Influence of ultrasonic vibration on metal foils surface finishing with micro-forming

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Abstract

Traditional processes used for surface finishing such as polishing, grinding, finishing or laser irradiation could produce quite smooth surface. However, it is not convenient to apply these processes in micro manufacture due to the small size of product. In this study, micro forming process with presence of ultrasonic vibration was introduced for metal foils surface finishing. Influences of ultrasonic vibration on surface roughness were obtained at different conditions and a surface grain model was employed to clarify mechanism of improvement by ultrasonic. Results showed that surface roughness reduction is linear to ultrasonic vibration amplitude and static stress. The large surface roughness reduction was believed to have close relation with surface / total grain ratio, which is a function of dimension.

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Keywords: Micro forming; Ultrasonic vibration; Surface finishing

1. Introduction

Pursuing smaller volume and more powerful functions is always an aim of most electronics producer to satisfy rapid growth of mobile business / communication activities. Challenges in micro manufacture come accompany...
with opportunities. High performance mobile devices rely on micro metal parts with high dimension accuracy and surface flatness. Traditional processes used for surface finishing such as polishing, grinding, finishing or laser irradiation could produce quite smooth surface. But there is difficulty in applying these processes in micro manufacture. Although some newly developed technology such as LIGA, ECM (Electrochemical Machining) or EDM (Electric Discharge Machining) could reduce surface roughness greatly (Abbas et al., 2007), the production efficiency is an obvious disadvantage.

Metal forming has high production efficiency, with plastic deformation of metal material, surface roughness could be reduced. Nevertheless, the high forming load involved in metal forming may damage the micro parts. Based on previous studies, ultrasonic vibration could reduce forming load and increase material plasticity, making metal forming possible for metal foils surface finishing. Izumi et al. (1966) conducted compression test with ultrasonic vibration, according to the results, ultrasonic vibration was found to have a softening effect (blaha effect) on the materials. Huang et al. (2009) found that the ultrasonic vibration settings had great influences on material flow stress reduction, and the flow stress decrease had a linear relation with vibration amplitude. To clarify mechanism of ultrasonic on metal deformation, Hirao et al. (2000) conducted observations for dislocation structure with TEM and found that the mobility and rearrangement of dislocations was drastically improved by ultrasonic vibration. Bunget and Ngaile (2011) applied ultrasonic vibration during micro-extrusion, and they concluded that the vibration could reduce friction and forming load during the metal forming process. Hung and Tsai (2013) carried out ultrasonic vibration-assisted micro-upsetting of brass. The results demonstrated the size effect that the flow stress decreased as the specimen was miniaturized. Different size specimens were compressed and influences of ultrasonic were analysed qualitatively.

The objectives of this study are to reduce surface roughness of metal foils by micro-forging process with presence of ultrasonic vibration, and state the mechanisms of ultrasonic vibration induced-improvement. In this work, surface roughness reduction at different conditions is carried out to obtain effect of ultrasonic vibration on surface finishing and the mechanism is discussed with surface grain model.

2. Experimental setup

The ultrasonic vibration-assisted surface deformation system contains an ultrasonic generator (USG-30), a load transducer, a signal amplifier and a data recorder (OMRON ZR-RX 70). Fig. 1 shows the picture and schematic of the system. The ultrasonic vibration frequency is 100 kHz and the maximum amplitude is 2 μm.

![Fig. 1. Ultrasonic vibration-assisted surface deformation system.](image)

The system is fixed on a precision desk top servo press system (DT-J312, Bisai-Kako Inc). The top board of the press machine is able to move at different speed (0.01~300 mm/s) both automatically and manually with maximum load of 30 kN. The motion resolution of the top board in vertical direction is 1 μm. The load transducer is located between the punch and the top board of the press machine. The punch used for surface finishing is made of tungsten-carbide alloy, and the diameter is 1 mm (Fig. 2). The punch surface was polished to $R_a$ surface roughness...
of 12 nm. The $R_a$ and $R_z$ surface roughness is measured with Atomic Force Microscope (KEYENCE Nanoscale Hybrid Microscope VN-8010), and the scanning area is set to $50 \times 50 \mu m$ for the measurement.

Fig. 2. Punch used for ultrasonic-assisted surface deformation.

