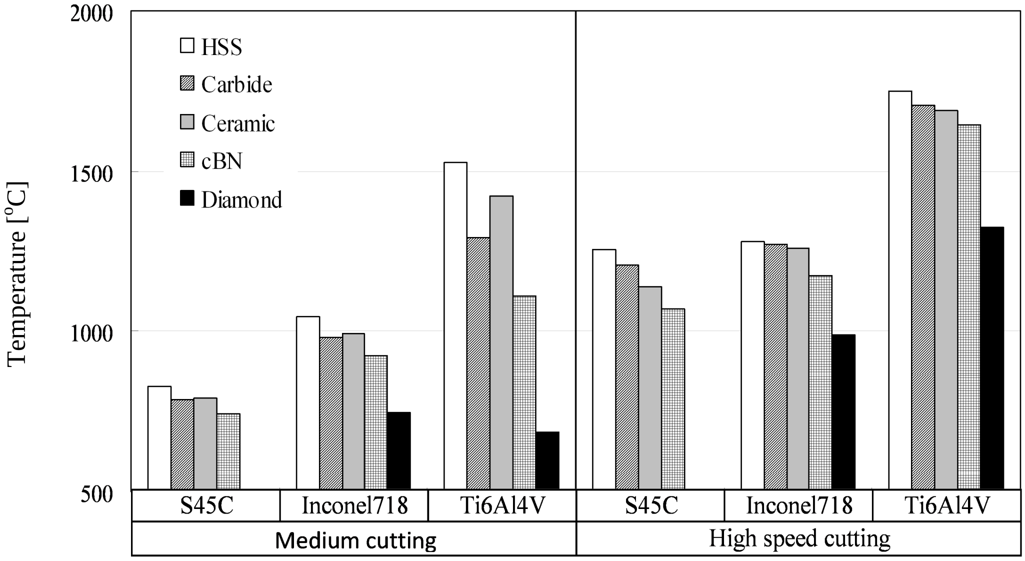

Fig. 3. Calculated results of temperature on the cutting by AdvantEdge

Fig. 4. The multiplication of thermal softening factor with the yield strength of the work piece at room temperature will give the actual strength of work piece at actual temperature. The thermal softening factors of mould making materials, SKD11, SKD61 and carbideV10 materials are shown from the experimental results of the authors [5]. From these results, it can be said that hardness of most of the metals are almost in a straight line relation with their temperature. On the other way, it can be said that if the temperature of a material is raised to half of its melting point, its strength will also become half of its original yield strength. At that condition, the cutting resistance of the work material could also become about half. However, for the case of cutting of titanium alloys and nickel alloys, the cutting tool tip becomes extremely high temperature during very short cutting time and decreasing its strength resulting extremely shorter tool life.

With the exception for the case of diamond cutting tool, there is no thermal dependency of the hardness till its temperature reaches 300°C and it is applicable for cutting titanium alloy and nickel alloy materials under this temperature.

The optimum cutting condition for cutting titanium alloys and nickel alloys can be obtained by using such explicit dynamic FEM cutting simulation with many steps of trial and error calculations. However, these application softwares are expensive and also take extremely long time for calculations.

