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Tool Wear in Cutting Glass-Fiber-Reinforced-Plastics* (The Relation between Cutting Temperature and Tool Wear)

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The temperature at the cutting edge of a tool in machining glass-fiber-reinforced-plastics was measured by a special thermocouple method, in which two insulated wires were embedded in the workpiece, and the hot junction of the thermocouple was established when these wires were cut together with the workpiece.

The temperature distribution along the cutting edge, and the relation between the physical property (thermal conductivity) of tool materials or cutting speed (spindle speed) and the temperature at the cutting edge were analyzed to estimate the relation between the cutting temperature and the flank wear of cutting tools.

1. Introduction

In general, the energy spent in cutting is almost entirely converted to heat. This causes a temperature rise of workpiece, chip and cutting tool simultaneously. In metal cutting, it is well known that the tool wear is promoted by the temperature rise at the cutting edge, and many studies⁽¹⁾ in this field have been performed until now. However, concerning the cutting of reinforced-plastics, there are very few reports on the cutting temperature because of the difficulty of its measuring. So, the relation between the cutting temperature and the tool wear is unclear.

Tsueda and others⁽²⁾ obtained the temperature distribution on tool flank in cutting of glass-fiber-reinforced and alumina-reinforced-plastics and they claimed that the tool wear is independent of the cutting temperature which is low. Kamogawa⁽³⁾ measured the internal temperature of the tool during cutting of paper-laminated phenol resin and he found that the limit of cutting temperature rise is about 310°C. These results seem to suggest that there is no effect of the cutting temperature on the tool wear.

In a previous report,⁽⁴⁾ the authors discussed the relation between the physical (mechanical) properties and the flank wear of the cutting tool in cutting of glass-fiber-reinforced-plastics, and showed that the tool wear (the critical speed) is influenced by the thermal conductivity of tool material; it is assumed that the critical speed decreases with a decrease

in the thermal conductivity of tool material since the accumulation of heat on the cutting edge results in a rising of its temperature. Besides, Tanaka and others⁽⁵⁾ calculated the tool-chip interface temperature in cutting of metals and plastics and they estimated that the tool wear is affected by the thermal conductivity of tool and work materials. From these results, it seems that the tool wear is influenced by the cutting temperature in cutting of the reinforced-plastics.

In this study, the temperature at the tool edge in cutting the glass-fiber-reinforced-plastics was measured by a special thermocouple method, in which two insulated wires were embedded in the workpiece and the hot junction of thermocouple was established when these wires were cut together with the workpiece, and the relation between cutting temperature and flank wear of cutting tools was discussed in cutting of the glass-fiber-reinforced-plastics.

2. Experimental equipment and procedures

2.1 Machine tool, cutting tool and workpiece

In this experiment, Okuma's LS type high speed lathe is used. The tested work material is glass-fiber-reinforced-plastics (matrix: epoxy resin, glass fiber: roving type) with the shape as shown in Fig.2. The tool tips are square inserts (SNP-432 type) with the tool geometry of ($-5^\circ, -5^\circ, 5^\circ, 5^\circ, 15^\circ, 15^\circ, 0.8\text{mm}$), and are set in a standard holder of JIS 32-3 type. The kinds of tested tool materials are Al_2O_3 type ceramics (symbol: CW), TiC type cermets (TiC) and sintered carbides (P20) and K10 (K10). These are selected referring to the experimental results in the previous report.⁽⁴⁾

2.2 Measuring method of temperature at cutting edge

Many methods to be used to measure the cutting temperature have been developed and the tool-work thermocouple method

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is widely used among them. However, this technique can not be used to measure the temperature in cutting the reinforced-plastics, because these work materials are not electric conductors. Therefore, some special methods have been tried for such work materials; e.g., the tool-constantan-thermocouple method using a welded constantan wire on the tool flank, and the embedded-thermocouple method with two embedded wires within the cutting tool. In these methods, however, the temperature is measured at a short distance from the cutting edge and it is very difficult to measure the temperature at the cutting edge, where a remarkable wear appears in cutting the reinforced-plastics.

