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On Transient cutting Mechanics at the Initial Stage of Peripheral Milling Process*

By Mikio OGURI**, Hiroshi FUJII**,

Katsumi YAMAGUCHI*** and Shinobu KATO****

Cutting mechanics at the initial stage of peripheral milling is precisely discussed on the basis of many data on various factors. Experiments carried out are measurements of cutting force and its vector representation, observations of chip formation process with microphotographs, and measurements of the stress distribution and chip contact length on the tool rake face and shear angle obtained from the chip thickness. Main conclusions are the followings.

(i) A transient period exists at the initial stage, where some factors to be effective on the mechanics vary with violence. In the period, up milling process and down milling process represent their characteristic feature.

(ii) The transient cutting mechanics changes its feature with tool advancement. Up milling has four processes which can be distinguished in a period from the first contact of tool with workpiece to the steady state. Down milling has two processes.

The mechanics of the above each process is discussed with experimental data.

1. Introduction

In peripheral milling process there are two possibilities of using either up milling or down milling. The selection is determined according as a selection by an operator who can take either clockwise turn or anticlockwise for the turning direction of spindle. It is not easy in practice, however, to determine which process is better for a material supplied and an accuracy required. A lot of difference exists between up milling and down milling with regard to a dimensional accuracy of product, surface finish, tool wear, vibration characteristic, etc.. These differences are, after all, yielded by a difference of mechanics of deformation of work material between both processes.

In the earlier investigations^{(1)~(4)} performed on the mechanics of milling process, the interests have been concentrated upon the difference and it has been often pointed out that the difference is caused by the variational configuration of undeformed chip thickness which increases

in up milling and inversely decreases in down milling. Mechanics of both up milling and down milling, however, should be greatly influenced also by a chip formation process just after the first engaging of tool with workpiece, as revealed in the previous paper⁽⁵⁾. An initial stage of up milling is a process in which an undeformed chip thickness is zero at the initial contact of tool and increases gradually under a very little increasing rate as a tool advances. This inclination of undeformed chip thickness to the tool advancement is generally less than 1/100. In down milling, on the other hand, thickness increases abruptly from zero to the maximum within a short tool advancement and after that, gradually decreases with an inclination by 1/100. This characteristics of variational configuration of undeformed chip thickness

Fig.1 Geometry of milling

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** Assistant Professor, Faculty of Engineering, Gifu University, Nakamonzen-cho, Kakamigahara, Gifu-pref.

*** Assistant Professor, Faculty of Engineering, Nagoya University.

**** Professor, Faculty of Engineering, Nagoya University.

in the initial stage greatly influences, of necessity, a deformation mechanics in the consecutive process. The authors also reported⁽⁶⁾ that, according to work material and other cutting conditions, a special case, where a phenomenon in the initial stage is dominant all over the process, can happen. In order to concretely understand the cutting mechanics of both milling processes, therefore, it is needed to know how a work material is deformed in the initial stage and how the initial condition influences the whole consecutive processes.

In this paper a cutting mechanics at the earliest stage of peripheral milling will be precisely investigated by means of collecting many data on the various factors to influence the initial cutting mechanics as the cutting force, its vector representation, the stress distribution on tool rake face, the tool-chip contact length, the thickness of chip and the shape of chip with microphotographs, and discussing the dynamic variation of the factors during machining in detail. Since the mechanics at the initial stage is considered to have a remarkable effect on a latter steady state, where the controlling factors for cutting mechanics do not vary in an abrupt and transitional behaviour and a chip flows out steadily. In the present paper, a cause and extent of this effect will also be dealt with and a mutual difference in cutting mechanics between both millings will be discussed.

2. Apparatus and Method of Experiment

Fig. 2 Experimental apparatus

Table 1 Cutting conditions

Tool (single tooth)	High speed steel	
	Rake angle	$\alpha = -5^\circ, 0^\circ, 20^\circ$
	Clearance angle	$\beta = 7^\circ$
	Helix angle	$\lambda = 0^\circ$
	Cutter radius	$R = 54.7 \text{ mm}$
Work material	0.35% Carbon steel (JIS S35C)	
	Rolled aluminium (99.7% purity)	
Cutting conditions (Peripheral milling)	Cutting speed	$u = 4.1 \text{ m/min}$
	Width of cut	$b = 3 \pm 0.02 \text{ mm}$
	Depth of cut	$d = 3 \text{ mm}$
	Feed per tooth	$f = 0.25 \text{ mm}$

