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EXAMPLE OF ANALYSIS METHOD CONSIDERING NONLINEAR CHARACTERISTICS FOR ULTRASONIC VIBRATION-ASSISTED MACHINING

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Abstract. Ultrasonic vibration has been applied to many machining processes. It has been reported that the application of ultrasonic vibration to machining has improved machining efficiency and accuracy. In this report, ultrasonic vibration is applied to welding, drilling, and knurling, and its effects are shown through experiments and analyses. In welding, it is shown that ultrasonic vibration can reduce tensile residual stress. In addition, the simulation method using a simple model showed that residual stress is reduced by the plastic deformation caused by ultrasonic vibration. In the drilling process, it was found that the surface roughness of the machined surface was improved when ultrasonic vibration was used. The conditions under which the surface roughness is improved by the impulse due to cutting resistance were also determined. In knurling, it was found that the pressing and friction forces were reduced by the use of ultrasonic vibration. It was also shown that the reduction in pressing force is expressed as the product of the equivalent mass and the amplitude of ultrasonic vibration.

1 INTRODUCTION

Ultrasonic vibration has been applied to many machining methods and reported to improve machining performance [1, 2]. This paper deals with the reduction of welding residual stress, the improvement of machined surfaces in the drilling of laminated materials, and the improvement of machining efficiency in knurling as examples of machining with ultrasonic vibration. First, the advantages of applying ultrasonic vibration are demonstrated through experiments. Furthermore, since machining is essentially a nonlinear phenomenon [3], simple analyses that take nonlinear characteristics into account will demonstrate the usefulness of ultrasonic vibration.

First, the reduction of residual stress is examined. An experiment was conducted in which welding was performed while ultrasonic vibration was applied. As a result, it was found that tensile residual stress was reduced. Since the yield stress near the weld immediately after welding is low, the residual stress was determined by simulation method using a model that takes plastic deformation into account. The results showed that welding while applying ultrasonic vibration reduced the residual stress.

Second, improvement of the machining surface in the drilling of laminated materials was examined. Experiments were conducted to drill holes in laminated materials while applying ultrasonic vibration at different drill rotation speeds and feed rates. As a result, it was found that the surface roughness of the machined surface was improved. Since the drill is expected to intermittently drill holes in the laminate material in this process, the impulse due to cutting resistance was calculated using a model that takes intermittent drilling into account. From the results, conditions for improved surface roughness were obtained.

Third, the improvement of machining efficiency in knurling was examined. An experiment was conducted in which knurling was performed while applying ultrasonic vibration. For simplicity, an experiment was conducted in which a groove was machined by pressing an indenter. The results showed that applying ultrasonic vibration reduced the pressing force and friction force. Assuming that the reduction of pressing force can be expressed in terms of inertia force, the product of the equivalent mass contributing to the reduction and the amplitude of ultrasonic vibration was determined.

2 APPLICATION TO WELD RESIDUAL STRESS REDUCTION

Welding is a widely used method for joining components. Because welding is a heat-applied process, residual stress is generated near the bead. Since tensile residual stress adversely affects fatigue strength and other properties [4], methods to reduce it have been studied. Heat treatment and shot peening have been studied and put to practical use [5, 6]. However, these methods require special equipment and are time-consuming. The author devised a method of applying ultrasonic vibration during welding and conducted experiments to study its effectiveness. An example of one experiment is shown below.

