Experimental Study of High-Frequency Vibration Assisted Micro/Mesoscale Forming of Metallic Materials

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Abstract
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Disciplines
Manufacturing | Metallurgy

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Micro/mesoscale forming is a promising technology for mass production of miniature metallic parts. However, fabrication of micro/mesoscale features leads to challenges due to the friction increase at the interface and tool wear from highly localized stress. In this study, the use of high-frequency vibration for potential application in micro/mesoscale forming has been investigated. A versatile experimental setup based on a magnetostrictive (Terfenol-D) actuator was built. Vibration assisted micro/mesoscale upsetting, pin extrusion and cup extrusion were conducted to understand the effects of workpiece size, excitation frequency, and the contact condition. Results showed a change in load reduction behavior that was dependent on the excitation frequency and the contact condition. The load reduction exhibited in this study can be explained by a combination of stress superposition and friction reduction. It was found that a higher excitation frequency and a less complicated die-specimen interface were more likely to result in a friction reduction by high-frequency vibration. [DOI: 10.1115/1.4004612]

Keywords: microforming, vibration, micro/mesoscale, friction

Introduction

There has been an increasing demand for 3D micrometallic parts for applications in microelectronics, biotechnology, optics, renewable energy, and environmental monitoring [1]. Scaling-down of the traditional metal forming processes, known for their high production rates and low equipment cost, has attracted much attention for mass-production of micro/mesoscale metallic parts [2–5]. The micro/mesoscale forming is the metal forming process with a feature size in micro/mesoscale typically ranging between 0.01 and 10 mm [6]. There are still numerous challenges that need to be addressed to expedite the technology transfer for market penetration [7]. The challenges for micro/mesoscale forming include reduced tool life due to high stress regions, severe tribological conditions induced by higher surface-to-volume ratio, and low surface quality of the final part [6]. High-frequency vibration applied in macroscale forming processes has shown to reduce the forming load, improve the tribological conditions, and enhances the surface finish [8]. Therefore, application of high-frequency vibration in micro/mesoscale forming can potentially aid in overcoming the challenges mentioned above. There are several difficulties, however, in developing vibration assisted micro/mesoscale forming system, which include understanding the mechanism of vibration in micro/mesoscale system and minimizing the complexity of integrating a vibration module.

In this study, a versatile apparatus for vibration assisted micro/mesoscale forming was developed. Experiments were conducted for vibration assisted micro/mesoscale upsetting, pin extrusion and cup extrusion to understand the effects of the excitation frequency and the contact condition on the process. Characteristics of the vibration assisted forming in micro/mesoscale system were identified and compared with the traditional macroscale system based on an oscillation model.

Background on Vibration Assisted Metal Forming

The application of high-frequency vibration in macroscale metal forming has attracted significant interest, since the 1950s [9]. High-frequency vibration has been applied to various metal forming operations including wire drawing [10–12], tube drawing [13–15], extrusion [16–18], bending [19], deep drawing [20], press forming [21], and upsetting [22–24]. The findings from these studies have consistently shown the significant improvement by high-frequency vibration in reducing the forming load and enhancing the part quality [8]. On the contrary, there are only a few scattered reports on actual adoption of the technology by the industry in macroscale metal forming processes. One major reason...
for this is the large energy consumption to excite the heavy tool and the complications to keep the system at the resonant condition [25]. Recently, several studies [26,27] investigated applying high-frequency vibration in the micro/mesoscale forming processes. They have found promising results on forming load and surface finish by vibration based on a carefully designed resonant system [26,27]. As the die system and the sample become smaller, it is expected that significant effect of high-frequency vibration can be obtained in micro/mesoscale system with less vibrational energy or even at off-resonant condition.