Fig. 3 Variational configuration of the resultant cutting force F and its direction θ

Measurement of cutting force was carried out by an optical method and an electrical method as reported previously⁽⁷⁾. The horizontal component F_H , the vertical component F_V and the angular displacement of tool φ shown in Fig. 1 were measured. From the measured values, the conventional cutting force F_T , the thrust force F_N , the resultant force F and its direction θ are obtained by calculation. In Fig. 1, the undeformed chip thickness is exaggeratedly drawn for the convenience of explanation. The value of inclination of the undeformed chip thickness is very small and less than 1/100 in both up milling and down milling.

Stress distribution on tool rake face was measured accurately by a method to use a special tool with the separated cutting edge, shown in the previous paper⁽⁸⁾.

In Fig. 2, a quick stopping device used for an observation of chip formation process is shown. Quick stop is realized in terms of that a transmission of power is cut off by rupture of the shear pin ⑨ with a notch when the cam ③ mounted on the tool holder ④ on an arbor of milling machine collides against the stopper ⑩. A location of stop was roughly situated, at first, at a certain position by using a scale ⑦ on the tool holder and after a quick interruption of cutting, the accurate location was determined from the measured volume of chip cut. On the basis of microscopic observation of

specimens obtained at many locations with this apparatus, the variations of the state of chip formation during the tool advancement was discussed. The value of so called the shear angle was determined by measuring a chip thickness with the microphotographs.

The tool-chip contact length was obtained for every quick stopped specimens in terms of measuring a peeled off length of organic soluble ink which was previously painted on the tool rake face by 0.5 mm in width. The width of ink painted is confirmed by a preliminary experiment to be so narrow comparing to the width of workpiece cut, $b=3$ mm, that the film of ink does not influence the cutting process.

The tool dimensions, work material and cutting conditions used are shown in Table 1. All experiments were carried out in orthogonal cutting with a single toothed peripheral milling tool, and in dry cutting condition without any cutting fluid.

3. Experimental Results and Discussions

3.1. Characteristic of the variational configuration of cutting force in the initial stage of milling process

Measured results of the cutting force both in up milling and down milling are shown in Fig.3 to 6. Fig.3 is an example of the variational configuration of the resultant cutting force F and its direction θ obtained with a carbon steel (JIS-S35C) as work material. It is seen from the figure that a transient cutting period exists in the earliest stage of process where the direction of action of the applied resultant force θ varies abruptly as follows. In Fig.3(a) for the small rake angle $\alpha=0^\circ$, the value of θ in up milling decreases rapidly from a large

value and tends to a constant value at φ_s . The value of θ in down milling, on the other hand, is small at the beginning and increases until it reaches constant at φ_s . This φ_s coincides with an angular displacement where the resultant cutting force F becomes maximum. The same tendency as mentioned above is seen also in Fig.3(b) for a large rake $\alpha=20^\circ$ although a degree of an increasing or decreasing rate becomes slightly less.

Especially for the variational configuration of resultant cutting force in this initial transient period, more detailed experiments were carried out. In Fig.4 the variational configuration of F and θ in a period of tool angular displacement from $\varphi=0$ rad to 0.06 rad, for up milling and $\varphi=0.333$ rad to 0.305 rad for down milling are shown for three different rake angles. When this figure is examined concerning up milling, it is seen that the value of θ decreases rapidly from about 70° at the beginning and becomes hardly to vary

Fig.4 Variational configuration of the cutting force in the earliest stage of peripheral milling process (the resultant cutting force F , its direction θ)

Fig.5 Vector representation of the cutting force (corresponding to the measured result in Fig.3)

Fig.6 Vector representation of the cutting force in the earliest stage of intermittent cutting process

after the tool displacement $\varphi=0.012$ rad. In other words, the rake angle does scarcely influence the initial stage of up milling. This phenomenon is considered to support that a deformation process of work material in the initial stage is not dependent on the tool rake angle at least at the first period just after the initial engagement, but dependent on the nose radius of cutting edge, because the undeformed chip thickness in up milling increases from $t=0$ mm with very small inclination 0.45/100, and so that a period while t does not reach the value equal to the nose radius of cutting edge can exist in the initial stage of up milling. With regard to such a manner, a further discussion will be done in the next section, too.