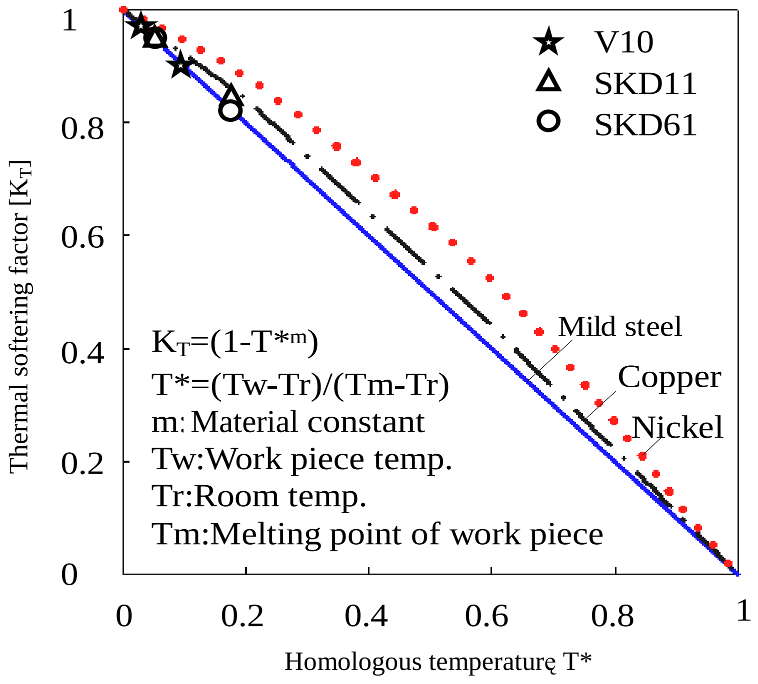

Fig. 4. Relationship between temperature and thermal softening factor for some materials

3. INVESTIGATION OF OPTIMUM CUTTING CONDITION BY CALCULATION

3.1. EXPLANATION OF THE OPTIMUM CUTTING CONDITION ESTIMATION TOOL

The high temperature at the cutting tool tip decreases hardness and strength of the cutting tool and thus, tool life also becomes shorter. The objective of this research is to develop an estimation tool to predict optimum cutting condition. Firstly, the simulation model for calculation of cutting heat generation and heat distribution on the cutting tool is developed. There also have several studies relating to the cutting heat generation and the heat distribution behaviors [6], [7]. In this research, the equations revealed by Hirao [7] are used for calculation of heat distribution. The heat generated during lathe turning process Q [W] can be considered as follow. The heat flux q_1 [W/m^2] generated by plastic deformation during chip formation at the shear plane, q_2 [W/m^2] generated by frictional abrasion between rake face of the tool and the chip and q_3 [W/m^2] generated by frictional contact between flank face of the tool and newly cut surface of the work piece. Among them, q_1 and q_3 are conducted into the work piece and q_2 and q_3 are conducted into the cutting tool. Taking R_1, R_2 as the fractions of the generated heat distributed to the chip from heat source q_1, q_2 and R_3 as the heat distributed to the work piece from heat source q_3 and the amount of heat received by work piece is Q_w [W], that for tool Q_t [W] and, for chip Q_c [W] can be represented by equations (1)~(3) respectively [8]. Moreover, taking the average arising temperature of tool T is 1/8 of infinite object (tool), and heat source q_2 at contact length between rake surface and chip l, depth of cut a_p for three dimensional cutting the average temperature on the surface of the object can be shown as in equation (4) [8].

$$Q_w = (1 - R_1)\, q_1 A + R_3 q_3 C \cdot \cdot \cdot \cdot \tag{1}$$

$$Q_t = (1 - R_2)\, q_2 B + (1 - R_3)\, q_3 C \cdot \cdot \cdot \cdot \tag{2}$$

$$Q_c = R_1 q_1 A + R_2 q_2 B \cdot \cdot \cdot \cdot \tag{3}$$

$$T = (1 - R_2)\, q_2\, l\, S / \lambda \cdot \cdot \cdot \cdot ` \tag{4}$$

Here, A [m^2] is the shear plane area of work piece and chip, B [m^2] is contact area between rake face and chip, C [m^2] is contact area between flank face and new work piece, S [-] is the geometrical factor determined from only relative format a_p/l of heat source q_2 , λ [W/mK] is thermal conductivity of cutting tool. The values in the left side of equations (1) to (4) varies with cutting conditions (cutting speed, feed speed, depth of cut), tool geometric shape (rake angle), physical properties of tool and work piece (thermal conductivity, specific heat, density), the coefficient of friction between the tool and chip. Using equations (1) to (4), the heat generated during cutting on work piece or cutting tool and the tool temperature can be calculated easily in the step before real cutting with this simple method. Moreover, the quantitative estimation of the heat distribution on work piece or cutting tool, for different frictional heat generation depending on tool geometry, size, material, surface treatment condition, and cutting condition can also be obtain easily by this method. In this research, the conventional cutting tool with clearance angle 6^{o} is used for the calculations of the evaluation using these model equations. Moreover, the friction between the work piece and flank face is taken to be negligible in the calculation.

These model equations are set on the excel spread sheet and filling the input factors for heat generating mentioned in above can easily be calculated Q_w, Q_t, Q_c, R_1, R_2 and T in very short time. Hereafter, this method will be called the estimation tool for optimum cutting condition.

