Paper:

Ultrasonic-Assisted Grinding of Ultra-High Purity SUS 316L

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Ultra-High Purity (UHP) alloys providing such excellent properties as high corrosion resistance and toughness are difficult to machine efficiently due to these very properties. To improve machining efficiency, we applied ultrasonic-assisted micro-grinding to UHP alloy machining. We discuss the theoretical model we built of ultrasonic-assisted grinding to study grinding force using statistical calculation. We theoretically estimated and experimentally confirmed the effect of ultrasonic assistance on reducing grinding force.

Keywords: ultrasonic-assisted grinding, ultra-high purity SUS316L, statistical model

1. Introduction

Local corrosion usually progresses from impurities in material, which makes Ultra-High Purity (UHP) alloy a corrosion-resistant alternative. The UHP alloy's difficulty in cutting lowers machining efficiency, thus preventing its wider use.

Ultrasonic-assisted grinding has been reported to effectively and efficiently machine difficult-to-cut materials authors such as Kumabe et al., Nomura et al., Tanaka et al. and Umino et al. [1–4]. Advantages of ultrasonic-assisted grinding include reduced grinding force and improved ground surface roughness. To make ultrasonic-assisted grinding applicable in industry and confirm the effect of ultrasonic assistance, an ultrasonic-assisted micro-grinding machine was developed, experiments conducted on a small workpiece for laboratory testing, an ultrasonic-assisted grinding model built, and a theoretical model proposed using statistics. Micro-grinding wheels tend to have uneven grain distribution due to having fewer grains than conventional grinding wheels, making it important to consider abrasive grain distribution in a micro-grinding model.

2. Theoretical Ultrasonic-Assisted Grinding Model

2.1. Assumptions

Figure 1 shows abrasive grain cutting in plunge grinding. The grain in **Fig. 1** is a cutting edge that begins cutting workpiece surface S_t. g_s is the cutting length measured on S_t. The maximum grain depth of cut g_m is obtained by using g_s, the wheel depth of cut Δ, and wheel diameter D. The relationship between g_m and g_s is defined as follows:

$$g_m = 2g_s\sqrt{\frac{\Delta}{D}} \qquad (1)$$

A statistical grinding model has been proposed for calculating ground surface roughness [5–7] assuming the following:

(1) A grain tip is a circular cone with a constant tip angle 2α and the conical axis is in the radial direction of the grinding wheel.

(2) Grain tips are distributed uniformly at random on the surface of a grinding wheel. The mean volume occupied by a grain tip takes constant W_0 in any place of the wheel if the space in the place is sufficiently large.

(3) Shapes of scratches on the ground surface are the same as grain tips, meaning that the elastic deformation of the workpiece and grain tips negligible.

(4) Grinding is proportional to the cross-section of cut S_c and S_c is proportional to the square of g_m.

Based on Eq. (1) and assumption (4), grinding force is obtained by calculating g_s, which is obtained statistically.

2.2. Statistical Calculation

Figure 2 shows positions of the grinding wheel and workpiece before and after one wheel revolution.

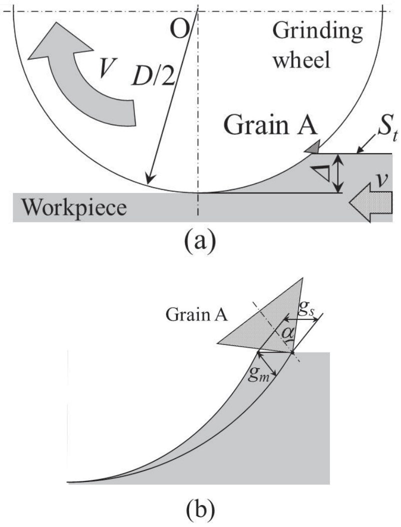

Fig. 1. Schematic of an abrasive grain cutting (a) Workpiece and grinding wheel, (b) Grain depth of cut (v, feed speed; V, wheel rotation speed; D, Wheel diameter; S_t, the top surface of workpiece; g_s, cutting length; g_m, maximum grain depth of cut).

