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Cutting Temperature and Forces in Machining of High-Performance Materials with Self-Propelled Rotary Tool*

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Cutting temperature and forces are two dominant parameters that influence finish quality and tool life in machining. This paper undertakes the evaluation of these two factors in relation to machining by a self-propelled rotary tool, an efficient cutter recently reported to be superior in cutting some new materials. Temperature analysis is based on a model of a heat source moving cyclically along the cutting edge. Both analytical and experimental results indicate that the rotating motion of the cutting edge transfers heat away from the cutting zone with the result being a reduced cutting temperature. Temperature of the cutting edge drops to the neighborhood of the ambient value after it passes the cutting zone. Cutting forces of the rotary tool are found to be smaller, especially the radial thrust component, which is 30-40 % lower, than those of the fixed circular tool.

***Key Words*:** Cutting Temperature, Cutting Force, Metal-Matrix Composite, Titanium Alloy, Rotary Tool, Moving Heat Source

1. Introduction

Just as conventional materials cannot meet the challenging requirements for the aggressive service environments, the traditional cutting techniques have been met with great difficulties in processing high-performance materials. To cope with this challenge in machining, a special cutter characterized by the freely rotatable circular cutting edge, called the self-propelled rotary tool, has been proposed and experimentally revealed to be superior in machining some high-performance materials[1]~[3]. Especially in cutting a certain metal-matrix composite, the rotary tool reportedly enhances the life of carbide tool over 40 folds as compared to the fixed circular one and 95 folds to the square one[1].

Concerning the mechanism of rotary tool performance, it is indicated[1] that the participation of the whole circular edge in cutting and lowered effective cutting speed due to tool inclination are two essential reasons for extended tool life. However, tested tool life was found to be considerably longer than that predicted by those two factors, implying the existence of an unknown mechanism which enhances the tool performance.

Because cutting temperature and forces are two dominant parameters that influence finish quality and tool life in machining, evaluation of the rotary tool is undertaken in this paper from the viewpoint of these two factors by means of both analytical and experimental investigations.

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2. Equivalent Cutting Model

Figure 1(a) gives an illustration of the self-propelled rotary tool. The tool is inclined at a definite angle so that it is driven by the work (chip) during cutting. Besides the motions of cutting V and feeding f, the circular cutting edge has a tangential motion (tool rotation) V_t. By neglecting the effect of feed rate f which is much smaller than the cutting speed V, the following relations are drawn from the velocity diagram in Fig. 1(b).

$$V = V_r + V_t, \quad (1)$$

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$$V_c = V_{cr} + V_t, \quad (2)$$

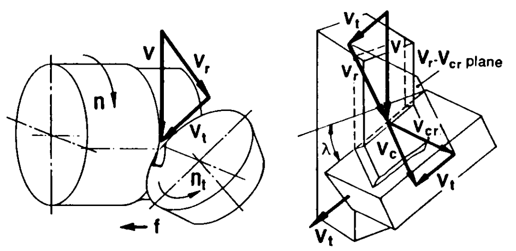
where V_r is the relative sliding motion called the effective cutting velocity, whereas V_c is the flow velocity and V_{cr}, the relative flow velocity of the chip.

Since the cutting edge is in motion, it is indicated that the cutting mechanism should be studied in the frame of reference determined by the effective cutting velocity V_r and the relative chip flow velocity V_{cr}, the plane of which remains nearly normal to the cutting edge[4]. The $V_r - V_{cr}$ plane, where the material flow could be treated as plain strain deformation with orthogonal cutting theory[5], as shown in Fig. 1 (b), is therefore assumed to be perpendicular to the edge. Discussions on cutting mechanism of the rotary tool hereafter will be made under this frame of reference.

3. Cutting Temperature Analysis

Heat generation in cutting with a sharp tool occurs principally in two zones, i. e., (1) the shear zone due to the energy released in the shear deformation, and (2) the tool-chip contact zone caused by friction.

An analytical approach is taken using a double treatment by considering the tool and the work (chip) separately, so that the partition of friction heat between them is calculated, and hence cutting temperature is determined. The free surfaces of the tool and work (chip) are assumed to be perfectly heat-insulated.