3.2. CALCULATION OF TOOL TIP TEMPERATURE USING ESTIMATION TOOL

Among the input factors of the estimation tool software, thermal dependence characteristic of thermal conductivity, specific heat and strength of materials also effects on the tool tip temperature. In the studies of heat distribution in cutting, the values of thermal conductivity and specific heat of the work piece and chip could become more accurate by considering thermal dependency of their mechanical properties. Here, thermal dependency of thermal conductivity and that of specific heat values considered for accurate calculation are shown in Fig. 5 and Fig. 6 respectively [9]. The input value for tensile strength of the work piece is taken from the yield strength value corresponds to the temperature of work piece from Fig. 4 (assuming inversely proportional and taking material constant =1). The calculation is taken for three kinds of work piece materials S45C, Inconel718 and Ti6Al4V. The same cutting condition as in previous cutting simulation (AdvantEdge Ver. 4.5) is used. The calculation results of tool tip temperature for medium cutting and high speed cutting using estimation tool are shown in Fig. 7. It is required to provide the temperature values of work piece and chip for accurate calculation considering thermal dependency property of thermal conductivity, specific and yield strength. For confirming the accurate and stable output results of tool tip temperature, some steps of trial and error calculations are taken. In this study, only 2~3 times of simple trial and error calculation meet the best convergence of results.

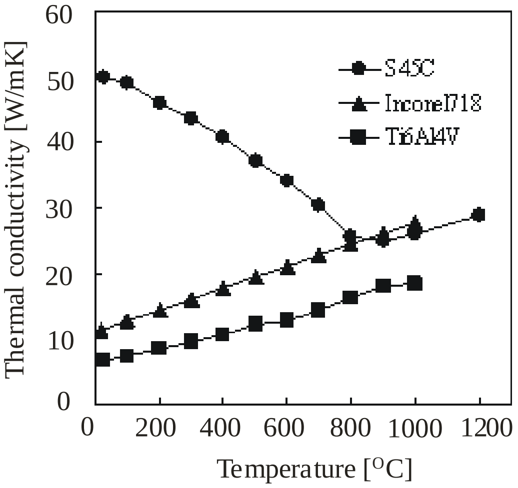

Fig. 5. Thermal dependency of thermal conductivity for soma materials

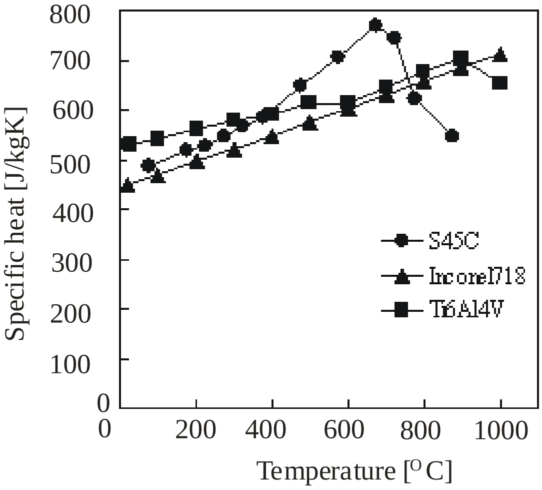

Fig. 6. Thermal dependency of specific heat for some materials

The percentages values shown in the figure represents the values of the percentage difference of results from previous calculation (Fig. 3) compared with newly developed estimation tool. From these results, it can be seen that the values exist between 74%~116% in comparing with the previous simulation result. For the case of without considering the thermal dependency for thermal conductivity, specific heat of work piece and chip, the values are between 50%~200% while calculating using normal properties. Therefore, the consideration of the thermal dependency is effective for the improvement of accuracy in the calculation.