Therefore, in the method used in this report, a small hole of 1.0~1.5 mm diameter is drilled in the workpiece (as shown in Fig.2) and two thermocouple elements are set in this hole and fixed by bonding. When these wires are cut together with the workpiece and the hot junction of thermocouple is established, the temperature at the cutting edge can be measured. The thermocouple elements are respectively insulated, and the pre-setting of these wires with each other is performed by three methods; i.e., two parallel wires (type I), two wires twisted together (type II) and two twisted wires winding with fuse-wire (type III). As described later, the measuring performance of these thermocouple was examined and type III thermocouple with better ability to form the hot junction was selected to measure the temperature at

the cutting edge with each tool material.

The thermocouple circuit is completed by connecting the wires through the workpiece and spindle hole to the mercury slip rings which are mounted at the rear of the lathe spindle and connecting these slip rings to an amplifier, and to a data recorder (TEAC-R210 type). The thermoelectric emf generated at the hot junction was recorded with a tape-speed of 76.2 cm/s in this recorder, and this emf was regenerated with a tape-speed of 2.38 cm/s (speed ratio; 1 : 1/32) and recorded on an oscillograph.

2.3 Cutting conditions

The cutting conditions are the same as described in the previous report⁽⁴⁾; face turning with a depth of cut 1.0 mm and feed rate 0.1 mm/rev. Several spindle speeds (i.e., cutting speed) are chosen referring to the experimental results in the previous report. In the performance test of the thermocouple, the depth of cut is varied ranging from 0.1 mm to 1.0 mm. All experiments were performed with dry cutting to keep the insulation of the thermocouple circuit.

3. Experimental results and discussions

3.1 Processing of experimental results

An example of cutting-edge-temperature recorded on the electromagnetic oscillograph is shown in Fig.3. Intermittent contact between a cutting edge and a thermocouple was repeated with a short interval. Since the theoretical number of contacts is 9~10 (from P to Q in Fig.7), it is supposed that the elastic deformation of workpiece is undone gradually and the contact between the end cutting edge and the thermocouple is continued even if the point of contact passes through the tool nose (point Q in Fig.7).

Fig.1 Types of thermocouples

Fig.2 Location to embed thermocouple

Depth of cut, 1.0 mm; feed rate, 0.1 mm/rev; tool material, P20; thermocouple, III type; spindle speed, 700 rpm; dry.

Fig.3 Typical record of temperature at cutting edge

The pillar-like waves generated in every contacting between the cutting edge and the thermocouple are magnified in the direction of the x axis (time axis) and are shown in Fig.4. Fig.4(a) is an enlarged view of point A in Fig.3 and Fig.4(b) shows another example (TiC tool, 600rpm). These waves indicate mainly the temperature on the side of the workpiece and it is seen that the machined surface is intensely heated only at the moment when the cutting edge passes, and then this surface is rapidly cooled. When the cooling curve reaches a steady state, the temperature of machined surface is relatively low (the level of base line in this wave), being $60\sim 70^{\circ}\text{C}$ in the case of Fig.3.

On the other hand, the cutting edge is almost continuously heated. Therefore, the temperature is measured only at a moment when the cutting edge passes over the thermocouple since there is no thermocouple on the side of cutting tool, and it is assumed that the maximum value in Fig.4, i.e., a top of the pillar-like wave in Fig.3 indicates nearly the temperature at the cutting edge.

This peak value rises with an increase in the number of contacts between the cutting edge and the thermocouple, and it decreases after the point of contact passes the tool nose (point Q in Fig.7). Therefore, the maximum value among these peaks in one test is selected excepting the case of temperature distribution in Fig.4, and hereafter this is termed the temperature at the cutting edge.

Fig.4(b) is a typical example of transient temperature curve in the case where the hot junction is relatively stable, and Fig.4(a) is for the case where the temperature-time curve is unstable. In the latter, it is thought that the hot junction is stepped down in size and in thermal capacity, and the rate of temperature rise increases on all such occasion. Thus, the state of hot junction differs slightly in this method. Therefore, the selection of the above-mentioned maximum value (i.e., cutting temperature at the cutting edge) was performed under the conditions that the temperature-time curves were stable,

Fig.4 Enlarged records of temperatures in direction of time axis

excluding the cases that the hot junction was broken after the cutting edge passed over the thermocouple (rather higher value indicated than that in the stable case of the hot junction).