For down milling, on the other hand, it is difficult to obtain enough informations only from the data as Fig.4. The undeformed chip thickness in the initial stage of down milling increases abruptly from 0 mm at the beginning to reach the maximum within a very short advancement of tool and decreases with the small inclination 0.45/100. Since this process, concerning its geometry, resembles an intermittent cutting encountered in shaping or planing, there may be a possibility of finding a common tendency between the characteristics of variational configuration of cutting force in the initial stage of down milling and that in the intermittent cutting process. In order to discuss the initial cutting mechanics of down milling, therefore, it seems fruitful to compare the characteristic of cutting force in down milling with that in the intermittent cutting. In Fig.5 and Fig.6, the variations of cutting force in milling and intermittent cutting, respectively, are shown on "a cutting force vector diagram" proposed in the previous paper⁽⁹⁾. Fig.5 is obtained from the value of cutting force both in up milling and down milling shown in Fig.3, through a procedure to plot the cutting component F_T on the abscissa and the thrust component F_N on the ordinate. The points on the figure correspond to the locations of the end point of cutting force vector represented by a straight line at each instance. Fig.6 shows a vector diagram for a transient period of intermittent cutting process, where a workpiece is cut under a constant undeformed chip thickness as we see in shaping and planing.

It is needed prior to a comparison of both figures to sum up what was found in

the previous paper⁽⁹⁾ by use of this vector diagram for intermittent cutting process. (i) The end points of cutting force vector shown in the figure make a straight line with an inclination. (ii) The inclination of the straight line is neither dependent on the depth of cut nor on the rake angle. (iii) A value of $|F_T^*|$, which is a value of F_T at a cross point of the extrapolated straight line and the F_T -coordinate (the abscissa), is proportional to the depths of cut t . (iv) A vector F_S in a steady state indicated by a straight line in Fig.6 comes on the same line although the depth of cut is varied. (v) The same tendencies as the above are always recognized also in the case of the other materials as aluminum, duralmine, copper, brass, etc.

Taking the above tendencies obtained for the earliest stage of intermittent cutting into consideration, we will observe the vector diagram of down milling in Fig.5. At first in Fig.5(a) for the rake angle $\alpha=0^\circ$, the full circle, which denotes the end point of the cutting force vector in down milling, begins to increase along a line with some inclination to the F_T -coordinate. Subsequently, a degree of an increase in the cutting component F_T decreases to reach the maximum value, while the thrust component F_N approaches the maximum after a little advancement of tool. After that, F_T and F_N decreases in the same proportion to make a straight line toward the origin.

In Fig.5(b) for a large rake angle $\alpha=20^\circ$, nearly the same tendency as in $\alpha=0^\circ$ is also seen except that a period until the maximum value appears is shorter. It should be noted here that the straight line, along which the end points of cutting force vector begins to increase in the initial cutting stage, intersects the F_T -coordinate at 40 kg both in $\alpha=0^\circ$ and 20° . This seems to correspond to the tendency (iii) in the intermittent cutting.

Thus, it could be made clear that a cutting mechanics in the initial stage of down milling is nearly the same as that in intermittent cutting and that it varies gradually to the region peculiar to the milling process where the undeformed chip thickness decreases with tool advancement. The further discussion in regard to the mechanics in this period will be carried out in section 3.3.

3.2. On chip formation process

It was found from the measured results of cutting force in the previous section

Fig.7 Chip formation process in the initial stage of up milling

Fig.8 Chip formation process in the initial stage of down milling

that an transient cutting process exists in the initial stage of milling and that a variational configuration of cutting force in the transient period differs between up milling and down milling. An object of the present paper is to discuss experimentally through what deformation process a chip is formed in this transient period. For the purpose of it, a dependable arrangement of the situations during deformation of work material is essential. In this section, whereabouts of process left unsolved will be looked for by the next two steps of procedure. At first, the deformation processes to pass through from the initial engagement with workpiece to the steady state will be mentioned on the basis of the tendency shown in the previous section and facts found in the earlier investigations. Secondly, we will pointed out about which process of the consecutive processes a deformation mechanics is made clear or enables to be predicted and about which process the data for deformation process has not been obtained.