To evaluate influences of process conditions including vibration amplitude and initial static stress on surface finishing, $\Delta R_a$ and $\Delta R_z$ roughness at different conditions were measured. The experimental settings are shown in Table 1. Specimens made from brass C3604 (JIS) foils with thickness of 100 $\mu m$ and grain size of 4 $\mu m$ were employed and cut into $10 mm \times 10 mm$ pieces for the experiment. The $R_a$ surface roughness of foils before treatment is around 96 nm. Pre-treatment was made for all samples to get rid of oxidation layer. No annealing process was conducted. Due to analysis of previous research (Bai and Yang, 2013), most of surface asperities plastic deformation takes place in the beginning stage of process, and if duration time is not very short, the influence of time is slight. So the vibration time is not investigated and the duration time is set to 3 seconds. $\Delta R_a$ and $\Delta R_z$ can be expressed as:

$$\Delta R_a = \frac{R_{a0} - R_a}{R_{a0}} \times 100\% ,$$

$$\Delta R_z = \frac{R_{z0} - R_z}{R_{z0}} \times 100\% ,$$

where $R_{a0}$ and $R_{z0}$ is the initial $R_a$ and $R_z$ roughness.

Table 1. Amplitudes and initial static stresses employed in ultrasonic-assisted surface finishing.

<table>
<thead>
<tr>
<th>Number</th>
<th>Amplitude: A ($\mu m$)</th>
<th>Initial static stress: $\sigma_0$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4 ~ 2</td>
<td>127</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>25.5 ~ 254.8</td>
</tr>
</tbody>
</table>

When different loads are applied on punch, the elastic deformation of punch will be different. If the amplitude is larger than elastic deformation, the punch will separate and compress specimen surface periodically, otherwise the punch keeps pressing specimen all through the process. In previous research, the author investigated influences of low frequency (frequency $<1000Hz$) vibration on metal foils surface deformation (Bai and Yang, 2014). It was found that impact effect was a very important factor for larger plastic deformation of metal. In this paper, the ultrasonic amplitude is smaller, and according to the measurement results, it is found that when static load is larger than 20 N, the punch keep compressing sample during the process, impact effect will be quite limited. Hence the impact effect is ignored in this paper.

3. Experimental results

3.1. Influences of ultrasonic vibration amplitude on surface finishing

Fig. 3 shows the surface topographies processed before and after micro-forging. As seen in the figure, there are many micro asperities formed during rolling process on the metal foils surface. In the process of surface finishing, when the stress applied on surface asperities exceeds yield stress of the material, plastic deformation occurs, and the asperities are compressed to be flatter. Based on this figure, it is found that compared with the samples surface before treatment, the surface asperities are compressed and $R_a$ surface roughness is lower.

According to the measurement of $R_a$ and $R_z$ roughness reduction shown in Fig. 4, it is found that even no ultrasonic vibration is applied, the $\Delta R_a$ and $\Delta R_z$ reduce by 18.1% and 21.8% respectively. Nevertheless, when ultrasonic vibration is applied, $\Delta R_a$ and $\Delta R_z$ is much higher, both increase with amplitude linearly. $R_a$ reduction
increases from 23.1% at amplitude of 0.4 μm to 41.6% at 2.0 μm; on the other hand, the $R_z$ reduction increases from 26.4% at 0.4 μm to 42.8% at 2.0 μm.

![Fig. 3. Comparison of surface topographies before and after micro-forging.](image)

Fig. 4. Surface roughness reduction at different amplitudes with same static stress.

3.2 Influence of initial static stress on surface finishing

![Fig. 5. Surface roughness reduction at different initial static stresses. (a) $R_a$ (b) $R_z$.](image)

Different initial static stresses were used in surface finishing. The relations between $\Delta R_a$ and initial static stress are shown in Fig. 5. Conspicuously, $\Delta R_a$ and $\Delta R_z$ increase with initial static stress linearly regardless of ultrasonic vibration. When ultrasonic is applied, $\Delta R_a$ and $\Delta R_z$ have sizeable improvement compared with that of without ultrasonic. For the static process, the maximum increase of $\Delta R_a$ is around 25%, this value is nearly 50% for the cases with ultrasonic vibration. Similar conclusions could be drawn for $\Delta R_z$. 
4. Discussions