3.2 relation between the depth of cut and the temperature at cutting edge

Since the work material used in this experiment is brittle, the machining surface is dug up with the glass fibers and the thermocouple in this method is apt to break without the formation of a hot junction. In this case, it is supposed that the side cutting edge of tool passes above the thermocouple without a contact although the tool nose and end cutting edge are able to contact with the thermocouple when they pass over the machined surface. Therefore, the relation between the depth of cut and the cutting temperature was examined and the results are shown in Fig.5.

It can be seen that the temperature at the cutting edge is almost proportional to the depth of cut. In GFRP cutting, the rate of the cutting temperature rise is relatively large, whereas in metal cutting the influence of the depth of cut on the cutting temperature is small and this influence will be ignored, comparing with that of other cutting conditions (the exponent is $0.04^{(6)}$ in the case of steel cutting). Besides, the number of contacts between the cutting edge and the thermocouple increases with an increase of the depth of cut. At the spindle speed of 300 rpm, a depth of cut 0.1 mm gives a mean number of 12 contacts, and 1.0 mm a number of 17 contacts. Thus, it seems that the region of contact between the cutting edge and the workpiece enlarges, the temperature at the cutting edge rises and the number of contacts between the cutting edge and the thermocouple increases with the depth of cut. Namely, it is concluded that this method will be able to measure the cutting temperature related to the depth of cut. Therefore, the following discussions were made with a depth of cut 1.0 mm.

Fig.5 Relation between depth of cut and temperature at cutting edge

3.3 Relation between the type of thermocouples and the temperature at cutting edge

Fig.6 shows the temperature measured by the use of three types of thermocouples in GFRP cutting with ceramic tool. In the comparison in sensitivity of three thermocouples, the indicated temperature is highest with type I thermocouple and lowest with type III thermocouple. It is supposed that this tendency is due to a difference in thermal capacity between the hot junction and the cutting area. Namely, type III thermocouple is made of two twisted wires winding with a wire-fuse in order to obtain a stable hot junction easily. Therefore, it seems that the indicated temperature is relatively low because the thermal capacity of hot junction increases as the cutting area enlarges.

Now, in the common method in which the hot junction is welded in advance, the selection of thermocouple considering the transitional characteristic is performed by decreasing the size of the thermocouple elements until the indicated temperature values can not be lowered any more. On the other hand, in this method in which the hot junction was formed by machining the workpiece, the size of the thermocouple elements affects the ability to form the hot junction; it is evident from this experiment that type III thermocouple can weld a hot junction at all cutting speeds (with all tool materials), whereas type I and type II thermocouples are able to weld one at low cutting speed (with ceramic tool), but can scarcely do so at high cutting speed (with cermet and carbide K10 tools).

Thus, the selection of thermocouple can not be performed according to the transitional characteristic as in the case of common method because the transitional characteristic and the ability of forming the hot junction have respectively an adverse effect on the performance of thermocouple, and it is very difficult to measure an exact temperature at the cutting edge. Therefore, the cutting temperatures in all tool materials were measured by the use of type III thermocouple in which the hot junction

Fig.6 Comparison between three types of thermocouples

tion is easily formed and it is possible to measure the temperature at high cutting speed although the indicated temperature slightly reduces with a lowering of the transitional characteristic.

3.4 Temperature distribution along cutting edge

The temperature measuring method, where the thermocouple and workpiece are cut simultaneously, in this experiment, makes it possible to investigate the temperature distribution along the cutting edge and the situation of contacting between the cutting tool and workpiece. Fig.7 shows an example of the temperature distribution along the cutting edge with the carbide P20 tool at the cutting speed 700 rpm (the thermo-electric emf in Fig.3 is calculated in terms of temperature), and it is seen that there is the maximum value slightly towards the side cutting edge from the position of the maximum depth of cut (point Q) and the heat generated in cutting concentrates near the tool nose.

It is thought that the temperature gradient in the contact area between the cutting tool and the workpiece or chip in metal cutting is relatively mild. For instance, Fujimura and others⁽⁷⁾ measured the temperature distribution in the tool flank in cutting cast iron. The results show that the distribution is almost uniform within the contact area between the workpiece and the tool. Also, in the results of the steel pipe cutting by Kato and others,⁽⁸⁾ the temperature difference is small within the contact area between the chip and the tool face. The temperature gradient is 50°C per 0.1 mm beyond the contact area. In the temperature distribution on the tool face (work material: S45C) obtained by Hirao and others,⁽⁹⁾ the distribution in the direction of the chip flow is nearly uniform (from the cutting edge to the deepest portion of crater wear) and its gradient is 90~100°C per 0.1 mm.