Firstly, up milling is dealt with. The process just after the contact of cutting edge with workpiece is a process which the undeformed chip thickness increases from zero with a very small inclination. The mechanics of cutting with the minute undeformed chip thickness has been well investigated by Yamamoto⁽¹⁰⁾ and Yuuta⁽¹¹⁾. When we follow the definition by Yuuta, a process (a) to (b) in Fig.7, which is drawn on the basis of their results, may be explained as follows. The process (a) is "a rubbing region where a tool rubs over a surface of work", and where "the phenomena by friction are dominant". Next to this region, after that "a normal force (F_N in the present paper) increases to exceed a critical value", the process does "a transition to a ploughing region (b)", where "a cutting edge begins to cut into work surface" and "work material becomes piled up onto the tool rake face by ploughing". When a tool advances after the process moreover, the piled up work material is pushed up along a rake face and flows out as a chip so called. Now, when we define a quasi-steady state as a situation that this chip flow becomes steady and the cutting force and other factors varies in proportion to the undeformed chip thickness (in Fig.7(d), such a quasi-steady

state is written simply as "a steady state" in this paper), it may be impossible that the steady state appears soon after the above two processes (a) and (b). The other transient period should exist between (b) and (d). A main subject in the next sec-

Fig.9 Chips obtained in the earliest stage of cutting

tion is to understand the phenomenon occurred in this process (c).

Secondly, we will consider a down milling process. In this process, an undeformed chip thickness reaches the maximum within a very short cutting length (about 0.23 mm) soon after a tool engagement with workpiece. A mechanics of deformation of material in this process just after the contact of tool is considered, at least in regard to the characteristics in a variation of cutting force, to be in nearly the same situation as an intermittent cutting process, as pointed out in the previous section. Okushima and others⁽¹²⁾, who made an attempt to analyze a transient phenomenon in the initial stage of this intermittent cutting by means of a theory of plasticity, found out that the initial cutting mechanics of the intermittent cutting process resembles a state in pushing a rigid wedge into a plastic material. The process (a) in Fig.8 expresses a situation at the initial stage of tool contact with workpiece in down milling, by taking the above two points into consideration. With regard to down milling, however, only a little data has been obtained on the deformation done when the tool advances further after the initial condition. In the next section, experimental studies will be carried out about a variation in cutting mechanics which appears during the consecutive processes from the initial process (a) to a steady state (d) through processes (b) and (c) where a chip begins to flow out and the situation continues for some length of cut.

3.3. Discussions on the experimental results and cutting mechanics

The data used here for discussion are the observation of microphotographs of chip, and the experimental result of the tool-chip contact length, the shear angle and the stress distribution on tool rake face, in addition to the measured value of cutting force.

Fig.10 schematically shows the shapes of chips obtained by tracing the photographs against the undeformed chip thickness which vary with the tool angular displacement φ . These figures become more interesting by comparing them with a deformation process, as shown later. Here, we will briefly mention the distinctive features shown in these figures. It is recognized in the photographs for up milling, espe-

cially in $\alpha = -5^\circ$ and 0° , that the chip thickness in the earliest stage is very thick as compared with the undeformed chip thickness. In down milling, the chip thickness is not so thick, and it increases for a while even though a tool passes by the location of the maximum undeformed chip thickness. Because of such a manner, the shear angle in down milling is shown in Fig.9(b) to be considerably large at $\varphi = 0.327$ to 0.318 rad, and to attain a saturated value at $\varphi = 0.305$ rad.

Now we discuss a mechanics of chip formation process basing upon the results obtained by carrying out the quick interruption of cutting on many situations in

Fig.10 Variation of chip shape in the earliest cutting stage

Fig.11 Transitional behavior of the factors in milling (F , θ , ϕ , Z_r)

Fig.11 Transitional behavior of the factors in milling (the resultant cutting force F and its direction θ , the shear angle ϕ , the tool-chip contact length l_r)

the transient cutting period in both milling processes and by making the same specimens for a micro-observation (about 170 specimens for different rake angles). In Fig.11 the shear angle ϕ obtained from the chip thickness at each location interrupted and the chip contact length on the tool rake face l_r obtained by measurement of the peeled off length of organic soluble ink painted on rake face are shown against the tool angular displacement ϕ together with F and θ as the data for cutting force.

At first, a deformation mechanics in the initial stage of up milling is considered with the figure. Here we will divide the period of $\phi=0 \sim 0.06$ rad of the initial stage into four processes a, b, c, c as a matter of convenience basing on the characteristics of a variation in ϕ and l_r ,

and study on each process on order.