The significant effects of high-frequency vibration on the forming processes have been validated, although the mechanism that explains these benefits is somewhat less clear. It has been widely accepted that the influence of high-frequency vibration can be classified as a volume effect and a surface effect [8,25,28]. The volume effect of high-frequency vibration is generated by the strain or stress oscillation in the workpiece. The oscillations superimposed, during the forming process are scattered and absorbed, leading to stress superposition and acoustic softening. Stress superposition is caused by an “unloading” effect in a material and thus reduces the average load. This phenomenon is discussed in detail in reference literature [29,30]. The mechanism of acoustic softening can be attributed to the absorption of acoustic energy in the highly localized regions, such as dislocations, voids, and grain boundaries [31,32]. The surface effect, occurring at the contacting interfaces between the workpiece and the die, is related to the change in frictional behavior. A high-frequency vibration triggers relative motion at the interfaces and leads to friction reduction, which is widely supported by several fundamental studies [33–36]. These studies show that the friction reduction only occurs when the relative velocity at the interface is larger than a critical value. As the process and system are scaled down for vibration assisted forming, it is also important to understand the miniaturization effect on the system behavior and governing mechanisms.

Experimental Setup

A versatile apparatus was designed and constructed to study the effect of high-frequency vibration on micro/mesoscale forming as shown in Fig. 1 Ref. [30]. There were two drives, which include a DC motor (071-300-0058, Bison) supplying the forming motion and static force, and a magnetostrictive (Terfenol-D) actuator (CU-18, Etrema Products Inc.) applying the high-frequency oscillation during the forming process. Magnetostrictive and piezoelectric actuators have their own advantages and disadvantages. Terfenol-D actuators are known for their larger blocked force, larger maximum no-load velocity, and larger maximum output capacity provided by the Terfenol-D actuator makes it suitable for vibration-assisted forming. In addition, magnetostrictive actuators can produce significant output vibration even at off-resonant condition due to their wider resonance peaks. Vibrations waves generated by the Terfenol-D actuator propagated through the horn to the die system. The horn (Etrema Products Inc.) was designed with a natural frequency of around 18 kHz. A force sensor (9133B, Kistler) coupled with a charge amplifier (5010B, Kistler) was used to measure the high-frequency force. A laser displacement sensor (optoNCDT 1401, Micro-Epsilon) measured the displacement of the stage carrying the actuator.

A simple fixture using copper wire has been made to hold the sample before the upsetting process. The position of the sample can also be adjusted based on this fixture to keep the sample at the center of the dies. The copper fixture is just used to aid the positioning of the sample and does not interfere during the upsetting process. A MATLAB/Simulink xPC Target was developed to control the system. The schematic block diagram of the control system is shown in Fig. 2. In this study, various vibration frequencies were investigated for comparison. However, the output amplitude of the horn tip may be different for various frequencies even with the same input amplitude of the excitation current. This is mainly due to the nonlinear properties of the Terfenol-D. To compensate for this nonlinear response, an effective control system has been developed. The displacement of the horn tip at different frequencies has been measured by using an inductive displacement sensor (SMU-9000, resolution 0.1 µm, Kaman). The amplitude of the vibration was then captured by a lock-in amplifier (SR830, Stanford Research Systems). The compensation control system was able to maintain the vibration amplitude of the horn tip nearly constant through-out the frequency ranges between 5 and 10 kHz.
The details of the control system are introduced in another publication [39].

The die system was flexibly designed to incorporate various micro/mesoscale forming processes, which include upsetting, pin extrusion and cup extrusion as shown in Fig. 1. Pure aluminum (99.99%) specimens with a diameter of 2 mm were cut in two lengths: 2 mm (for upsetting and pin extrusion) and 3.5 mm (for pin extrusion). All specimens were annealed at 320°C for 1 h to remove any prior work hardening. The parameters used in the experiments are listed in Table 1.

### Experimental Results

#### Sweeping Test of the System

A sweeping test was conducted to check the frequency response and investigate the resonant frequency of the system. The sweeping signal applied to the Terfenol-D actuator was sinusoidal signal generated by a function/arbiter waveform generator (33220A, 20 MHz, Agilent). The response signal was detected by the force sensor. The results validated that there is a significant resonant peak around 18 kHz. The working frequency range was selected at 5–10 kHz, where there was no significant peak or valley. This range is far from the resonant peak, therefore, the frequency response at this range is relatively low but flat. In addition, based on the compensation control system, the amplitude of the vibration became more uniform at the range of 5–10 kHz. A sweeping result in the working frequency range with an input amplitude of 5 V is shown in Fig. 3. It can be seen that the change of the vibration amplitude with various frequencies is negligible. The results also confirmed the design and the effectiveness of the active compensation control system.