As mentioned above, when the amplitude is small and static stress is larger than 20 N, the influences of impact effect could be ignored. Although the static stress applied on foils surface is only 127 MPa, which is much lower than yield stress of the material, considerable plastic deformation takes place on surface asperities. Foils surface asperities deformation is actually micro compression of surface asperities. However, the small size of asperities makes the deformation differs from macro process due to size-induced deformation behavior (Geiger et al., 1994). It is well known that the material flow stress has a close relation with dislocation density: in normal metal materials, with higher dislocation density, the dislocation motion is more difficult, and the material could endure higher stress, leading to a higher flow stress. As the mobility of dislocation increases because of ultrasonic stimulation (Lasgesecker, 1966), more dislocations annihilate on the surface of samples, which results in less dislocation tangling and lower dislocation density in surface layer grains, and this makes the surface layer easier to deform compared with inner grains.

Based on the surface grain theory (Lai et al., 2008), the material flow stress is a compromise of the property of surface layer grains and inner grains. Given the surface grains become softer, the material would be easier to deform. As the specimens size downscaling, the surface / total grains ratio increases, and the ultrasonic softening effect will increase.

On the metal foils surface, there are many asperities and valleys formed in rolling process as shown in Fig. 3. These asperities and valleys increase surface grains area, leading to a softer surface layer. To investigate surface / total grain ratio of foils quantificationally, a simplified surface model was proposed to represent the real foil surface as shown in Fig. 6.

![Fig. 6. Simplified surface profile (a) real surface profile (b) simplified surface profile.](image)

In Fig. 6, \(a\) is a constant to be determined representing surface asperities width, \(h\) is asperities height, \(l\) is a given length, \(n\) is twice of the number of asperities in the given length \(l\), \(t\) is thickness of deformation area. Based on the simplified surface model, \(h\) has a relation with \(R_z\) surface roughness as follows:

\[
R_z = 2h.
\]  

Unlike conventional sheet metal forming processes such as tensile and deep drawing, the deformation area across all the whole section, in the surface deformation, the plastic deformation takes place only on the surface of the foil, so only the contact surface (top surface) is in consideration, and \(t\) is set 20 \(\mu m\) in this research.

In the simplified model shown in Fig. 6 (b), the surface grain number \(N_{sur}\) could be obtained using Eq. (4). The expressions of total grains number \(N\) and surface / total grains ratio \(\eta\) could be written in Eqs. (5) and (6), where \(S_c\) is area of cross section, \(s\) is area of a single grain.

\[
N_{sur} = (n\sqrt{a^2 + h^2})/d - 0.5n,  
\]

\[
N = S_c/s = (lt)/(\pi d^2) = (4tna)/(\pi d^2),
\]

\[
\eta = N_{sur}/N = ((\pi d\sqrt{4a^2 + R_z^2})/(8ta)) - ((\pi d^2)/(8ta)) = (\pi d\sqrt{4a^2 + R_z^2})/(4ta) - (\pi d^2)/(8ta).
\]

Value of constant \(a\) could be obtained as follows: assume an absolute smooth surface, the \(R_z\) equates to 0, and there are only one grains layers, the surface / total grains ratio equates to one, and \(d\) equates to \(t\), applying \(t=d\), \(R_z=0\) and \(\eta=1\) in Eq. (6), the value of \(a\) could be obtained as 4.82 \(\mu m\). This means the asperities width is 9.64 \(\mu m\), which is quite close with the observed results. The initial \(R_z\) surface roughness of sample is 1061 nm.
Substitute $R_z$, $t$, $d$ and $a$ in Eq. (6), the calculated value of $\eta$ is 39.2%. The high $\eta$ value suggests large surface grain area and the dislocations are more prone to annihilate on the grain surface than macro deformation process. Dislocation tangling and pile-up in the surface grains is fewer, hence slip system movement is easier compared with the inner grains which reduces deformation resistance of the material. As a result, plastic deformation of metal foil takes place even the stress is low.

5. Conclusions

The influences of ultrasonic vibration on surface finishing are investigated in this study. Metal foils surface is compressed with ultrasonic vibration at different amplitudes and initial static stresses. The results show that with presence of ultrasonic vibration, plastic deformation of surface asperities is increased significantly. Surface roughness reduction is approximately linear to ultrasonic vibration and initial static stress. By calculating surface / total grain ratio of metal foils with a simplified model, it is found that the high surface / total grain ratio due to surface asperities should be responsible for the large surface roughness reduction.

References