Fig.7 Temperature distribution along cutting edge

In this experiment, the temperature gradient at the end cutting edge is $70 \sim 90^\circ\text{C}$ per 0.1 mm and the gradient at the side cutting edge is $100 \sim 150^\circ\text{C}$ per 0.1 mm (the latter is slightly steeper than the former). Although it is difficult to compare directly this experiment with the above-mentioned metal cutting because these cutting conditions are different from each other, in GFRP cutting the gradient at the temperature of $400 \sim 500^\circ\text{C}$ is $100 \sim 150^\circ\text{C}$ per 0.1 mm , whereas in metal cutting it is less than 100°C per 0.1 mm at the temperature over 1000°C (especially, in cast-iron cutting⁽⁷⁾ the gradient on tool flank is uniform). Namely, in GFRP cutting the heat concentration is higher than that in metal cutting (especially cutting the cast-iron above mentioned⁽⁷⁾) and it is assumed that the remarkable nose wear in the shape of a triangle is accelerated by this heat concentration and the ploughing (brushing) action of glass fiber. The highest cutting temperature appears at a point corresponding to a mean number of 8.3 contacts.

Besides, the number of contacts increases due to the recovery from an elastic deformation and others although the theoretical number of contacts between the cutting tool and the thermocouple is $9 \sim 10$, and the average practical number of contacts is 17. Thus, it is seen that the area of contact between the end cutting edge and the workpiece spreads. It is considered that the spreading of the contact area causes an accumulating of the cutting heat at the cutting edge as above mentioned and promotes the nose wear in the shape of a triangle and an adjacent flank wear to this (the nose). Moreover, as stated in the previous report,⁽⁴⁾ the growth of groove wear on the end cutting edge is larger than that on the side (Fig.8) in GFRP cutting, unlike in metal cutting, and there seems to be a strong correlation between this groove wear growth and the above-mentioned spreading of the contact area.

Tool material, TiC; spindle speed, 400 rpm; depth of cut, 1.0 mm; feed rate, 0.1 mm/rev; number of cuts, 30 th; dry.

Fig.8 Typical patterns of tool wear (some of results in previous report⁽⁴⁾)

3.5 Relation between the tool material and the temperature at cutting edge

In this method of measuring the cutting temperature, it is thought that the hot junction is welded with the burs of two thermocouple elements and a wire-fuse when cutting these together, and the welding state of the hot junction depends on the cutting speed and the sharpness of cutting tool; this welding state affects the transitional characteristics of thermocouple. Therefore, it is assumed in the following discussion that the condition of hot junction is constant regardless of the cutting speed and others although the latter need to be considered when discussing the experimental results in a strict sense.

Fig.9 shows the relation between the spindle speed and the temperature at the cutting edge obtained for each tool material. In every tool material, the temperature at the cutting edge rises gradually with an increase of the spindle speed and does rapidly over a somewhat low side of the critical speed as shown later in Fig.11 (CW: 225 rpm, TiC: 350 rpm, P20: 650 rpm, K10: 1800 rpm).

When mutually comparing each tool material, in lower speed range (under the critical speed where the wear rate is relatively small) the temperature at the cutting edge rises with the same tendency and the higher the thermal conductivity of the cutting tool, the lower the temperature at the cutting edge and the rapidly rising point of the cutting temperature shifts to the higher side of the cutting speed. The relation between the thermal conductivity of the tool material and the temperature at the cutting edge is shown in Fig.10 in order to illustrate more precisely the relation above mentioned. Namely, it is concluded that the higher the thermal conductivity, the lower the temperature at the cutting edge and this tendency becomes more evident with an increase of spindle speed (cutting speed) i.e., a rises of cutting

Fig.9 Relation between spindle speed and temperature at cutting edge

temperature.

The influence of the tool material (the thermal conductivity of cutting tool) on the cutting temperature is hitherto reported a little. For example, Kato and others⁽⁸⁾ describe about steel cutting as follows; the temperature near the cutting edge obtained by the estimating method from the experimental curve (extrapolation method) does not differ with the tool material and if the temperature on the tool face is influenced by the tool material, it is attributed mainly to the differences of the friction state on tool face and the thermal conductivity of tool material. However, the difference in the coefficient of friction is little with the tool materials and although the maximum temperature (estimated value) rises a little with a decrease of the thermal conductivity the difference in the thermal conductivity between the practical tool material.