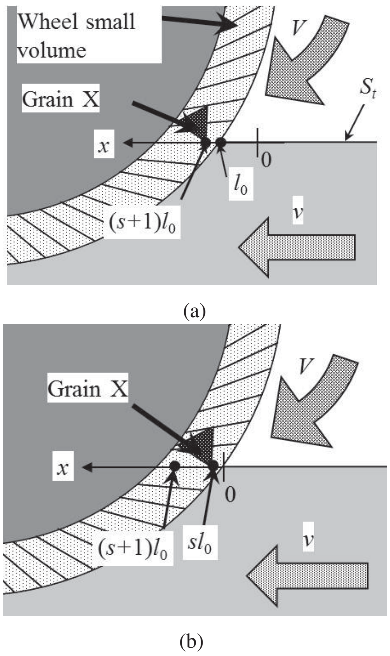

Fig. 2. Position of a grinding wheel and workpiece (a) Before one wheel rotation, (b) After one wheel rotation (l_0, the feed length during one wheel revolution).

Fig. 2(a) shows that abrasive grain X has just started cutting the workpiece and **Fig. 2(b)** shows positions after one wheel revolution. The coordinate in **Fig. 2** is fixed at S_t and the x axis is parallel to the direction of workpiece feed. The coordinate origin is at the intersection of S_t and the outermost wheel surface when X has started the latter cutting shown in **Fig. 2(b)**. sl_0 is the distance between X and the outermost wheel surface, s the length ratio coefficient, and l_0 the feed length during one wheel revolution. l_0 is shown as follows:

$$l_0 = \frac{v}{V}\pi D \quad \text{. . . . . (2)}$$

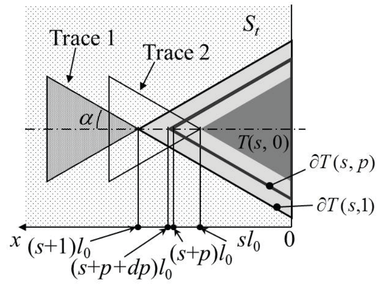

Fig. 3. Cutting trace of grain X on S_t ($T(s,p)$, triangle area where the tip-top is $s+p$; $\partial T(s,p)$, the edge area between $T(s,p)$ and $T(s,p+dp)$).

where v is feed speed and V wheel rotation speed.

$f_g(x)$, which is the density of grains through S_t, is needed to use a statistical method. $f_g(x)$ is calculated by mapping grain tips from the wheel to S_t as follows:

$$f_g(x) = \begin{cases} \dfrac{2\pi}{W_0}\sqrt{\Delta D}\dfrac{x}{l_0} & x \le l_0 \\[2ex] \dfrac{2\pi}{W_0}\sqrt{\Delta D} & x > l_0 \end{cases} \quad \text{. . . . . (3)}$$

Figure 3 shows the cutting trace of grain X on S_t. The former cutting trace is trace 1 and the latter trace 2, corresponding to **Figs. 2(a)** and **(b)**. The maximum length of g_s is equal to l_0 theoretically, but g_s becomes shorter than l_0 if other grain tips cut the front triangle before grain X starts latter cutting. $T(s,\ p)$ is defined as a where the top-tip is $s+p$ and $\partial T(s,p)$ is defined as the edge between $T(s,p)$ and $T(s,p+dp)$. If a grain cuts $T(s,0)$, g_s is equal to zero and grain X passes through S_t without cutting. If a grain cuts $\partial T(s,p)$ and no grain cuts $T(s,p)$, g_s is equal to pl_0. g_s is therefore obtained by the cutting probability in $T(s,p)$, $P(s,p)$.

$1/f_g(x)dx$ is the average grain distance on x when dx is an infinitely small interval. $p_t(x,s,p)$, which is the grain existence probability on x in $T(s,p)$, is considered the proportion of the length of $T(s,p)$ on x to $1/f_g(x)dx$, so $p_t(x,s,p)$ is as follows:

$$p_t(x,s,p) = \frac{2\{(s+p)\,l_0 - x\}\tan\alpha}{1/f_g(x)} \quad \text{. . . (4)}$$