If the "rubbing region where a cutting edge rubs over a work surface" as defined by Yuuta⁽¹¹⁾ exists at a stage just after the initial tool engagement, both the shear angle ϕ and tool chip contact length l_r can not be measured. A location where the value of ϕ begins to be measured should be the entrance boundary to the next "ploughing region [Fig.7(b)]", where a cutting edge begins to pierce into the workpiece. In the experimental result in Fig.11, ϕ is measured firstly at $\phi \approx 0.004$ rad independently on the rake angle, and the values of ϕ for the different rake angles are all 8° . The value of ϕ begins to increase after this stage, but the degree of its increment differs depending upon the rake angle. This tendency seems to mean that, in the process a in the figure, a nose radius of cutting edge is dominant, while the rake angle scarcely influence. It is considered from the variation of ϕ and l_r mentioned above that a boundary between the process a and b is just on the situation where a mechanics of cutting does a transition from the rubbing region to the ploughing region as defined by Yuuta, so that the process a and b corresponds to the rubbing region and the ploughing region, respectively.

In the next process c, the contact length l_r begins to be measured and increases with a tool advancement up to a certain level which differs depending on the rake angle. Although the shorter contact length than $l_r = 0.025$ mm is not measured in the figure for $\alpha = 20^\circ$, this should be recognized as that the value of l_r increases rapidly from 0 to 0.025 mm during the very short cutting time. This process marked with the sign c, is one of two processes c₁ and c₂, which are introduced by dividing the process (c) into two processes in order to consider the process. In the previous section the process (c) was defined as a process between the ploughing region (b) and the steady state (d). From a discussion in this chapter, however, it was found that the process (c) should be considered as a region constructed by two processes c₁, c₂, as classified above. Firstly, we deal with the deformation in the process c₁. The experimental result that the chip contact length l_r increases rapidly is considered to reflect a phenomenon that a work material to pile up in front of the rake face is being pushed upward. The length continues to increase until it can apply an enough force on work material in front of the rake face for flowing out as a generally observable chip and reaches a level as like as shown in the experiment.

The consecutive process c_2 is a process defined between the process c_1 and the steady state. It is seen in the experimental result that, while the value of l_r in this process is nearly constant, the resultant cutting force F and the shear angle ϕ increase depending on the rake angle and that θ decreases gradually. The value of l_r is much larger than the undeformed chip thickness, so that at the angular displacement $\varphi = 0.04$ rad, for example, l_r is 10 to 12 times of the undeformed chip thickness $t = 0.01$ mm for $\alpha = -5^\circ$, 0° and about 3 times even for $\alpha = 20^\circ$. Determining the duration of the process c_2 , which is defined as a period up to the beginning of steady state, from the variational configurations of ϕ and l_r in the figure and θ in Fig. 3, the duration is found to be extend over $\varphi = 0.025$ rad to 0.05, 0.028 rad to 0.06 and 0.014 rad to 0.06, for $\alpha = -5^\circ$, 0° and 20° , respectively. They are all considerably long. From the above experimental results, this process c_2 may be concluded to be in a situation that an amount of work material piled up on the rake face is so much that the chip contact length can not increase. In other words, this process is, as it were, in an over-accumulated situation of chip, and it is suspected that the tool chip contact length has been kept constant in the process until the undeformed chip thickness and the cutting force increase and the normal stress on the rake face arrives at a certain level.

Thus, it is concluded in up milling process that a transient period becomes stationary through the above four processes a, b, c_1 , c_2 and that a quasi-steady state of cutting is reached.

Subsequently, we will study on down milling. For convenience' sake, the transient period in the initial cutting stage is discussed in order by means of dividing it into three processes a, b and c.

The first process a is defined as a period from the initial engagement of tool up to the location of the maximum undeformed chip thickness. The cutting edge advances by about 0.23 mm from the point E to C in Fig. 1 during the period. It is obvious from the experimental result in cutting force in Figs. 3 to 6, the observation results of microphotographs in Fig. 9 and 10 and the observation by Okushima et al.⁽¹²⁾, that a deformation in this process a is nearly the same kind of deformation as in the initial stage of an intermittent cutting process and/or in an indentation by a rigid wedge. In this process, as recognizable from the measured values in Fig. 11, both the resultant cutting force F and its direction θ are small, the shear angle ϕ is large and the chip contact length l_r is very small.