In the study⁽⁹⁾ (work material: S45C) by Hirao and Sata on comparing sintered carbide tool P20 with ceramic tool, for instance, at the cutting speed of 300 m/min (depth of cut of 2 mm, feed rate of 0.25 mm/rev) the maximum temperature on tool face is about 1300°C with P20 tool and 1500°C with ceramic tool, and a difference of 100~200°C is invariably observed. The temperature at the cutting edge is not measured, so this temperature is estimated from the temperature distribution on the tool face (by the extrapolation method) and the temperature difference between carbide P20 and ceramic tools obtained is about the same value as the maximum temperature on the tool face. However, the thermocouple elements are located respectively in different tool materials (cutting tools) in spite of the identical method of measuring the temperature being used. So, it is supposed that the thermal characteristics of detecting portion are different from each other and the ceramic tool has a tendency to resist a higher temperature than the

carbide tool. Besides, Tanaka and others⁽⁵⁾ assumed that in cutting the identical work material with the identical cutting condition, the cutting mechanism is unchangeable regardless of the tool materials, and calculating the tool-chip interface temperature generated by the frictional heat, they concluded as follows; in cutting of the high thermal conductivity materials such as brass etc., there is little temperature difference depending on the tool materials, whereas, in cutting of the low thermal conductivity materials such as resin, there is a large influence of the tool material on the cutting temperature. Now, in their report, a discussion is made for the cutting speeds of 2000~8000 m/min and the influence of the thermal conductivity becomes smaller (decreases) with an increase of cutting speed.

From above-mentioned reports of other researchers and this experimental result, the effect of tool material on the cutting temperature is conjectured as follows. In cutting of a metal with a high thermal conductivity, the maximum temperature on the tool face is slightly affected by the tool material and there is little effect of the tool material on the temperature at the cutting edge. In other words, it is assumed that there is little effect of tool material on the temperature at the cutting edge although there is a little influence of tool material on the mean temperature⁽¹⁰⁾ obtained by the tool-work thermocouple method. However, the thermal conductivity of the reinforced-plastics is generally very low in comparison with that of the metal. For example, the thermal conductivity of iron is about 65 kcal/mhr°C and that of aluminum is about 190 kcal/mhr°C. On the other hand, the thermal conductivity of unsaturated polyester is 0.1~0.3 kcal/mhr°C⁽¹¹⁾ i.e., its value is 1/100~1/1000 of that of the metal. It is considered that in cutting of such a very low thermal conductivity material, the influenced of the thermal conductivity of tool material appears not only in the temperature on tool flank but also largely in the temperature at the cutting edge.

This is too inferred also from the fact that the interface temperature⁽¹²⁾ in frictional rubbing between two materials (thermal conductivity; λ_1, λ_2) rises proportionally to the value of $1/(\lambda_1 + \lambda_2)$. Namely, in the case that the thermal conductivity λ_1 of one material is equal to or higher than the conductivity λ_2 of another material, even if the conductivity λ_2 varies to some extent, there is little influence of λ_2 on the value of $1/(\lambda_1 + \lambda_2)$. On the other hand, when the thermal conductivity λ_1 of one material is extremely lower than another conductivity λ_2 , the value of $1/(\lambda_1 + \lambda_2)$ depends almost on the thermal conductivity λ_2 of another material. In the latter case, i.e., in GFRP cutting, it is concluded that the heat generated near the cutting edge (the heat generated by the friction between the cutting edge and work material, etc.) is scarcely transferred through the workpiece or the chip and most of it flows into the

Fig.10 Relation between thermal conductivity of tool material and temperature at cutting edge

tool, so the temperature at the cutting edge depends strongly on the thermal conductivity of tool material. It is thought that above-mentioned conjectures are proved by the results shown in Fig.9 and Fig.10.

When considering the relation between the cutting temperature and the tool wear on the basis of the above-described discussions, it is understood, because in metal cutting there is little effect of the tool material on the temperature at the cutting edge as shown in other literature,⁽¹³⁾ that in the cutting of the high thermal conductivity materials, the heat transfer from the cutting zone to the tool is hindered with the use of the low thermal conductivity tool, and a better transfer and radiation of the heat through the workpiece prevent a rising of the internal temperature of tool (softening of tool), and these are effective to reduce the tool wear.