Additional tests were conducted to understand the response of the system at the working frequency range. The vibration at different locations in the system, such as the platform and the slider, was detected by an accelerometer (352A24, PCB Piezotronics Inc.). The results supported that the vibrations at other locations in the system were negligible compared with the vibration in the die/workpiece system.

#### Vibration Assisted Micro/Mesoscale Upsetting

Experiments were conducted for micro/mesoscale upsetting using the apparatus shown in Fig. 1(d). Vibration with excitation frequencies in the range of 5–10 kHz was cycled on for an interval during the micro/mesoscale forming process. The experimental results with various excitation frequencies have been compared. Since the working frequency range is far from the resonant peak (around 18 kHz), the effect of the natural frequency on the results is considered to be minor. The parameters applied in the experiments are listed in Table 2. The voltage amplitude of the signals applied to Terfenol-D actuator was 40 V for various excitation frequencies. The power applied to the actuator, which varied for different frequencies, was around 16 W at the working frequency range. There was no lubricant used in the experiments.

At least three experiments were conducted for each setting, and the results were repeatable within approximately ±5%. Typical results of micro/mesoscale upsetting with an interval of superimposed high-frequency excitation of 6, 7.5, and 9 kHz are shown in Fig. 4. When vibration with a frequency of 6 kHz was applied, the mean load reduced immediately due to the stress superposition. The load immediately recovered when vibration was stopped. No permanent influence was detected after the vibration stopped. When the vibration was applied, the path of maximum oscillatory force, shown as the dashed line, was nearly consistent with the static force without vibration. This phenomenon can be explained by the stress superposition of high-frequency vibration. When vibration with a frequency of 7.5 kHz was applied, the average load and the path of maximum oscillatory force fell below the static load without vibration. This result cannot be totally explained by stress superposition. It is likely that the higher excitation frequency resulted in higher relative velocity and induced friction reduction. Therefore, the reduction of load in Fig. 4(b) can be explained by the combined effect of stress superposition and friction reduction. A similar response was observed in the macroscale upsetting processes [22]. When vibration with a frequency of 9 kHz was applied, a similar trend to that seen for 7.5 kHz was observed, but the effect of high-frequency vibration became more significant. The results under three frequencies showed that increasing the excitation frequency led to an enhanced friction reduction effect. When vibration frequency was between 9 and 10 kHz, the load reduction effect was similar. There was no evidence for the emergence of a significant acoustic softening shown in these results.

#### Vibration Assisted Micro/Mesoscale Pin and Cup Extrusion

Experiments were also conducted for micro/mesoscale pin extrusion and cup extrusion. The parameters used in the experiments were also consistent with the upsetting processes. Typical results of micro/mesoscale pin extrusion and cup extrusion with several intervals of superimposed 9 kHz harmonic excitation are shown in Figs. 5 and 6, respectively. The mean load is reduced when vibration of 9 kHz is applied. The path of maximum oscillatory force is detected to be consistent with the static force without vibration. Therefore, stress superposition is considered to be the dominant effect of load reduction in both the pin and cup extrusion processes.

### Table 1 Dimensions of dies and samples used in the experiments

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Values (mm)</th>
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</thead>
<tbody>
<tr>
<td>Upsetting</td>
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<tr>
<td>Sample diameter</td>
<td>2.0</td>
</tr>
<tr>
<td>Sample length</td>
<td>2.0</td>
</tr>
<tr>
<td>Pin extrusion</td>
<td></td>
</tr>
<tr>
<td>Inlet diameter</td>
<td>2.0</td>
</tr>
<tr>
<td>Sample length</td>
<td>3.5</td>
</tr>
<tr>
<td>Exit diameter</td>
<td>1.2</td>
</tr>
<tr>
<td>Cup extrusion</td>
<td></td>
</tr>
<tr>
<td>Sample diameter</td>
<td>2.0</td>
</tr>
<tr>
<td>Sample length</td>
<td>2.0</td>
</tr>
<tr>
<td>Punch diameter</td>
<td>1.2</td>
</tr>
</tbody>
</table>