$P(s,p)$ is calculated by integrating $p_t(x,s,p)$ from 0 to $s+p(=q)$ by x as follows:

$$P(s,p) = \begin{cases} \dfrac{C_0}{3l_0}q^3 & q \le 1 \\[2ex] \dfrac{C_0}{3l_0}\left(3q^2 - 3q + 1\right) & q > 1 \end{cases} \quad \text{. (5)}$$

where C_0 is defined as follows:

$$C_0 = \frac{2\pi\sqrt{\Delta D}}{W_0} l_0^3 \tan\alpha \quad \text{. . . . . (6)}$$

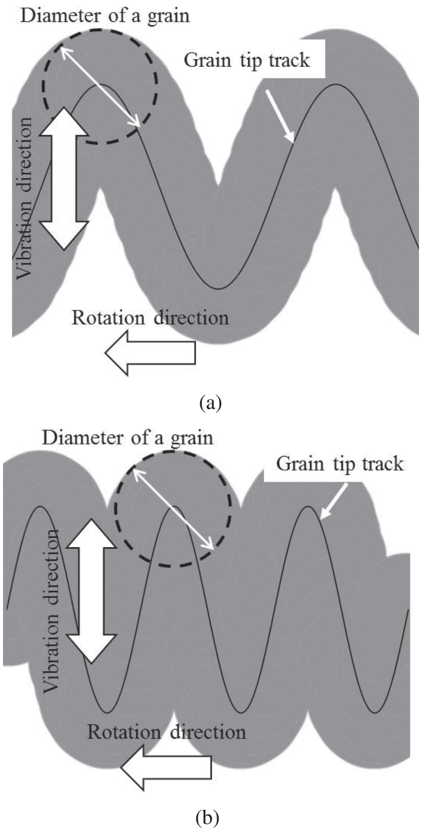

Fig. 4. Overlapping area, (a) $2\pi fA/V = 2$, (b) $2\pi fA/V = 4$.

Cutting probability on $\partial T(s,p)$, $\partial P(s,p)$, is obtained by the differential of Eq. (5):

$$\partial P(s,p) = \begin{cases} \dfrac{C_0}{l_0} q^2 dp & q \le 1 \\ \dfrac{C_0}{l_0}(2q-1)\,dp & q > 1 \end{cases} \quad . . . (7)$$

Maximum q, q_{max}, is the solution to the following equation:

$$P(s,p) = 1 \quad . . . . (8)$$

Eq. (8) means that at least one grain tip is included in $T(s,p)$, assuming that $q_{max} \le 1$ and the mean length of g_s, $\bar{g}_s$, is calculated as follows:

$$\bar{g}_s = \frac{\int_0^{q_{\max}} \left[\int_0^{q_{\max}-s} pl_0 \partial P(s,p)\right] ds}{\int_0^{q_{\max}} ds} \quad . . . . (9)$$

The mean length of g_m, $\bar{g}_m$, is calculated using Eqs. (1) and (9) as follows:

$$\bar{g}_m = \frac{3}{10}\sqrt[3]{\frac{3}{2} W_0 \frac{v}{V}\frac{\Delta}{D}\cot\alpha} \quad . . . . (10)$$

Based on assumption (4), grinding force F is expressed as follows:

$$F/b = k_1 \left(W_0 \frac{v}{V}\frac{\Delta}{D}\cot\alpha\right)^{\frac{2}{3}} \quad . . . . . . (11)$$

Table 1. Comparison of components.

Composition	UHP SUS316L	JIS SUS316L
C	0.003	< 0.030
Si	< 0.01	< 1.00
Mn	< 0.01	< 2.00
P	< 0.001	< 0.045
S	0.0011	< 0.030
Ni	14.80	$12.00 \sim 15.00$
Cr	16.23	$16.00 \sim 18.00$
Mo	2.01	$2.00 \sim 3.00$
O	0.0033	–
N	0.0017	–

Unit: mass%, –: not defined

where b is grinding breadth and k_1 is a coefficient, and tangential grinding force F_t and normal grinding force F_n can be calculated using coefficients k_{1t} and k_{1n}.