2.1 Experiment

A built-up welding was applied to a thick plate specimen with the dimensions shown in Figure 1 and a thickness of 30 mm. The weld was made along the centerline for 150 mm in the direction from point B to point C. During welding, ultrasonic vibration was applied to the two points indicated by ● in the figure. The ultrasonic vibration frequencies were 37.5 kHz and 47.5 kHz. For comparison, experiments were also conducted using a single ultrasonic vibration and without ultrasonic vibration. Residual stresses in the bead direction were measured every 10 mm on the bead as shown in Figure 1. Three specimens were made for each case, and the results of the average of the residual stresses are shown in Figure 2. It is clear that the use of one

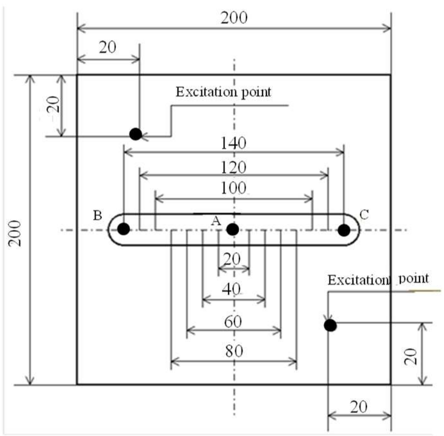


Figure 1: Dimensions of specimen (mm)

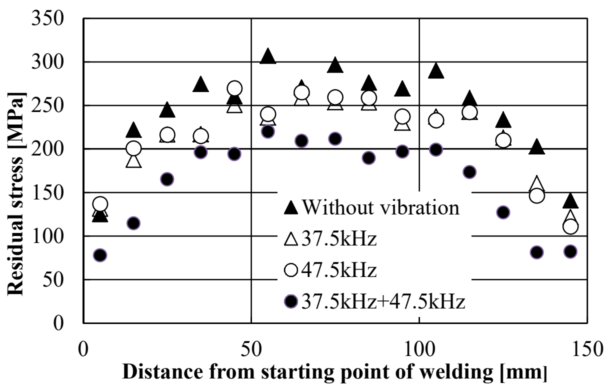


Figure 2: Residual stress using ultrasonic vibration

ultrasonic vibration reduced the residual stress more than the use of no ultrasonic vibration, and the use of two ultrasonic vibrations reduced the residual stress more than the use of one ultrasonic vibration.

2.2 Analysis Method

The above experimental results are examined analytically. The area around the weld immediately after welding is susceptible to plastic deformation due to the high temperature. The reduction of residual stress was studied using a model that takes plastic deformation into account, as shown in Figure 3. The y-axis is the bead direction and the x-axis is the bead perpendicular direction. y-axis springs are pulled by Z_e and then subjected to ultrasonic vibration input in the x-axis direction. The springs yield according to the Tresca yield criterion, and each time they yield, the residual stress is reduced. Table 1 shows the ratio of the residual stress with one ultrasonic vibration to the residual stress without ultrasonic vibration, where F_x/mU is the ratio of the yield force to the ultrasonic vibration input amplitude. Values in the table are less than 1, indicating that the residual stress is reduced by the addition of one ultrasonic vibration. Table 2 shows the ratio of the residual stress with two ultrasonic vibrations to the residual stress without ultrasonic vibration. The values in Table 2 are less than 1, which is smaller than the values in Table 1. This indicates that the use of two ultrasonic vibrations reduces the residual stress more than the use of one ultrasonic vibration. This simulation method qualitatively explains the experimental results. Furthermore, it is predicted that the smaller F_x/mU, i.e., the larger the ultrasonic amplitude, the more the residual stress is reduced.

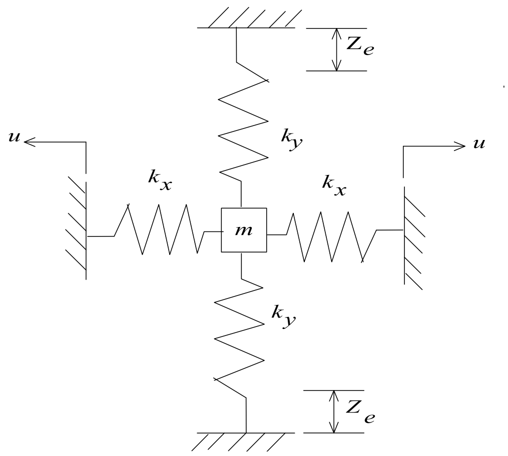


Figure 3: Analytical model for reduction of residual stress

Table 4: Ratio of residual stress using one ultrasonic vibration to that without vibration