On the other hand, in this report, i.e., in GFRP cutting, the temperature at the cutting edge lowers with a higher thermal conductivity of tool material (Fig.10), and the rapidly rising point (cutting speed i.e., spindle speed) of the cutting temperature with a higher cutting speed shifts to the higher side of cutting speed with a higher thermal conductivity of the tool material (Fig.9), and the critical speed in the relation between the physical (mechanical) properties of tool material and the tool wear in the previous report⁽⁴⁾ i.e., the spindle speed which increases suddenly the tool wear rises with an increase of the thermal conductivity (Fig.11) and the rapidly rising point (cutting speed) of cutting temperature in Fig.9 agrees relatively well with the critical speed in Fig.11. Thus, it is concluded that the thermal conductivity of tool material strongly affects the temperature at the cutting edge and remarkably affects the tool wear (the critical speed).

Therefore, in cutting of the very low thermal conductivity material such as GFRP, it is favorable to use a tool material with a high thermal conductivity because

Fig.11 Relation between critical speed and thermal conductivity of tool material (some of results shown in previous report⁽⁴⁾)

the workpiece is a heat insulating material. So from better transfer and radiation of heat through the cutting zone to the tool, a lowering of the heat concentration or temperature at the cutting edge and a reducing of the tool failures (abrasive wear and thermal cracks) can be expected.

3.6 Consideration of measured temperatures

The temperature at the cutting edge in the discussions as described above are measured by type III thermocouple shown in Fig.1, and the indicated temperatures differ with the type of thermocouple as mentioned previously (Fig.6). The same results are reported by Hirao and Sata⁽⁹⁾; in comparison between the maximum temperature obtained by the local measuring method in which an insulated thermocouple element is embedded in the cutting tool and the mean temperature obtained by the tool-work thermocouple method, the former is generally higher than the latter and the ratio of both is 1.3~1.4 (unchangeable and nearly constant in the range of cutting speeds 100~300 m/min). In comparison of two methods as the measuring equipment, it is considered that the indicated temperature by the tool-work thermocouple method is a mean value and its value is lowered by the large hot junction and the very large thermal capacity of this thermocouple as a whole.

In this study, the mean ratio two indicated temperature by type I and type III thermocouples shown in Fig.6 is 1.4. Assuming that this ratio is constant regardless of the cutting speed and the tool material, it is likely that the true temperatures at the cutting edge in Fig.9 and Fig.10 are respectively over 1.4 times the indicated temperatures. Besides, the transient temperature-time curve in Fig.4 is assumed as follows:

$$\theta = \theta_0 (1 - e^{-t/T}) \quad (1)$$

where θ is the indicated temperature (°C), θ_0 is the true temperature at the cutting edge (°C), t is the measuring times (s) and T is the time constant (s). Now, the temperature difference $\Delta\theta$ (°C) between two points separated by time Δt (s) is given by

$$\Delta\theta = e^{-t/T} \theta_0 (e^{-\Delta t/T} - 1) \quad (2)$$

Taking logarithms of both sides,

$$\ln \Delta\theta = -\frac{1}{T}t + \ln \theta_0 + \ln(e^{-\Delta t/T} - 1) \quad (3)$$

Fig.12 Relation between t and $\Delta\theta$

Here, if it is assumed that Δt is a constant, the second and third terms of right side are constant. So, from the relation between t and $\ln \Delta \theta$, the time constant T is obtained and the true temperature θ_0 can be estimated. For example, in the case of Fig.4(b), it is thought that the transient temperature-time curve belongs to the secondary time-lag system judging its form (S figure type as shown in Fig.12). Therefore, equation (1) is applied to the region after point Q except about 1 ms (from point P to point Q) and the relation between t and $\Delta \theta$ which is obtained with $\Delta t = 2.5$ ms is shown in Fig.12. The time constant T obtained from its slope is about 4.8 ms and the estimated value of the true temperature θ_0 obtained by substituting the temperature after 4.8 ms from point P into equation (1) is 788°C, and the estimated temperature is about 1.6 times the indicated temperature.