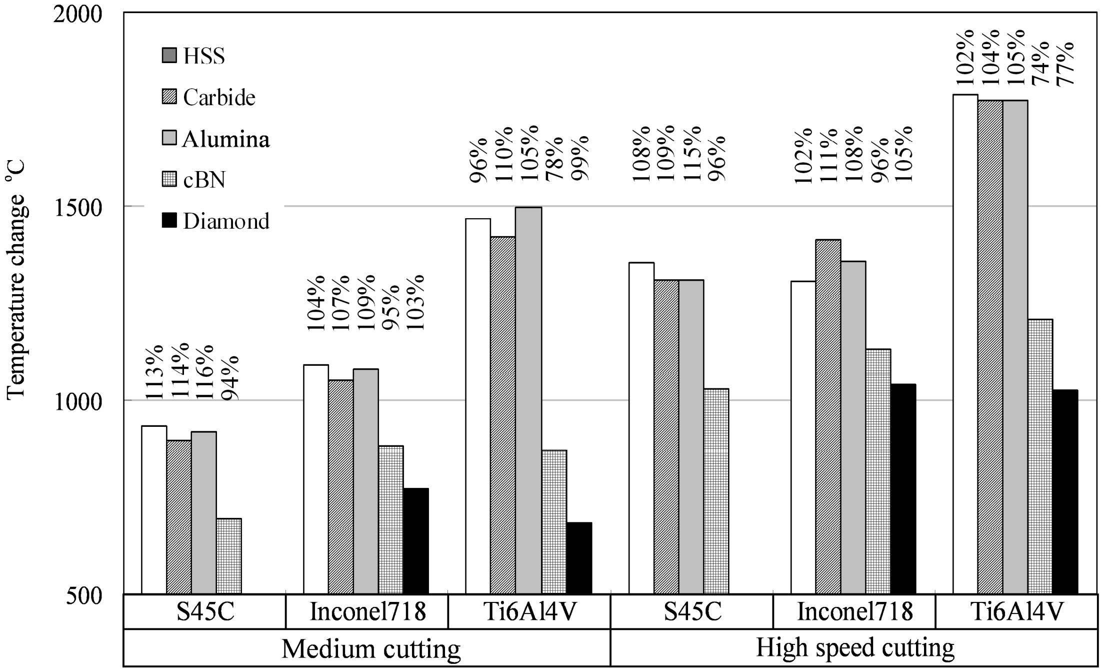

Fig. 7. Calculated results of temperature on the cutting point

In the next step, the calculation method for optimum cutting condition using estimation tool relating to the work pieces Inconel718 and Ti6Al4V will be explained. As an example, the cutting process of Inconel 718 and Ti6Al4V with carbide tool P20 will be considered. Here, the determination of limit cutting condition (at which tool tip temperature reach its maximum limit), is undergone based on the condition for cutting work piece S45C, carbide tool P20 with medium cutting condition (Table 1). Although the amount of heat distribution to the cutting tool Q_t depends on the thermal conductivity of work piece, the heat entering area (contact area of rake face and chip) may also change depending on the specification of work piece and cutting tool, which is largely effect on Q_t. Therefore, the temperature on the tool tip is chosen as basic temperature value for the calculation here as it is directly effect on the softening coefficient (Fig 4). It can be considered that, if the tool tip temperature while cutting Inconel718 and Ti6Al4V could maintain as same temperature as in cutting S45C, the mechanical properties of the cutting tool will also be maintained in the same condition as cutting S45C. The machinists can easily calculate the tool tip temperature under desired cutting condition using this estimation tool for optimum cutting condition and easily define the standard optimum cutting condition for each material.

As a standardization, the optimum cutting condition for cutting work piece S45C with P20 carbide tool at which tool tip temperature would reach $T_{S45C}=849.8\ ^{\circ}C$ is calculated by using estimation tool. After that, the optimum cutting condition for work piece Inconel718, Ti6Al4V is estimated by changing cutting condition (cutting speed, depth of cut, feed speed) to keep tool tip temperature below 849.8 °C. Although the optimum value can be obtained easily [10], some trial and error calculations are repeated here.

Table 2 shows the estimated results of optimum cutting condition. Here, the optimum cutting condition is estimated by changing any of the parameters from cutting speed, depth of cut and feed speed. To achieve nearly the same cutting tool temperature as cutting S45C material, it is necessary to reduce any of the cutting condition is as usual. However, for the cases of cutting Inconel 718 and Ti6Al4V, changing the cutting speed is the best choice for maintaining the high productivity and tool tip temperature under desired value compare to changing other conditions by considering metal removal rate. This estimation tool for optimum cutting condition is much easier, lower cost and shorter calculation time compare with using cutting simulation (AdvantEdge Ver. 4.5) in the previous section. It is applicable in the industries for practical usage of cutting processes. Moreover, even though the specific cutting resistance of each kind of work piece may differ and the cutting characteristic may also change. However, it can be controlled by considering the specific cutting resistance of work piece, hardness and using thermal softening coefficient from Fig. 4.