	F_x/mU		
Frequency	0.005	0.007	0.010
37.5kHz	0.92	0.97	0.98
47.5kHz	0.95	0.98	0.99

Table 5: Ratio of residual stress using one ultrasonic vibration to that without vibration

	F_x/mU		
Frequency	0.005	0.007	0.010
37.5kHz+47.5kHz	0.79	0.87	0.93

3 APPLICATION TO DRILLING PROCESS

Laminated materials are used in many structures because of their high strength-to-weight ratio [7]. Laminated materials require secondary processing such as drilling to connect with other members. During drilling, delamination can lead to poorly machined surfaces. To prevent this, using ultrasonic vibration is considered. Experiments were conducted to confirm the effectiveness of this method, and an analytical method was presented to explain the experimental results.

3.1 Experiment

As shown in Figure 4, an ultrasonic vibration generator was attached to the spindle of a general-purpose drilling machine, and holes were drilled while applying ultrasonic vibration. The matrix of the laminated material is epoxy, and glass fiber is used as a reinforcement. The number of laminations is 23, the thickness is 5 mm (each layer is about 217 μm), and the size is 300 × 200 mm. The laminated material is plain woven and stacked in the same direction. The laminated material was fixed in a vise on a table. The ultrasonic vibration frequency was 17.8 kHz, the drill material was cemented carbide (JIS: K10), and the drill diameter was 8 mm. The holes were drilled perpendicular to the lamination surface. The acceleration amplitude at the drill tip was 300 G or 640 G at full amplitude, resulting in a displacement amplitude of 0.118 μm or 0.251 μm, respectively.

First, the rotation speed was fixed at 384 rpm, and the feed rate was varied between 0.05 mm/rev and 0.10 mm/rev for drilling. Next, the feed rate was fixed at 1.0 mm/s, and the rotation speed was varied between 800 and 2400 rpm.

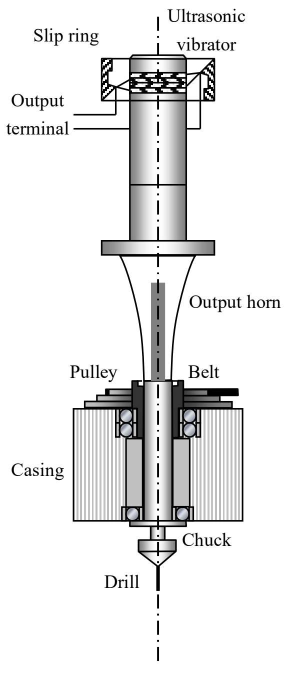


Figure 4 : Ultrasonic vibration drilling system

The surface profile was evaluated in terms of surface roughness in the machining direction. The laminated material was cut through the center of the hole using a fine cutter, and the arithmetic mean roughness of the machined surface was measured. The measurement conditions for surface roughness were a feed rate of 0.5 mm/s, a cutoff value of 0.8 mm, and an evaluation length of 2.5 mm.

Figure 5 shows the results for different feed rates, and Figure 6 shows the results for different rotation speeds. The symbols ● indicate the surface roughness without ultrasonic vibration, and the symbols ○indicate the surface roughness with ultrasonic vibration. The surface roughness is reduced when drilling is performed while ultrasonic vibration is applied. Therefore, it is clear that drilling while applying ultrasonic vibration improves the machined surface profile.