Although the indicated temperatures with cermet and carbide P20 and K10 tools over the critical speed are about 500°C, from two discussion of the indicated temperature it is estimated that the true temperatures are over 700~800°C. Also, it is conjectured that the cutting edge reaches a very high temperature from other phenomena, e.g., the thermal crack and offensive smell in the range over the critical speed as shown in the previous report.⁽⁴⁾ Therefore, even in GFRP cutting that involves a relatively small cutting resistance and a low consumption of energy, it is concluded that the tool wear is strongly influenced by the temperature at the cutting edge. In the case of ceramic tool, the temperature at the cutting edge is relatively low for the greater tool wear (it is extremely larger than that of other tool materials), and so this phenomenon suggests that it is hereafter necessary to investigate the effect of other factors on the tool wear excepting the temperature at the cutting edge (the thermal conductivity of tool material).

4. Conclusions

From the results of measuring the temperature at the cutting edge and discussing the relation between this temperature and the tool wear, the following conclusions have been derived:

(1) The temperature distribution along the cutting edge is non-uniform and the maximum value appears slightly towards the side cutting edge from the position of the maximum depth of cut, and the temperature gradient is relatively steep. The heat generated in cutting concentrates near the tool nose. It is considered that such heat concentration induces a remarkable nose wear in the shape of a triangle shown in the previous report.⁽⁴⁾

(2) Although the theoretical number of contacts between the cutting tool and the thermocouple is 9~10, the practical number of contacts is about 17 and the area of contact between the end cutting edge and the workpiece largely spreads. It is thought that in GFRP cutting the higher

growth of the groove wear on end cutting edge than on side cutting edge is caused by this spreading of the contact area.

(3) The temperature at the cutting edge rises gradually with an increase of spindle speed (cutting speed) and does rapidly over a certain speed. This tendency is relatively similar to that of the wear rate shown in the previous report⁽⁴⁾; it is supposed that there is a strong correlation between the rapid rising of the cutting temperature and the existence of the critical speed which rapidly increases the tool wear.

(4) The temperature at the cutting edge lowers with a higher thermal conductivity of tool material and the rapidly rising point of cutting temperature shifts to the higher side of cutting speed; in cutting of a very low thermal conductivity material such as GFRP, it is favorable to use a tool material with a high thermal conductivity because the workpiece is a heat insulating material, so that a lowering of the heat concentration (temperature) can be expected. Thus, it is assumed that the critical speed increases due to a reducing of the temperature rise with a higher thermal conductivity of tool material.

Now, in this method of temperature measurement, it is favorable for the ability to form the hot junction that a soft metal such as wire-fuse is employed with the thermocouple elements. However, there is still some room for improvement as regards the transitional characteristic.

References

- (1) E.g., Takeyama, H. and Murata, R., Jour. Japan Soc. Precis. Engng. (in Japanese), Vol.27, No.1 (1961-1), P.33.
- (2) Tsueda, M., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.34, No.266 (1968-10), P.1813.
- (3) Kamogawa, A., Jour. Japan Soc. Precis. Engng. (in Japanese), Vol.34, No.6 (1968-6), P.377.
- (4) Sakuma, K. and Seto, M., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.44, No.381 (1978-5), P.1752.
- (5) Tanaka, Y., et al., Jour. Japan Soc. Precis. Engng. (in Japanese), Vol.32, No.10 (1966-10), P.683.
- (6) Takeyama, H., Science of Machine (in Japanese), Vol.13, No.9 (1961-9), P.1195.
- (7) Fujimura, Y., et al., Jour. Japan Soc. Precis. Engng. (in Japanese), Vol.42, No.4 (1976-4), P.268.
- (8) Kato, S., et al., Trans. ASME, Vol.98, Ser.B, NO.2 (1976-5), P.607.
- (9) Hirao, M. and Sata, T., Jour. Japan Soc. Precis. Engng. (in Japanese), Vol.40, No.2 (1974-2), P.156.
- (10) Sakuma, K., et al., Science of Machine (in Japanese), Vol.28, No.1 (1976-1), P.8.
- (11) Ohashi, K., et al., Reinforced Plastics Hand Book (in Japanese), (1975), P.289, Nikkan-kogyo.
- (12) Bowden, F.P. and Tabor, D., The Friction and Lubrication of Solids, Oxford (1954), (in Soda's Japanese version).
- (13) Ber, A., Ann. C.I.R.P., Vol.21, No.1 (1972), P.21.