(a) Illustration of rotary cutting (b) Cutting model

Fig. 1 The self-propelled rotary cutting tool

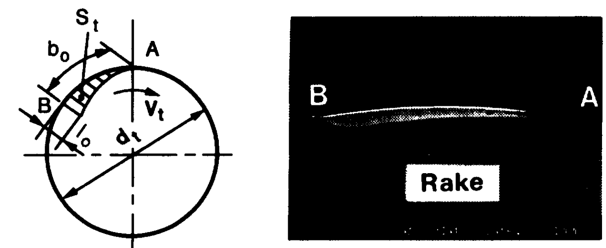
3.1 Temperature analysis of the tool

3.1.1 Moving heat source model If the inclination of the cutting edge is set to be positive as shown in Fig. 1, the tool-chip friction zone can be taken as a heat source S_t moving clockwise along the circular cutting edge in relation to the tool, Fig. 2 (a).

Although it is difficult to detect the shape of the tool-chip friction zone in rotary cutting, it could be simplified to be a right-angled triangle by observing the worn rake face of the fixed circular tool, as illustrated in Fig. 2 (b), where the worn width increases with uncut chip thickness.

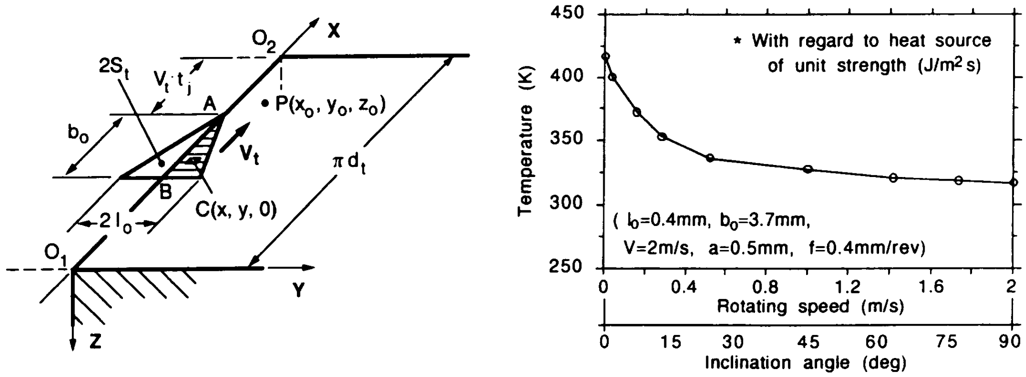
Provided that the rake and clearance angles are not too large, the circular cutting tool could be treated as a quarter-infinite body as shown in Fig. 3 (a). The cutting edge extends along the x-axis and the rake, in the x-y plane. The shaded area represents the moving heat source with the area of the tool-chip interface. Further simplification by symmetry is made by assuming a heat source $2S_t$ moving along the x-axis at the surface of an adjoining semi-infinite body, provided that the x-z plane is a perfect insulator and the heat source $2S_t$ is of the same strength, yet double symmetrical area of the original S_t.

Accordingly, the heat source S_t rotating along the circular edge could be treated as a problem of $2S_t$



(a) Rotating friction zone (b) Shape of the worn rake face (fix. circular tool, SiCw/Al cutting)

Fig. 2 Rotating heat source and the tool-chip friction zone



(a) Moving heat source model (b) Effect of rotating speed V_t

Fig. 3 Moving heat source model of rotary tool cutting and the computed temperature as a function of the heat source sliding speed (tool rotation)

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periodically entering at an end 0_1, moving at speed V_t along the x-axis in the x-y plane and exiting at another end 0_2, the interval of which corresponds to one rotational period of the tool.

3.1.2 Temperature rise due to moving heat source The approach to a similar problem suggested by Jaeger(6) is adopted in this study.

The analysis is based on the partial differential formation of heat conduction in a body as the following.

$$\frac{\partial\theta}{\partial t}=K\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right), \quad (3)$$

where θ is the temperature and K, the diffusivity.

The temperature rise $\Delta\theta$ is then derived for any point $P(x_0, y_0, z_0)$ in an infinite body in time t after a heat Q is liberated instantaneously at a point $C(x, y, z)$:

$$\Delta\theta=\frac{Q}{8\rho c(\pi Kt)^{3/2}}\exp\left(-\frac{\Delta r^2}{4Kt}\right), \quad (4)$$

where ρ is the density and c the specific heat of the body, while Δr is the distance between the two points $\{\Delta r^2=(x_0-x)^2+(y_0-y)^2+(z_0-z)^2\}$. If point C is on the surface of a semi-infinite body, $\Delta\theta$ will be double that of Eq. (4) because the heat transfer path is reduced by half.