### Table 2 Parameter values used in the experiments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
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<td>Speed of the punch (generated by the motor)</td>
<td>0.08 mm/s</td>
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<tr>
<td>Amplitude of signals applying to the actuator</td>
<td>40 V</td>
</tr>
<tr>
<td>Vibration amplitude at the horn tip (no load)</td>
<td>1 μm</td>
</tr>
<tr>
<td>Duration of the vibration</td>
<td></td>
</tr>
<tr>
<td>Upsetting</td>
<td>3 s</td>
</tr>
<tr>
<td>Pin extrusion</td>
<td>3 s</td>
</tr>
<tr>
<td>Cup extrusion</td>
<td>2 s</td>
</tr>
</tbody>
</table>
extrusions. While 9 kHz excitation frequency was enough to cause the friction reduction in upsetting, it was not high enough in pin and cup extrusions with the same amplitude. The photograph of samples fabricated by vibration assisted micro/mesoscale forming is shown in Fig. 7.

Discussion

A simplified 1D oscillation model, illustrated in Fig. 8, has been developed to discuss the characteristics of the vibration assisted forming in micro/mesoscale. This simplified model is used to help explain and understand some of the experimental phenomena in conjunction with the physical nature of the system. Several influencing factors on vibration assisted forming process, including size scaling, excitation frequency and the contact condition, are discussed.

In the oscillation model, two ends of the workpiece are assumed to be in contact with a die and an oscillatory component, which are represented by a contact spring, respectively, \((k_1\) and \(k_2\)). The die/punch–sample interface in extrusion processes was simplified as a flat surface in this model; however, the contact stiffness was estimated based on the actual interface in extrusion processes to capture the contact condition at the interfaces. The workpiece has cross-sectional area \(A\), length \(L\), mass density \(\rho\), and Young’s modulus \(E\). The input is \(x(t) = x_0 \sin(\omega t)\) with an excitation frequency of \(f = \omega / 2\pi\). The stress and strain are considered to be uniformly distributed within the cross-section of the sample. Then, the stress and strain along the axial direction can be analytically solved. Furthermore, the time-dependent stress field \(\sigma(x,t)\) in the workpiece and the relative velocities at the two interfaces \(\delta_1(t)\) and \(\delta_2(t)\) can be obtained (See Appendix for the solution procedure).

Fig. 4 Load–displacement curves of micro/mesoscale upsetting with an interval of superimposed vibration at (a) 6 kHz, (b) 7.5 kHz, and (c) 9 kHz

Fig. 5 Load–displacement curve of micro/mesoscale pin extrusion with three intervals of superimposed high-frequency excitation

Fig. 6 Load–displacement curve of micro/mesoscale cup extrusion with two intervals of superimposed high-frequency excitation

Fig. 7 The photograph of the samples fabricated by vibration assisted micro/mesoscale forming
Mechanisms of Load Reduction by Vibration. The volume effects induced by the high-frequency vibration include two typical mechanisms, acoustic softening and stress superposition. The effect of acoustic softening is closely related to the input and the coupling of the acoustic energy in the system [40]. Previous studies have found that the effect of acoustic softening was not easily obtained even at resonant conditions [40]. The tests were conducted at off-resonant conditions, therefore, it is not surprising that the effect of acoustic softening was not evidently detected based on the current setup. However, acoustic softening may emerge if the system works at resonant condition or the excitation amplitude is significantly increased. The load reduction by stress superposition is generated from the elasto-plastic properties of the metallic materials [30], which directly depends on the stress oscillation in the workpiece. The effect of stress superposition appeared in all the processes in this study, including upsetting, pin extrusion, and cup extrusion. Since the volume effects induced by the high-frequency vibration are closely related to the stress oscillation in the workpiece, the amplitude of stress oscillation in the workpiece, \(S(x)\), can be regarded as an indicator of the volume effect.