Table 2. Calculated result of limit of cutting condition

Material	S45C	Inconel 718			Ti6Al4V		
Modification of cutting parameter		Cutting speed	Cutting depth	Feed speed	Cutting speed	Cutting depth	Feed speed
Cutting speed m/min	150	74.8	150	150	37.8	150	150
Cutting depth mm	1	1	0.075	1	1	0.047	1
Cutting speed mm/rev	0.2	0.2	0.2	0.072	0.2	0.2	0.016
Tool temperature °C	849.8	849.7	849.8	848.5	849.3	849.6	849.6
Material removing rate mm^3/s	500.0	249.3	375.0	180.0	126.0	23.5	39.3

3.3. INVESTIGATION OF THE STRESS ANALYSIS ON RAKE FACE OF THE CUTTING TOOL

In this section, the stress distribution on the rake face of the cutting tool is investigated using simple and effective static implicit FEM analysis method. And then, the method for estimation of cutting stresses on the tool during cutting of titanium alloy and nickel alloy was evaluated.

Fig. 8 shows the stress analysis model of cutting tool tip and Table 3 shows the analysis condition and the cutting tool geometry. In the simulation, the cutting condition in table 1 is used and the cutting force exerting on the cutting area of the tool rake surface (depth of cut a_p× feed f) is obtained by calculation using the estimation tool for optimum cutting condition explained in previous section. The restraints for the cutting tool taken in FEM simulation are; both sides of the rake face are made to be roller supported and, the upper surface and the opposite side of the rake surface is made to be fixed as shown.

Fig. 9 shows the stress distribution along the rake surface obtained by calculation using static implicit FEM method (Cosmos Works) and dynamic explicit method (AdvantEdge Ver. 4.5) for cutting Ti6Al4V material with carbide tool K10. The horizontal axis is the distance along the rake surface from the edge of cutting tool. The results obtained from both CosmosWorks and AdvantEdge are about the same values for the distance between 0.1 ~ 0.6 mm. However, in the region from 0 ~ 0.1 mm, the results are different about 5 times. The reason can be considered that, in the Cosmos Works stress analysis, the value of input cutting force obtained by using the optimum cutting condition estimation tool is assumed to be uniformly distributed throughout the whole tool cutting area on the rake face (depth of cut a_p × feed f). However, in the practical cutting, the stress distribution is largely concentrated near the cutting edge of the tool and causing higher stress near the edge. Moreover, similar results were exhibited for the other combinations of tools and work pieces.

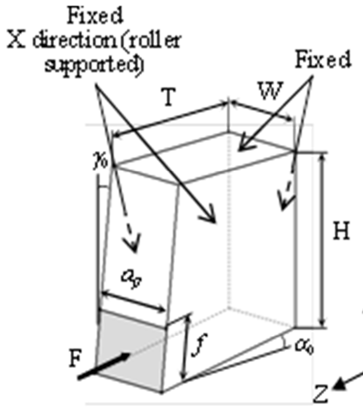

Fig. 8. Model for calculation of stress on the rake face

Table 3. Tool geometry and analysis conditions for stress on the rake face

Rake angle

Depth of cut : a_p	1mm
Feed rate : f	0.2 mm
Tool height : H	2 mm
Tool thickness : T	2 mm
Tool width : W	1 mm
Rake angle : γ_0	5^{o}
Clearance angle : α_0	10^{o}
Cutting force : F	Value calculated by excel
Room temperature : Tr	20^{o}C