3.2 Analysis Method

Assuming that the elastic deformation of the laminated material during drilling is negligible, the conditions under which the machined surface shape is improved were determined. To simplify the theoretical analysis, it is assumed that the cutting resistance can be replaced by the resistance generated by damping. Several models have been proposed for the damping properties of laminated materials [8], but for simplicity, viscous damping is assumed here. The impulse of the forces generated by the damping elements in the laminated material during one vibration cycle is considered. The laminated material is assumed to be drilled in the depth direction during one cycle as shown in Figure 7. Figure 7 (a) shows the displacement of the drill tip in the laminated material when no vibration is applied. Figure 7 (b) shows the displacement of the drill tip in the laminated material when vibration is applied.

When no vibration is applied, the displacement x_0 of the drill tip is given by

$$x_0 = a\frac{\omega}{2\pi}t \tag{1}$$

where a is the displacement of the drill tip per vibration cycle. The displacement x_1 of the drill tip when drilling while applying vibration is given by

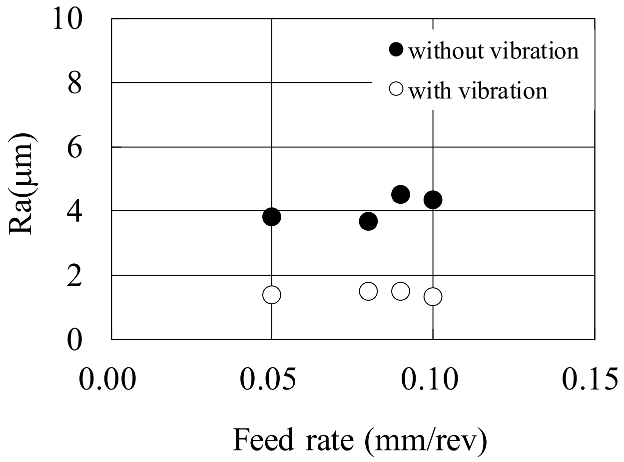


Figure 5: Surface roughness (384rpm)

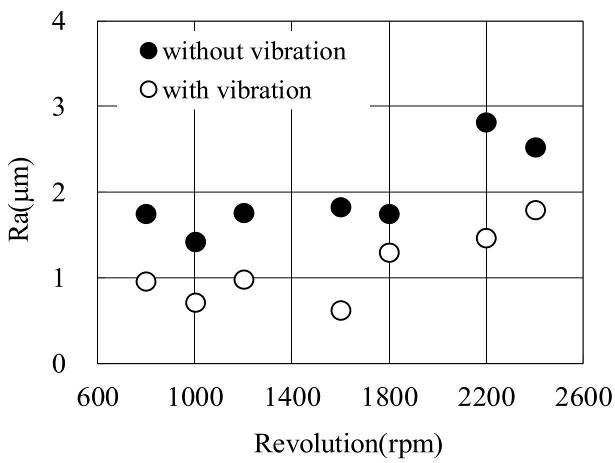


Figure 6: Surface roughness (1.0mm/s)

$$x_1 = a\frac{\omega}{2\pi}t + b\sin\omega t \qquad (2)$$

where b is the displacement amplitude of the ultrasonic vibration and ω is the circular frequency of the ultrasonic vibration.

Assuming that the viscous damping coefficient is c, the impulse E_0 during one vibration cycle when drilling without vibration is given by the following equation.

$$E_0 = \int_0^{\frac{2\pi}{\omega}} c\dot{x}dt = \int_0^{\frac{2\pi}{\omega}} c\left(\frac{\omega}{2\pi}\right)dt = ca \qquad (3)$$