For simplification, it is supposed that the moving heat source $2S_t$ is a uniformly distributed triangular one, the strength of which is Rq_t, where q_t is the mean rate of heat dissipated at the tool-chip interface per unit time per unit area, and R is the mean fraction of q_t that flows into the tool.

For numerical computation based on the model described in Fig. 3(a), the moving heat source $2S_t$ is divided into finite elements, and so is the circular edge with fineness depending on the distance from the working section of the cutting edge. The movement of $2S_t$ along the cutting edge is treated as a series of momentary heat sources occurring successively along each sequential element of the edge. The temperature rise at any point of the cutting edge due to heating for one rotational period of cutting is then obtained by integrating the temperature effect caused by each individual element of the heat source using Eq. (4) over the area of $2S_t$, and summing this incrementally throughout one period. In steady cutting when the tool reaches its thermal equilibrium state, the temperature distribution along the cutting edge will be the cumulation of the temperature rise due to each rotational period until $2S_t$ has cycled for a considerably large number of periods. Thereafter, cutting temperature θ_0 will be the average value over the area of $2S_t$. This computation, together with that concerning the work (chip) as described in the following section, was performed in the SUN 4/110 Working Station.

Diagram (b) in Fig. 3 represents a sample result of the analysis with regard to a heat source of unit strength (J/m²s) and an ambient temperature of 273.2 (K). Cutting temperature shows significant reduction as the tool starts turning, and such decrease becomes moderate as the rotating speed V_t increases associated with the greater inclination angle λ.

3.2 Temperature concerning the work (chip)

For mathematical simplification, it is assumed that the heat flow is two-dimensional in the V_r-V_{cr} plane where material flow could be treated as a plain strain problem, as discussed in Chapter 2.

By means of the analytical approach presented by Loewen and Shaw(7), temperature rise in the shear plane and that of the chip underside can be derived, the details of which are not presented here. In this case, all the data involved, such as cutting forces, tool-chip contact length, kinematic and geometric data, are those measured in the V_r-V_{cr} frame of reference. Cutting temperature θ_0' will be

$$\theta_0'=\theta_s+\Delta\theta_t, \quad (5)$$

where θ_s is the average shear-plane temperature and $\Delta\theta_t$, the average temperature rise in the tool-chip interface with the parameter R yet unknown, the mean fraction of heat liberated at the interface that flows to the tool.

3.3 Cutting temperature computed By equating analytically the two values of θ_0 and θ_0' described in Sections 3.1.2 and 3.2, respectivly, the fraction R is determined along with cutting temperature θ_0, as well as the temperature distribution along the cutting edge.

4. Experiments

4.1 Cutting temperature measurement

To verify the above analysis, temprature experiments were performed by turning on a HOSHOI HCN450 CNC milling machine with the work chucked vertically on the spindle. The cutting temperature was measured by means of the tool-work thermocouple technique, as illustrated in Fig. 4. Temperature rises at the cold junctions of both the tool and the work were read simultaneously by the copper-constantan (CC) thermocouple for compensation. A specially designed mercury junction with two isolated chambers was used to transfer the signal from the rotating thermocouple.

Temperature fluctuation at a particular part of the cutting edge was also examined by burying a copper wire of 0.32 mm in diameter into a tiny groove leading to the edge ground on the flank face.

4.2 Cutting force experiment

Cutting force measurement was conducted by turning on an OKUMA LC10 CNC lathe. Both the

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rotary tool and the fixed circular one were tested for comparison under the identical conditions in cutting.

4. 3 Experimental conditions

(1) Work materials

The materials tested were a SiC whisker reinforced aluminum (hereafter referred to as SiCw/Al) composite, a family of metal-matrix composites which has been practically applied to some newly developed high-performance motor engines, and Ti-6Al-4V, presently a widely used titanium alloy. The physical properties of the materials concerned are listed in Table 1.

(2) Cutting tools

Rotary tool : circular carbide insert (K10 with TiN-coated, $\phi 27$, $\gamma=0$, $\alpha=8°$).

Fixed circular tool : the same as the rotary tool but fixed.

(3) Cutting conditions

The cutting conditions are specified in Table 2.