The surface effect induced by the high-frequency vibration mainly leads to friction reduction at the interfaces. There are several mechanisms that discuss the friction reduction caused by high-frequency vibration when a lubricant is used [10,28,41]. However, a lubricant layer will make it difficult to identify the mechanism contributing to the friction decrease. In this study, friction was significantly reduced by vibration in the upsetting process without using a lubricant. Besides the mechanisms related to lubrication, the friction reversal effect is another friction reduction mechanism that has been discussed in several previous studies [34,36]. However, it is not applicable to the upsetting condition due to the configuration of the process. In this study, the reduction of time-averaged real contact area is considered to be a possible explanation for the friction decrease. The real area of contact, which depends on the normal force, has direct influence on the contact friction [42]. Applying vibration leads to a fluctuation of the real contact area, and thus results in an overall decrease of the radial friction force. As an extreme case, when the vibration amplitude or the frequency increases to a very large magnitude, the real contact area may become zero during short periods in a vibration cycle. This extreme case has been discussed in several previous studies, which is often referred to as “separation mechanism” [10,28]. No matter which mechanism is used to explain the friction reduction, the vibration-induced friction reduction depends on the relative vibration at the interfaces [10,36]. The increase of the relative velocity at the two interfaces leads to higher likelihood of friction reduction. Therefore, the amplitude of the relative velocities at the two interfaces \(\Delta_1\) and \(\Delta_2\) can be regarded as indexes for the friction reduction effect by high-frequency vibration.

Workpiece and System Size Scaling. When a forming process is scaled down to micro/mesoscale, the tribological conditions become very critical due to the increasing surface-area-to-volume ratio [6,43]. This may result in so-called size effects originating from nonproportional scaling aspects of a process when miniaturization occurs. Taking the upsetting process as an example, the workpiece-die contact and the workpiece-horn contact can be modeled as a elastic contact between a cylindrical flat indenter and a flat surface [44]. Then the contact stiffness \(k_1\) and \(k_2\) can be expressed as

\[
k = 2\pi E^*\]

[1]

where,

\[
\frac{1}{E^*} = \frac{1}{E_1} - \frac{1}{E_2}
\]

[2] can be expressed as

\[
\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}
\]

where, \(E\) is the radius of workpiece; \(E_1\) and \(E_2\) are the Young’s moduli; and \(\nu_1\) and \(\nu_2\) are the Poisson’s ratios associated with each contacting body. Equation (1) shows that the contact stiffness varies when the workpiece size changes. The die material and workpiece were steel and aluminium, respectively. Parameters used in the subsequent calculations are listed in Table 3.

The effect of excitation frequency on the stress field in a miniature workpiece was investigated based on the above model and assumptions. The stress at different locations along the workpiece was calculated using Eq. (A3) in the Appendix. The results are shown in Fig. 9. The stress in the workpiece had no significant variation for different locations along the workpiece with relatively low frequencies up to 80 kHz. Nodes and antinodes could only be obtained with extraordinary high excitation frequencies for micro/mesoscale workpiece. A vibration actuator with a frequency around 20 kHz is typical in vibration assisted forming [26,45]. In this frequency range, there is nearly uniform amplitude of stress oscillation for different locations along the workpiece. Therefore, the stress oscillation amplitude, \(s_0\), at a single point at \(x = 0\) was selected to represent the stress field in the workpiece.

The predicted scaling effects on the stress oscillation in the workpiece and the relative velocity at the interfaces are shown in Fig. 10. It is clear that there is an increasing stress oscillation when the workpiece is scaled down. Therefore, vibration assisted forming may achieve more significant volume effect for the workpiece in the micro/mesoscale. For smaller workpiece, a more uniform surface effect is expected at both ends of the workpiece from the relative velocity response at the interface. This is opposed to large scale upsetting with vibration applied to one end which showed that the effect was significant at only one end of the workpiece [46].