2.3. Effect of Ultrasonic Assistance

Grinding force reduction with ultrasonic assistance is considered due to S_c being lowered by cutting overlap. **Fig. 4** shows the relationship between ultrasonic vibration and overlapping area whose size depends on the ratio of ultrasonic vibration speed $2\pi fA$ to rotation speed V where f and A are vibration frequency and half amplitude. The cutting speed of ultrasonic assisted grinding V_u is the result of ultrasonic vibration and rotation speed. Average speed $\bar{V}_u$ is as follows:

$$\bar{V}_u = V\frac{2\sqrt{1+n^2}}{\pi} E\left(\frac{n^2}{n^2+1}\right) \quad . . . . . (12)$$

$$n = \frac{2\pi fA}{V} \quad . . . . (13)$$

where $E(k)$ is the complete elliptic integral of the second kind.

Grinding force with ultrasonic assistance is calculated by substituting $\bar{V}_u$ of Eq. (12) into V of Eq. (11).

3. Experimental Conditions

Table 1 shows components of UHP SUS316L. **Fig. 5** shows the ultrasonic-assisted micro-grinding device. The bolt-clamped Langevin transducer on the spindle vibrates a micro-grinding wheel axially. The dynamometer under the workpiece measures the grinding force. **Table 2** shows conditions for ultrasonic-assisted grinding experiments. V, A, and f keep a constant value. v and Δ change with condition in the table.

4. Results and Discussion

Figure 6 shows ultrasonic-assisted and conventional ground surfaces. Note grinding and vibration tracks on

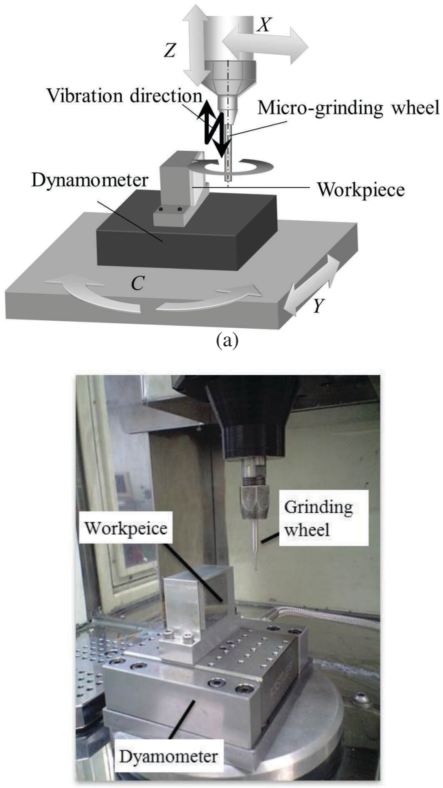

Fig. 5. Developed ultrasonic-assisted grinding device, (a) schematic, (b) photo.

Table 2. Experimental conditions

Grinding wheel	ϕ1 electroplated diamond
Grit size	#170
Feed speed v	0.5, 1, 2, 5 mm/min
Wheel depth of cut Δ	10–150 μm
Rotation speed V	6.3 m/min (2000 rpm)
Vibration frequency f	62 kHz
Half amplitude A	3.5 μm
Grinding breadth b	3 ~ 5 mm
Grinding fluid	Solution type

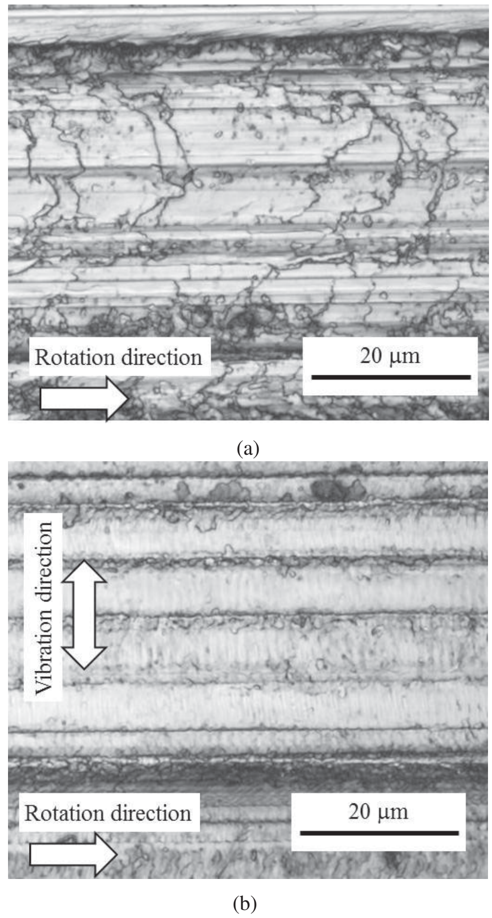

Fig. 6. Laser microscope photographs of ground surfaces, (a) Normal grinding, (b) Ultrasonic-assisted grinding.