Table 1 Physical properties of the materials

Materials	SiCw/Al	AC8A	SiCw	Ti-6Al-4V	K10
Density (kg/m^3)	2860	2720	3190	4460	14900
Ten.strength (GPa)	0.44	0.27	6.89	1.42	–
Young's mod. (GPa)	114	76.5	549	110	627.5
Therm.cond.(W/mK)	143.5*	117	134	6.27	79.5
Specific heat (J/gK)	1.14*	0.96	0.67	0.57	0.21
Hardness	HB100	HB75	HV2100	HB321	HRA92.5

* Data measured at 577K

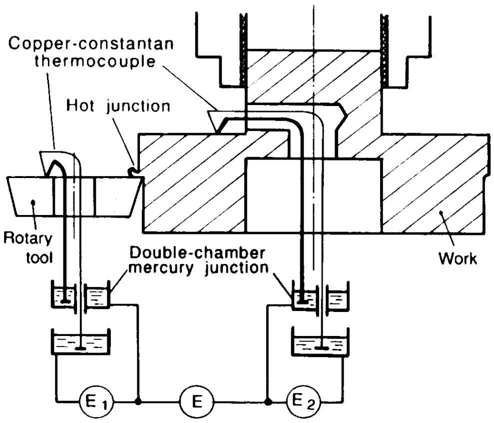


Fig. 4 Arrangement for cutting temperature measurement in rotary cutting

5. Experimental Results and Discussion

5. 1 Cutting temperature

Diagrams in Fig. 5 illustrate cutting temperature as a function of cutting speed and the inclination angle in turning the SiCw/Al composite. Increasing the cutting speed leads to a rise in cutting temperature as shown in diagram (a). It is noted that the rotary tool gives a temperature reading about 80K lower than that of the fixed circular one. The greater inclination angle of the rotary tool definitely results in decreased temperature, though such an effect is moderate in cutting the composite, diagram (b).

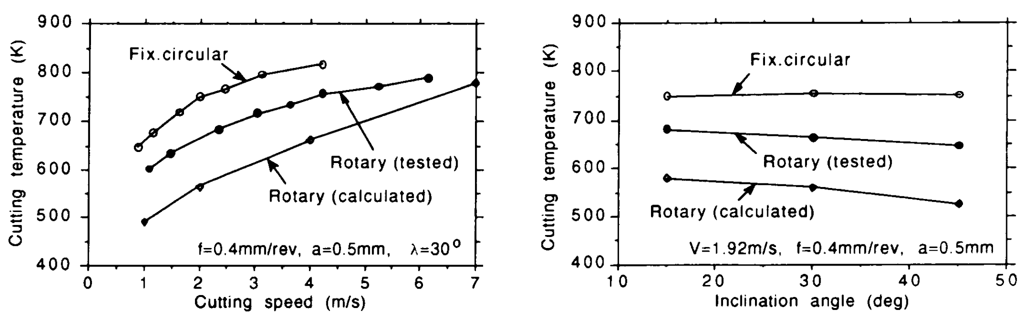
The analytical results are also represented in the diagrams of Fig. 5. Calculation was performed using the kinematic data of Ref. (1) and the cutting force data of Fig. 8 transformed into a normal coordinate system, the y-z plane of which coinciding with the $V_r - V_{cr}$ plane, and the origin at the centroid of the uncut chip area where the resultant cutting force was assumed to pass through. The calculated cutting temperature shows a similar variation tendency as that of the experimental data.

In turning Ti-6Al-4V alloy, the difference in cutting temperature by the alternative tools is much more obvious. As shown in Fig. 6, applying the rotary tool lowers the temperature about 220 K over that of the fixed circular one.

Obviously, reduced cutting temperature is one of the essential features of the rotary tool. Although it is reported that temperature has little influence on tool

Table 2 Cutting conditions for the tests

Work	SiCw/Al	Ti-6Al-4V
Tool	Rotary / Fix.cir.TL	Rotary / Fix.cir.TL
Cut. speed V	1.0 - 6.7 m/s	0.67 - 2 m/s
Feed rate f	0.4 mm/rev	0.4 mm/rev
Dep.of cut a	0.25 - 1.0 mm	0.25 mm
Inclination λ	15 - 45 deg	30 deg
Cut.fluid	dry cutting	dry cutting



(a) Effect of cutting speed (b) Effect of inclination angle

Fig. 5 Cutting temperature as a function of the alternative factors (SiCw/Al cutting)

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wear in turning the SiCw/Al composite[8], this feature is believed to be significant in machining materials with low thermal conductivity, such as titanium alloys.