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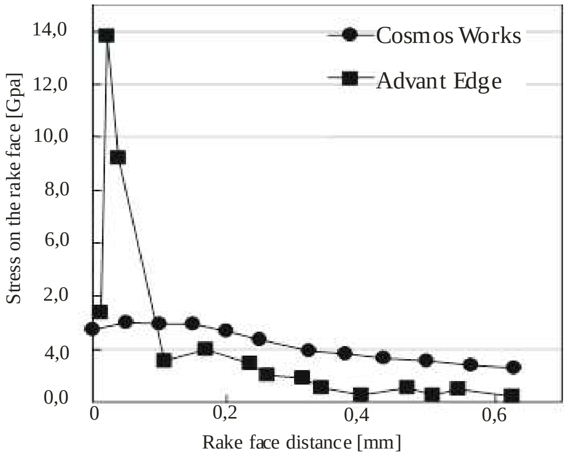

Fig. 9. Calculated values of stress on the rake face

When the temperature of a material becomes higher, its yield strength also decreases. This fundamental also effect on the cutting tool, decreasing its strength and hardness with rising temperature. Especially, in the case of cutting Inconel718 and Ti6Al4V, thermal conductivity of those materials are very low and most of the cutting heat is conducted to the cutting tool, resulting very high tool temperature and shorter tool life. By using static implicit FEM analysis, the average stress distribution on the tip of the tool is well understood. And then, the temperature on the tip of the tool could be estimated well by using the developed estimation tool for optimum cutting condition.

4. EVALUATION OF PROPOSED METHOD

Here, the developed estimation tool for optimum cutting condition is evaluated by cutting experiment of Ti6Al4V and carbide tool P20 using lathe turning process and the temperature of the tool during cutting and the tool life are measured. The medium cutting condition shown in Table 4 is used in the experiment.

Table 4. Cutting condition and specification of tool

Type of cutting		Medium cutting	New method in section 3
Work piece		S45C, Ti6AL4V	Ti6Al4V
Cutting speed		150 m/min	37.8 m/min
Cutting depth		1mm	
Feed rate		0.2 mm/rev	
Tip	Kind of material	Carbide P20	
	Geometry	CNMG120408 (Tungaloy)	
Holder		PCLNR2525M12 (Toshiba Tungaloy)	

Fig. 10 shows the results of the temperature at the cutting tool tip. The temperature on the tool tip is interpolated by using FEM (CosmosWorks) based on the measured temperature values at the points near tool tip. For the case of cutting Ti6Al4V at cutting speed 150 m/min, it was failed to measure the temperature due to chip moving direction and tool damage. Therefore, the cutting speed is reduced to 100 m/min. The result of the temperature calculated using ‘estimation tool for optimum cutting condition’ is also shown for comparison. It can be seen that the temperature for cutting Ti6Al4V with medium cutting condition is extremely higher and it can be reduced to the value nearly same with cutting S45C carbon steel by controlling cutting condition with using the proposed method.