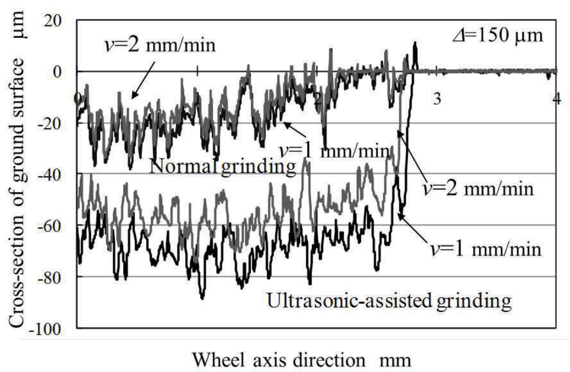

Fig. 7. Measured cross-section profile.

both.

Figure 7 shows the amount of material removed, obtained using cross-section profiles of surfaces before and after grinding. Note that ultrasonic-assisted micro-grinding obtains over 4 times more grinding material removal than in commercial operations. More material could also be removed at slower v, but the effective wheel depth of cut Δ_e could not reach set value Δ Due to grinding wheel bending.

Figure 8 shows the effect of reduced grinding force by ultrasonic assistance. Note that the density of the conventional grinding force F_n/b component is reduced considerably by ultrasonic-assisted grinding comparing to conventional grinding. According to the gradient of each graph, a slower v was verified to contribute to lower grinding force.

Since v affects Δ_e and F_n, and Δ_e affects F_n, the effect of the ultrasonic assistance cannot be verified quantitatively, so it is considered using Eq. (11). **Fig. 9** shows the relationship between $(v\Delta_e/VD)^{\frac{2}{3}}$ and F_n/b. The two approximation lines are almost parallel, and the ordinate intercept of ultrasonic-assisted micro-grinding is smaller than that of conventional micro-grinding, which confirms that the grinding threshold is reduced by ultrasonic assistance.

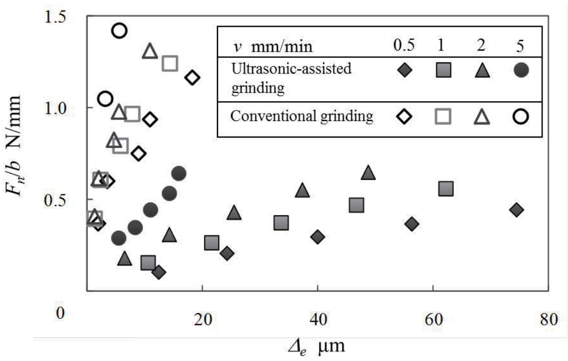

Fig. 8. Acknowledgements Effect of grinding force reduction by ultrasonic-assistance.

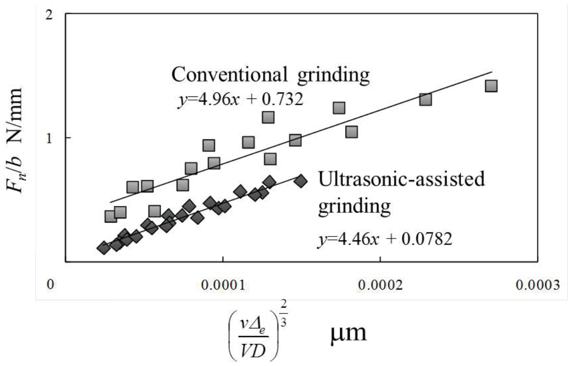

Fig. 9. Substitution of experimental results of Eq. (11)

5. Conclusions

Ultra-High-Purity SUS316L has been processed by ultrasonic-assisted micro-grinding. An expression of grinding force with ultrasonic assistance has been obtained statistically. The main conclusions obtained in this study are as follows:

- Ultrasonic-assisted micro-grinding reduces grinding force compared to conventional micro-grinding in machining UHP SUS316L.
- Theoretical estimation was obtained using a statistical method, which was confirmed by experimental results.

Acknowledgements

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