Excitation Frequency. In vibration assisted forming, the vibration may be applied either at resonate condition or at off-resonate condition [25]. Excitation at resonate condition potentially provides large oscillation amplitude, and therefore, is the typical design approach in the macroscale vibration assisted systems [47]. However, if the sample geometry undergoes a significant change during the forming processes, the resonant frequency will vary in the processes. For this case, additional online control system is required to adjust the system to always work at resonant

### Table 3 Parameter values used in the simulation

<table>
<thead>
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<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Yong’s modulus of the workpiece</td>
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</tr>
<tr>
<td>Equivalent modulus at the interfaces</td>
<td>59.3 GPa</td>
</tr>
<tr>
<td>Density of the workpiece</td>
<td>2.7 g/cm³</td>
</tr>
<tr>
<td>Amplitude of the input vibration</td>
<td>1 μm</td>
</tr>
</tbody>
</table>

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frequency, which may be difficult and challenging. In addition, the system becomes more complex and not flexible [25]. Nearly all the prior studies on vibration assisted forming focused only on one excitation frequency (usually at resonate frequency) because the effect of vibration at other frequencies was too poor to have any significant impact. Consequently, there were only a few studies discussing the influence of different excitation frequencies in vibration assisted forming [29]. The magnetostrictive actuators adopted for this study have wider bandwidths when compared with commonly used piezoelectric actuators, and thus are capable of providing larger amplitude of oscillations even at off-resonance conditions. On the other hand, as shown in Fig. 10, the oscillation in the workpiece can be significantly increased when the workpiece is scaled down to micro/mesoscale. Therefore, the forming load in micro/mesoscale can be significantly reduced even at an off-resonant condition. If there is no requirement to tune the system to the resonant condition, vibration assisted microforming will become more versatile, wide-range and suitable for industrial application.

Using the model demonstrated in Fig. 8, the predicted effects of excitation frequency on stress oscillation in the workpiece and the relative velocity at the interfaces are shown in Fig. 11. It demonstrates that the effect of excitation frequency on the amplitude of the stress oscillation is negligible when the frequency is below 20 kHz. However, increasing the excitation frequency will definitely increase the relative velocity at the two interfaces. Therefore, a relatively high excitation frequency is likely to trigger the friction reduction effect. These predicted results clearly agree with the experimental results for vibration assisted micro/mesoscale upsetting shown in Fig. 4.

Contact Condition. The contact condition is related to the die/workpiece material and interface geometry. In pin and cup extrusion, contact between the workpiece and die becomes a conforming contact at some interfaces [48] resulting in higher stiffness than the contact in upsetting. This effect is captured in the model of Fig. 8 by adjusting the values of \( k_1 \) and \( k_2 \), appropriately. The effects of contact stiffness on stress oscillation in the workpiece and the relative velocity at the interfaces are shown in Fig. 12. From Fig. 12(a), it can be seen that an increase of contact stiffness leads to higher stress oscillation in the workpiece. This implies that a larger contact stiffness leads to a more significant effect of stress superposition. Comparing Fig. 4 with Fig. 6, it can be found that the vibrational stress in the extrusion is larger than the one in the upsetting. This phenomenon can be explained by that the contact stiffness in the extrusion is relatively larger. The predicted results also indicate that acoustic softening is more likely to be achieved with a securer connection between the workpiece and the excitation source. For example, a very significant acoustic softening was achieved using a threaded connection in a tensile test with ultrasonic vibration [31]. Figure 12(b) shows that the relative velocities at the interface will increase when the contact stiffness is reduced. This means that a forming process with unsecure contact condition is more likely to result in a friction reduction by vibration. Figure 12(b) shows the stress oscillation in the workpiece and the relative velocity at the interfaces by changing the \( k_1/k_2 \) ratio. When \( k_2 \) has a fixed value, the increase of the contact stiffness \( k_1/k_2 \) ratio leads to higher stress oscillation in the workpiece. The interface with lower contact stiffness will have larger relative velocity, and therefore, is more likely to achieve friction reduction.