Secondly, the cutting edge comes into the process represented with the mark b in Fig. 11, after the edge passes through the location of the maximum undeformed chip thickness. This process is defined here

as a period while the value of l_r begins to increase rapidly from a very small value and reaches the maximum. Observing Figs. 9 and 10 in regard to the feature of the chip, little difference between the feature of chip formed in the process b and in the previous process a is found. This matter is common also in the measured results in Fig. 11. The resultant cutting force and its direction increases continuously all through the processes a to b, and decreases also in the same manner. The maximum values of l_r , which are yielded at the last of this process b, take the different value depending upon the rake angle. It ranges $l_{r \max} = 0.16$ mm to 0.22 mm, which are less than 3 times as thick as the undeformed chip thickness at the point indicated by the dot-and-dashed line in the figures. These values are very small as a tool-chip contact length comparing with a generally observable values.

The above experimental results show that the situation of chip formation in the previous process a, which was found to be nearly the same as in the deformation by the wedge indentation, is kept in continuity without interruption also in this process b, and that a decrease in the undeformed chip thickness does scarcely influence on the deformation. Thus it may be concluded that, since the work material undergoes a plastic deformation as same as in a wedge indentation all through the process a to b, and since the cutting force vector in the initial stage of down milling has the same characteristic as in the intermittent cutting process, the chip formation mechanics in the process a to b in the earliest stage of milling process is little different from that in the initial condition in intermittent cutting process. As a matter of fact, the tendency in Fig. 11, i.e., the value of F and θ increase gradually from a very small value at the beginning, is one of the principal characteristics in the initial stage of intermittent cutting process.

Fig. 12 Variation of the stress distribution on the tool rake face in the initial stage of intermittent cutting (Work material: Rolled aluminium, Rake angle: $\alpha = 20^\circ$, Cutting velocity: $u = 14$ m/min.)

Thirdly, the process c is defined in a period from point where the value of l_r reached the maximum at the last of the previous process b to point where a quasi-steady state is attained. "A quasi-steady state" used here for down milling (written simply as "a steady state" in the latter part of this paper) is defined as the term which represents a situation that the thickness of chip decreases in proportion to a decrease in the undeformed chip thickness, and that the cutting force vector decreases to be shortened along a straight line in the vector diagram. The measured results in Fig.11 show that, until this steady state is attained in the process c, a long tool advancement is needed. That is, the region between the point where l_r arrives at the maximum in this figure and the point where θ reaches a constant extends over $\varphi=0.324$ rad to 0.230 for the case of $\alpha=-5^\circ$ and $\alpha=0^\circ$ and $\varphi=0.327$ rad to 0.290 for $\alpha=20^\circ$. It is clear from an observation of Fig.11 concerning the variations of factors during the process that no additional increase in l_r is yielded to the maximum value at the end of process b although the shear angle ϕ is decreasing and the cutting force F is increasing. The value of l_r limited very small during the earlier process a to b is kept up to the steady state. These tendencies, however, can not be given a rational explanation only by the data previously mentioned. In the present experiment, therefore, in order to more concretely clarify the deformation mechanics in the transient region in the initial process of both up milling and down milling, the stress distribution on tool rake face was measured and further discussions were carried out.

Fig.12 shows the variation of the distribution pattern of the normal stress p and shear stress τ during from initial engaging to steady state in an intermittent cutting. The thickness of chip and the tool chip contact length in the figure are represented as a non-dimensional amount divided by the undeformed chip thickness. It is clear from the figure that in the initial stage of intermittent cutting process the shear stress τ distributed in the narrower region comparing with the distribution pattern of normal stress p . As a tool advances, the width of the shear stress distribution extends increasingly to approach to that of the normal stress. This measured result seems full of suggestions and is considered to enable to take out the important informations about the deformation mechanics in the initial stage of down milling, as follows. At the stage just after the first tool engagement with work piece in down milling (the process a to b in Fig.11), the normal stress p will uniformly distribute over the whole contact area of chip with tool, while the shear stress τ will be concentrated into the adjacent area to the tool edge where a chip is most severely deformed. It is considered, therefore, that the characteristics in the stress distribution pattern observed

in Fig.12, i.e., the width of stress distribution at the initial stage of intermittent cutting is wide for the normal stress p and narrow for the shear stress τ , correspond exactly to the stress distribution on the rake face in the process a to b.