5.2 Heat cycling of the cutting edge

As demonstrated in Fig. 7, both the analytical and experimental results reveal that the cutting edge is cooled down to the neighborhood of the ambient temperature after it passes the cutting zone. On the other hand, such a fluctuation in one revolution of the tool may give the cutting edge a periodic thermal impact, which is considerable in cutting materials with low thermal conductivity where cutting temperature is high. Thermal cracks found normal to the rotary cutting edge in machining either Ti-6Al-4V or 18Mn steel, as reported[3], are understood to result for this reason.

Because the experimental data are of the average temperature of the copper-wire/tool contact area, the measured temperature fluctuation appears much more moderate compared with that of the calculated one where a theoretical point of the edge is concerned.

5.3 Cutting forces

Diagrams in Fig. 8 show the manners in which cutting forces of the alternative tools vary by a number of factors in turning the SiCw/Al composite. The force component in the cutting direction F_v of the rotary tool is found to be 10-15% lower than that of the fixed circular tool, while that in feeding direction F_f of either of the tools takes a similar value. It is noted that by switching the fixed circular insert to the rotary tool, the force component in the radial thrust direction F_t decreases by 30-40%, which is significant in relieving the flank wear. Of both the alternative tools, cutting forces increase proportionally with the depth of cut and decrease slightly with increased cutting speed, as shown in diagrams (a) and (b). As a function of the inclination angle, variations in F_v, F_t and F_f of the fixed circular tool are moderate compared with the rotary tool, diagram (c).

Transformed into the normal coordinate system

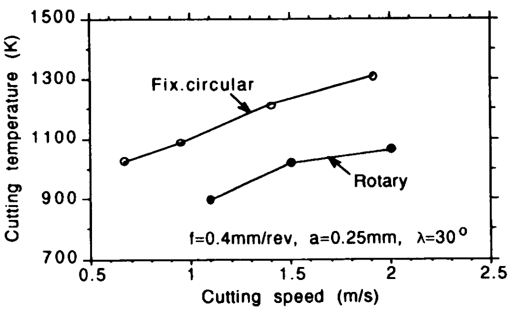

Fig. 6 Measured cutting temperature in machining Ti-6Al-4V

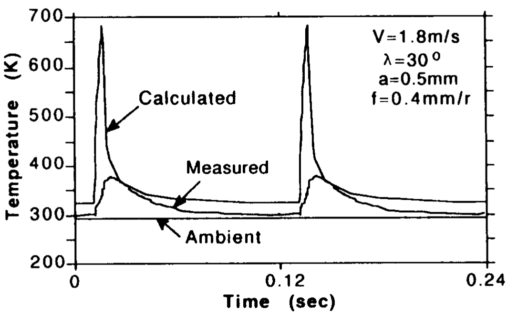

Fig. 7 Temperature fluctuation of the cutting edge (SiCw/Al composite cutting)

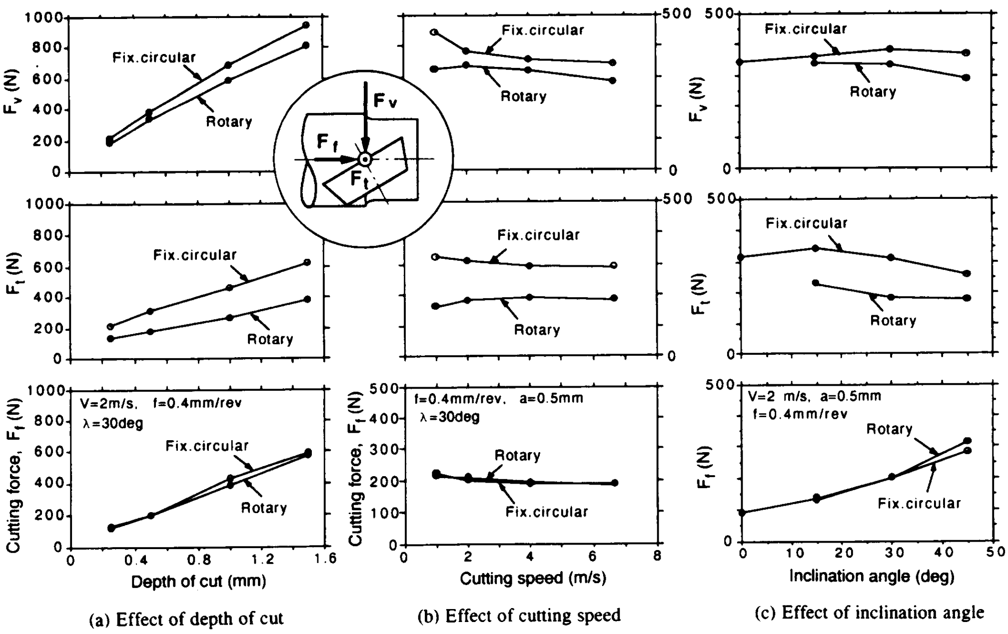

Fig. 8 Comparison of cutting forces of the alternative tools (SiCw/Al composite cutting)