From the predicted results in Fig. 12(a), the relatively lower contact stiffness \((k)\) leads to larger relative velocities \((\Delta_1 \text{ and } \Delta_2)\) at the die-specimen interfaces. The contact stiffness at the die-workpiece interface is much larger in pin and cup extrusions than in upsetting. Therefore, friction reduction is more likely to occur in the upsetting process than the pin/cup extrusions. The experimental results also support this analysis. For the case of upsetting with simple contact condition, and therefore, low stiffness, 9 kHz was enough to induce the friction reduction behaviour (see Fig. 4(c)). On the other hand, friction reduction was not observed in pin and cup extrusions (see Figs. 5 and 6).

Conclusions and Future Work

The characteristics and mechanisms of vibration assisted forming in micro/mesoscale were investigated in this study. Micro-mesoscale upsetting, pin extrusion and cup extrusion were performed to understand the load reduction behavior of high-
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Appendix: Derivation of Model Equation

A 1D oscillation model is developed to analyze the vibration assisted forming process as shown in Fig. 8. The workpiece is simplified as a cylinder. Two ends of the workpiece are assumed to be in contact with a die and an oscillatory component, which are represented by a contact spring, respectively. The die is modeled as a rigid body, and the oscillatory part is modeled as a harmonic vibration source. Since there are only metals in the oscillation system, it is considered as a weak-damping system. Therefore, the damping is neglected in the calculation. The workpiece is simplified as an elastic body in the vibration analysis.

The workpiece has volume $A L$, mass density $\rho$, and Young’s modulus $E$. The input is $x_d(t) = x_d \sin \omega t$ with an excitation frequency of $f = \omega / 2\pi$. Therefore, the steady state response of the displacement field $u(x, t)$ in the workpiece is governed by the partial differential equation [49]

$$E \frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2}$$

(A1)

with boundary conditions

$$\frac{\partial u}{\partial x} \bigg|_{x=0} = \frac{k_1 u(0, t)}{E A} \quad \text{and} \quad \frac{\partial u}{\partial x} \bigg|_{x=L} = \frac{k_2 [u(x, t) - u(L, t)]}{E A}$$

(A2)

where $k_1$ and $k_2$ are the contact stiffness of the two contact springs denoted in Fig. 8. The oscillation system governed by Eqs. (A1) and (A2) can be analytically solved. Substituting $x = x(t) = x_0 \sin \omega t$ into the solution, the time-dependent stress field in the workpiece can be obtained as

$$\sigma(x, t) = \frac{[E r k_1 k_2 \cos(rx) - E^2 A r^2 k_2 \sin(rx)] X_0 \sin \omega t}{E A (k_1 + k_2) \cos(rL) - (E^2 A r^2 - k_1 k_2) \sin(rL)}$$

$$= S(x) \sin \omega t$$

(A3)

where $r = \sqrt{\rho / E \omega}$. The effects of stress superposition and acoustic softening are closely related to the stress oscillation in the workpiece. Consequently, the amplitude of stress oscillation, $S(t)$, can be regarded as an indicator of the volume effect due to high-frequency vibration.

The relative velocities at the two interfaces can be expressed as

$$\delta_1(t) = \frac{d[u(0, t) - 0]}{dt} = \frac{E A r k_2 X_0 \cos \omega t}{E A (k_1 + k_2) \cos(rL) - (E^2 A r^2 - k_1 k_2) \sin(rL)}$$

$$= \Delta_1 \cos \omega t$$

(A4)
\[ \delta_1(t) = \frac{d[u(t)]}{dt} - u(L, t) \]
\[ = \frac{E \alpha k_1 \cos(rL) - E^2 \alpha^2 r^2 \sin(rL)\alpha_k \cos \omega t}{\rho} \]
\[ = \Delta_2 \cos \omega t \]

(AS5)

where \( \Delta_1 \) and \( \Delta_2 \) are the amplitude of the relative velocities at the two interfaces. Since the surface effect is related to the vibration at the interface, the increase of the relative velocity at the two interfaces leads to higher likelihood of friction reduction [10]. Therefore, \( \Delta_1 \) and \( \Delta_2 \) can be regarded as indexes for the friction reduction effect by high-frequency vibration.

References