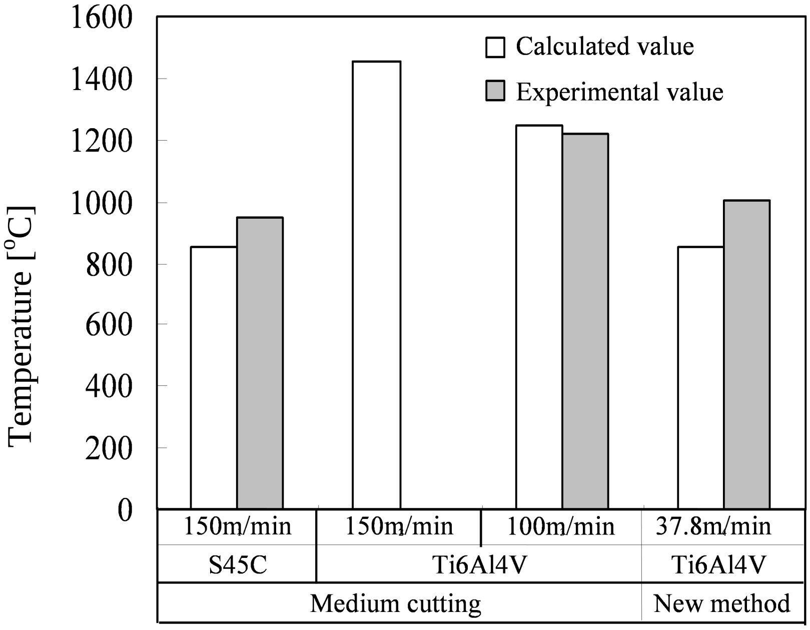

Fig. 10. Experimental results for evaluation of temperature on the edge of tool

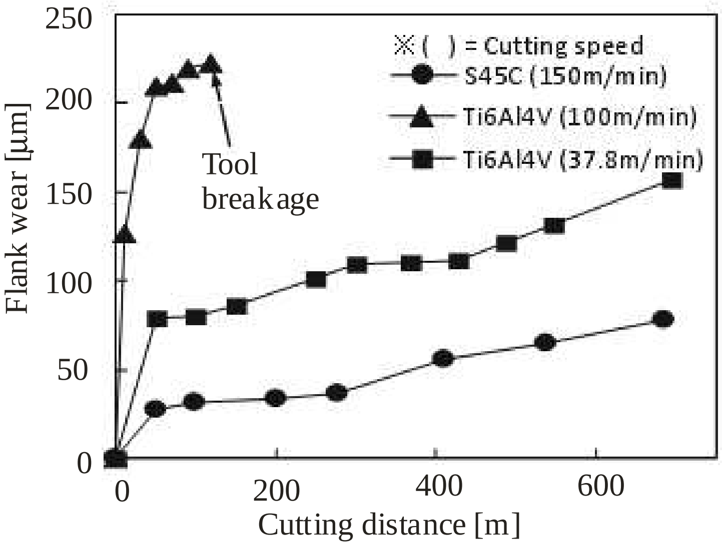

Fig. 11. Experimental result of tool life test

Finally the tool life experiment is taken for the evaluation of the applicability of proposed estimation tool. The experiments are taken for each cutting conditions and flank ware is measured for 700 m cutting length. Fig. 11 shows the experiments result of the tool life test. The flank ware of the cutting tool for cutting Ti6A15V with using estimated optimum cutting condition is much longer than that of medium finishing cutting without using estimation tool.

5. CONCLUSION

From the above results, it is confirmed that the developed estimation tool for optimum cutting condition is capable of controlling the tool tip temperature by investigating the suitable cutting condition. Therefore, the developed estimation tool is very effective for predicting cutting heat generation with maintaining cutting tool life longer.

The following advantages are obtained from this research.

(1) The developed ‘estimation tool for optimum cutting condition’ is very effective for investigating the optimum cutting condition of cutting titanium alloys and nickel alloys.

(2) The optimum cutting condition for cutting low thermal conductivity materials can be estimated with easy, faster and economy by using the proposed estimation tool.

REFERENCES

[1] NARUTAKI N., YAMANE Y., 1993, *High-speed machining of Inconel 714 with ceramic tools*, CIRP Annals, 42/1/103-106.

[2] USUKI H., SATO K., FERUYA S., 2005, *High Speed Dry End Milling of Titanium Alloy with Coated Carbide Tool*, Journal of the Japan Society for Precision Engineer, 71/4/491-495.

[3] KITAGAWA T., KUBO A., MAEKAWA K., 1997, *Temperature and wear of cutting tools in high-speed machining of Inconel 714 and Ti-6Al-6V-2Sn*, Wear 202, Elsevier Science, 142-148.

[4] JOHNSON G. R., COOK W.H., 1983, *A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperature*, Proc. 7th Int. Symp. on Balistic, The Hague, 541-547.

[5] TANABE I., BINH H. T., SUGAI H., INOUE M., 2007, *Cutting With Heating of Work Piece and Cooling of Tool Regarding Cemented Mould and Die*, Transactions of the Japan Society of Mechanical Engineer, Series C, 73/727/885-890.

[6] The Japan Society of Mechanical Engineer, 1998, *Ultraprecise Process Technology*, Corona publishing Co., Ltd.

[7] HIRAO M., TERASHIMA A., HO Y.J., SHIRASE K., YASUI T., 1998, *Behavior of Cutting Heat in High Speed Cutting, Journal of the Japan Society for Precision Engineer*, 64/7/1067-1071.

[8] TAKEYAMA H., 1998, *Cutting Process*, Maruzen Co., Ltd, 35-47

[9] The Japan Institute of metals, 1976, *Iron and Steel Material Handbook*, Maruzen Co., Ltd, 56-59.

[10] MIZUMOTO H., 1977, *Industrial Mathematics II*, Morikita publishing Co., Ltd, 35-55.