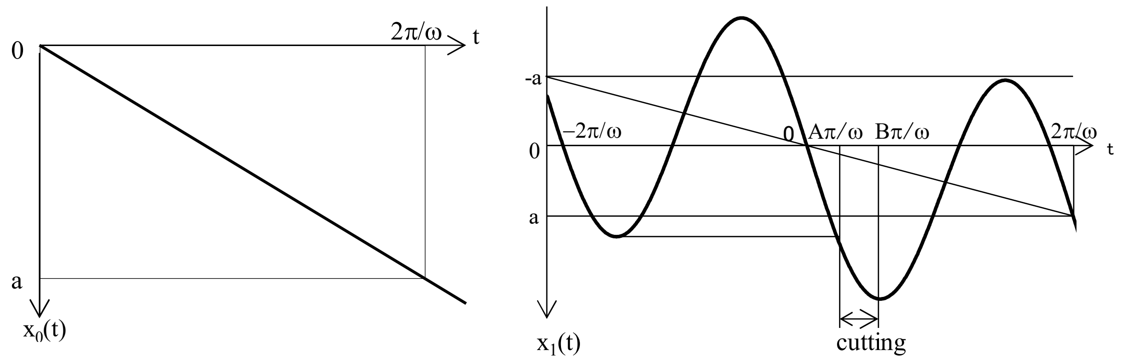
When drilling while applying vibration, as shown in Figure 7 (b), there is a section where drilling is performed by the drill and a section where the drill leaves the laminated material. The section where drilling is performed in one vibration cycle is defined as $A\pi/\omega < t < B\pi/\omega$. In other sections of one vibration cycle, the drill leaves the laminated material. Therefore, the impulse E_1 in this case is given by

$$E_1 = \int_{\frac{A\pi}{\omega}}^{\frac{B\pi}{\omega}} c\dot{x}dt = \int_{\frac{A\pi}{\omega}}^{\frac{B\pi}{\omega}} c\left(a\frac{\omega}{2\pi} + b\omega\cos\omega t\right)dt = c\left\{\frac{a\omega}{2}(B-A) + b(\sin B\pi - \sin A\pi)\right\} \qquad (4)$$

In the experiment in which the effect of feed rate was examined, the acceleration amplitude at the drill tip was 300 G for the total amplitude. The displacement amplitude b of the drill tip is 0.115 μm. On the other hand, in the experiment where the effect of rotation speed was examined, the amplitude was 640 G for the total amplitude. The displacement amplitude b of the drill tip was 0.251 μm. In the experiment to study the effect of feed rate, the values of A and B for the interval $A\pi/\omega < t < B\pi/\omega$ where drilling takes place can be calculated numerically as shown in Table 3. Table 4 shows the results of obtaining E_0 and E_1 from equations (3) and (4), respectively, and for the experiment in which the effect of rotation speed was examined, A = 0.29 and B = 0.51, resulting in $E_0 = E_1 = 0.0541 \times 10^{-8}$ c (Ns). From these results, the impulse when ultrasonic vibration is applied is smaller than or almost equal to the impulse when ultrasonic vibration is not applied. Therefore, the following equation is considered to hold.

$$E_1 \leq E_0 \qquad (5)$$

Equation (5) is considered to be a condition for improved surface profile. It is considered that ultrasonic vibration improves the surface profile because the cutting resistance acts in a short period.



(a) without vibration (b) with vibration

Figure 7: Location of drill tip in composite material

4 APPLICATION TO KNURLING

Sliding surfaces in mechanical systems are required to move smoothly and stop at a target position. Sliding surfaces move and stop by applying an appropriate friction force. The friction force is controlled by a technology that forms small textures on the surface at intervals of several micrometers to several hundred micrometers. If this technology is applied to large-area sliding surfaces such as generators and machine tools to reduce friction force, the processing effect will be dramatically improved [9,10]. There is a need to develop a processing technology that creates textures with high precision and high efficiency. Knurling is one of the texture-creating methods [11, 12].