In the following process c after a further tool advancement in down milling, as previously mentioned, the resultant cutting force F and its direction θ are increasing while the tool chip contact length remains constant as it is. This tendency, that an increase in F is accompanied by an increase in its direction θ , means that an increase in the cutting force component F_T is larger than an increase in the thrust component F_N . In the other words, the increase in F in Fig.11 is mainly caused by an increase in F_N , so that the increase in the value of θ results. Consequently, to satisfy the condition that the value of F_N increases without any additional increment in the tool chip contact length l_r , all of the increment in F_N should be supported by extending of the distribution width of shear stress. It is considered, therefore, that in the process c a chip is formed in manner that the distribution width of shear stress elongates leaving a limited contact length l_r as it is, and after that, the quasi-steady state is attained. This inference may be supported also by the measured result in Fig.12, that is, the distribution width of shear stress τ extends and approaches to the width of normal stress p , as a tool advances in the process c.

Fig.13 Stress distribution on the tool rake face in the steady state of milling process (Work material: Rolled aluminium, Rake angle: $\alpha=20^\circ$, Cutting velocity: $u=50$ m/min)

The experimental result, that l_r does not increase in the process c, is deduced to be caused by that the contact length can not easily extend while the shear stress is concentrated into the adjacent region to the cutting edge, because a stiff adhesive lamella produced on the tool chip interface in the initial cutting stage a to b acts as like as a tool with restricted rake face.

Lastly, we will examine the stress distribution on the tool rake face in up milling. Fig.13 shows the stress distribution at the middle stage in both milling. In the figure, the distribution of p and τ in up milling are more concentrated into the vicinity of cutting edge than that in down milling. This is considered to be resulted from the following characteristics in the early stage of up milling carried over up to the steady state. In the process a to b, that is, from the rubbing region to the ploughing region, the tool engaging is limited into the nose part of cutting edge, so that a highly strained work material is stucked as an adhesive lamella which often leads a creation of built up edge. In the consecutive process c, where the tool chip contact length rapidly increases, therefore, the distribution patterns of p and τ are inferred to be concentrated to the vicinity of the cutting edge and become less as far as it aparts from the cutting edge. In the next process c_2 , there is little possibility of varying the above distribution since the value of l_r is remarkably large comparing with the undeformed chip thickness as previously mentioned. Thus, it is considered to become rational that the concentrating stress distribution into the vicinity of cutting edge, the pattern of which is formed in the process c_1 under the influence of the characteristics in the process a to b, is carried over to the steady state and leads the stress distribution as is seen in the figure.

4. Conclusions

In order to analyze the mechanics in the initial stage of peripheral milling process, a measurement of the cutting force in up milling and down milling, its vector representation, an observation of chip with microphotograph, measurements of the stress distribution on rake face, the tool-chip contact length and the shear angle were carried out, and many data collected extending over many factors were discussed in detail. Main conclusions obtained are the followings.

(1) Mechanics of milling process is not only characterized by a variation of the undeformed chip thickness as it has been noted in the earlier investigations, but also remarkably influenced by a transient mechanics in the initial stage.

(2) The transient cutting mechanics varies in the initial cutting stage as a tool advances. This transient period can

be clearly divided into four processes for up milling and into three processes for down milling.

(3) In up milling, as the undeformed chip thickness increases gradually from zero at the beginning with a very small inclination; the steady state is attained after passing through the four processes as the rubbing region (the process a), the ploughing region (the process b) defined by Yamamoto⁽¹⁰⁾ and Yuuta⁽¹¹⁾, the region while the tool chip contact length rapidly increases (the process c_1) and the region while the influence of the piled-up chip on the rake face is dominant (the process c_2). The stress distribution on the tool rake face in up milling was found to concentrate into the adjacent part to the cutting edge.

(4) In down milling where the undeformed chip thickness abruptly increases from zero to the maximum and decreases with a small inclination, the deformation soon after the first tool engaging (the process a to b) is little different from that in the initial stage of intermittent cutting process, so that the normal stress on the tool rake face distributes uniformly and the shear stress distributes concentrating into the cutting edge. As a tool advances, the distribution pattern of the shear stress extends in the process c, while the tool-chip contact length does not increase regardless of an increase in the cutting force.

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