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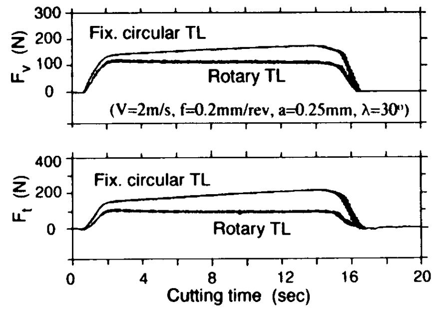

Fig. 9 Cutting force variations of the alternative tools during machining (SiCw/Al composite cutting)

for numerical calculation of the cutting temperature as described in Sections 3.2 and 5.1, it is noted that the force component tangential to the cutting edge takes a negligible magnitude, and its direction coincides with the tool rotation counterbalancing the friction of the rotary system. A similar experimental result in cutting of brass with a rotary tool made of high-speed steel (HSS) was also presented by Kasei and Masuda[4]. It is understandable because the self-propelled rotary tool has a rotational freedom about its axis. This dynamic characteristic is probably an essential reason for the reduced cutting forces in rotary cutting.

Comparison of the variations in cutting forces, $\boldsymbol{F}_v$ and $\boldsymbol{F}_t$, for example, of the alternative tools during machining is given in Fig. 9. In rotary cutting, the cutting forces vary moderately in both the cut-in and cut-out processes, and remain almost stable during steady cutting. Nevertheless, those of the fixed circular tool increase noticeably as machining progresses, about 23% in $\boldsymbol{F}_v$ and 36% in $\boldsymbol{F}_t$ with a 0.11-mm width of flank wear developed in one machining cycle, 16 seconds of the cutting time. This is understood to be a result of rapid tool wear.

6. Conclusions

Based on the theoretical analyses and experimental investigations, the following points are concluded.

(1) The tangential motion of the cutting edge in rotary cutting leads to a reduced cutting temperature, about 80K in cutting the SiCw/Al composite and 220K in turning Ti-6Al-4V compared with that of the fixed circular tool.

(2) Temperature of the cutting edge is cooled down to the neighborhood of the ambient value after it transits the cutting zone. This gives the cutting edge a periodic thermal impact, which is noticeable in cutting the materials with low thermal conductivity.

(3) Cutting forces of the rotary tool are found to be smaller, especially the radial thrust component which is 30-40% lower, than those of the fixed circular one in turning of the composite.

Consequently, reduced cutting temperature and decreased cutting forces are found to be features of the rotary tool.

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References

(1) Chen, P. and Hoshi, T., Characteristics of Self-Propelled Rotary Tools in Machining High-Performance Materials, J. of JSPE, (in Japanese), Vol. 57, No. 10 (1991), p. 90.

(2) Flom, D. G., Advanced Machining Research Program (AMRP) Final Tech. Report, Air Force Contract No. F33615-79-C-5199, GE Report No. 83-SRD-040, (1983).

(3) Chen, P. and Hoshi, T., Tool Wear in Machining Some Difficult-to-cut Materials With Rotary Tool, Proc. of 1990 JSPE Autumn Conf., Sapporo, Japan (in Japanese), (9/1990), p. 375.

(4) Kasei, S. and Masuda, M., Researches on Turning with Self-propelled Rotary Cutting Tool (Part 5), J. of JSPE, (in Japanese), Vol. 42, No. 6 (1976), p. 550.

(5) Venuvinod, Pk. and Reddy, P. N., Some Studies on Cutting with Self Propelled Rotary Tools, ASME, 83-WA/Prod-16, (1981).

(6) Jaeger, J. C., Moving Sources of Heat and the Temperature at Sliding Contacts, Proc. Roy. Soc. of New South Wales, Vol. 76, (1942), p. 203.

(7) Shaw, M. C., Metal Cutting Principles, Oxford Sci. Publ., (1984).

(8) Chen, P. and Miyake, Y., Machining Characteristics of SiC Whisker Reinforced Aluminum, Proc. of 1989 ASM Int. Conf. & Workshop on Machinability, Cincinnati (9/1989), p. 69.

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