4.1 Experiment

In this paper, knurling is focused on creating texture. The experiment was conducted to create a texture on a sliding surface to improve the friction characteristics of the surface. As a basic experiment, grooves were machined while applying ultrasonic vibration. Figure 8 shows the experimental setup for machining grooves. The workpiece material is aluminum (JIS: A2017), and it is bolted to a 2-axis feed table via a 3-D dynamometer under the table. Pressing force and friction force were measured by the dynamometer. The pressing tool consists of a 30 kHz bolting Langevin-type ultrasonic transducer, a carbon steel horn, and a conical indenter. The target depth was determined, and the table was moved after that depth was reached to machine the groove without applying ultrasonic vibration. Ultrasonic vibration was applied 30 seconds after the table was moved. Figures 9 (a) and 9 (b) show the pressing force (red line) and friction force (blue line) at target depths of 10 μm and 30 μm, respectively. The point where the ultrasonic vibration is applied is shown in Figure 9 (a) and (b). From both figures, it is clear that the application of ultrasonic vibration reduces the pressing force and the friction force. Although the pressing force and friction force vary with time, the average value of the pressing force can be obtained as shown in Figure 10. This figure shows the pressing force without ultrasonic vibration (blue line) and with ultrasonic vibration (red line) at the target depth. For

Table 3: Values of A and B

Feed rate (mm/rev)	a (μm/cycle)	A	B
0.05	0.0180	0.330	0.510
0.08	0.0288	0.290	0.510
0.09	0.0324	0.275	0.510
0.10	0.0360	0.265	0.510

Table 4: Impulse during one cycle of vibration

Feed rate (mm/rev)	E_0 (10^{-8} Ns)	E_1 (10^{-8} Ns)
0.05	$1.80c$	$1.67c$
0.08	$2.88c$	$2.83c$
0.09	$3.24c$	$3.24c$
0.10	$3.60c$	$3.56c$

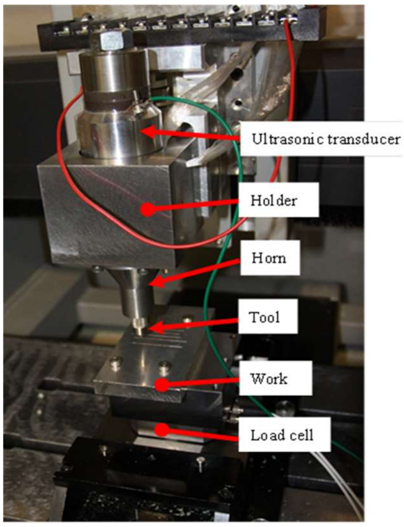


Figure 8: Experimental setup

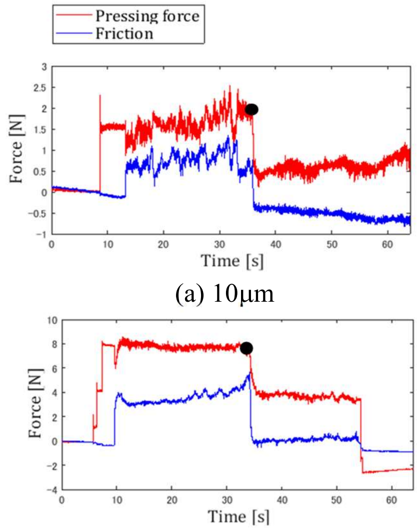


Figure 9: Pressing force and friction force

all target depths, ultrasonic vibration reduces the pressing force. Figure 11 shows the reduction of the pressing force. The reduction is almost proportional to the target depth. The approximate straight line is shown as a dashed line in the figure.

4.2 Analysis Method

The reduction of pressing force is considered to be due to the Blaha effect [13]. The reduction in force due to the Blaha effect can be explained as the force corresponding to the average of the forces caused by ultrasonic vibration being reduced [14]. Assuming that the reduction of the pressing force is entirely expressed by the inertia force, the reduction of the force F is given by the following equation.

$$F = mX(2\pi f)^2 \tag{7}$$

where m is the equivalent mass contributing to the inertia force, X is the amplitude of ultrasonic vibration, and f is the frequency of ultrasonic vibration. Since the frequency of ultrasonic

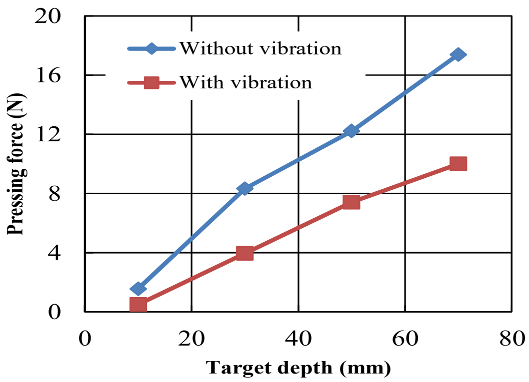


Figure 10: Average value of pressing force to target depth

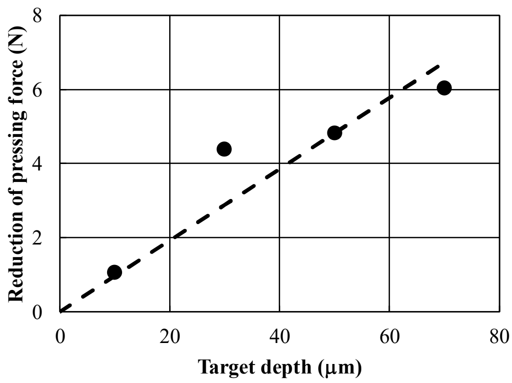


Figure 11: Reduction of pressing force

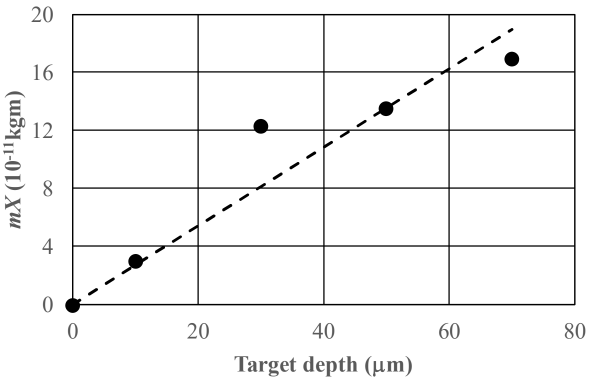


Figure 12: Product of equivalent mass and amplitude of ultrasonic vibration

vibration is known, mX in Equation (7) can be obtained as shown in Figure 12. In general, the amplitude of ultrasonic vibration is small, so the value of mX is small, but even taking this into account, the equivalent mass that contributes to reducing the pressing force is also expected to be small. As shown in Figure 12, mX is approximately proportional to the target depth.

5. CONCLUSIONS

Examples of the application of ultrasonic vibration to machining to improve machining efficiency and accuracy are shown for welding, drilling, and knurling. For each of these, the effects of using ultrasonic vibration were demonstrated through experiments, and then theoretical analysis methods were presented to explain the experimental results.

In welding, it was found that tensile residual stress, which adversely affects fatigue strength, was reduced by welding while applying ultrasonic vibration. The temperature near the weld immediately after welding is high, and plastic deformation is considered to occur with a small amount of force. Therefore, simulations using a mechanical model that takes plastic deformation into account show that the use of ultrasonic vibration reduces residual stress.

In the drilling process, the surface roughness of the machined surface was improved by using ultrasonic vibration during machining. Assuming that cutting resistance can be expressed as a viscous damping force, the impulse during one cycle of vibration generated in the damping element was determined. The results showed that surface roughness is improved when the impulse with ultrasonic vibration is greater than or equal to the impulse without ultrasonic vibration.

In knurling, for simplicity, the tool was pressed against the workpiece and the groove was machined at different target depths. It was found that the pressing force and friction force were reduced when machining while applying ultrasonic vibration. It was found that the reduction of pressing force was almost proportional to the target depth of the groove. Assuming that the reduction in pressing force can be expressed in terms of inertia, the product of the mass contributing to the reduction in pressing force and the amplitude of ultrasonic vibration was determined.

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