Micro Pin Extrusion of Metallic Materials Assisted by Ultrasonic Vibration

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Abstract
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Keywords
extruding, vibration

Disciplines
Manufacturing | Metallurgy

Comments

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MICRO PIN EXTRUSION OF METALLIC MATERIALS ASSISTED BY ULTRASONIC VIBRATION

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ABSTRACT

Micro extrusion is an economically competitive process to fabricate micro metallic parts. However, fabrication of extremely small geometric features leads to challenges in tool wear due to localized high stress and friction increase at the interface. This study focuses on micro pin extrusion of aluminum with assistance of ultrasonic vibration. Experiments were conducted with and without ultrasound using magnetostrictive actuator. Load-displacement curves from the experiments showed a load reduction when ultrasonic vibration was applied. Experiments of ultrasonic micro pin extrusion with two configurations were performed. The load reduction behaviors at off-resonance and in-resonance conditions were compared. The reduction can be explained by stress superposition of ultrasonic vibration.

KEYWORDS
Microforming; ultrasonic vibration; extrusion; stress superposition

INTRODUCTION

There is increasing demand for micro parts for applications in electronics, biotechnology, communication, medicine, optics, renewable energy and environmental monitoring. Microforming is a promising technology due to its high production rates and low equipment cost [1]. The development of various microforming processes was reviewed by Engel et al [2] and Geissdorfer et al [3]. Among microforming processes, micro extrusion can be used to fabricate miniature screws, IC connector pins, micro springs and pins for IC sockets, which attracts great attention these years [4-6]. However, there are still numerous technical challenges that need to be addressed before microforming become a commercially viable manufacturing process. Technical challenges for microforming include severe tribological conditions induced by higher surface-to-volume ratio, short tool life due to high stress regions, and low surface quality of the workpiece.

In macro-scale forming, application of ultrasonic vibration has shown to lower forming loads and reduce friction [7]. The concept of ultrasonic-assisted forming in macro-scale can be traced back to 1950s. Langemecker et al [8] and Schinke et al [9] have done several investigations on ultrasonic superimposed tension test. Lucas et al [10] studied the effect of ultrasonic vibration on compression test recently. There has been applications of ultrasonic vibration in wire drawing [11], tube drawing [12], deep drawing [13]. In particular, there were several studies focusing on ultrasonic-assisted extrusion process [14, 15].

Study on application of ultrasonic vibration in microforming is a recent development. Bunget et al [16] have studied ultrasonic assisted micro-extrusion. In their study, load reduction was detected when ultrasonic vibration was applied. The reduction was explained by friction reduction between tools and workpieces. But the optimization of ultrasonic
frequency and amplitude and the mechanisms of ultrasonic effect on microforming still need to be further investigated.

In this study, micro pin extrusion of pure aluminum was conducted to understand effects of ultrasonic vibration on load reduction. Load reduction behaviors of off-resonance and in-resonance system were compared. The mechanisms of load reduction in ultrasonic assisted micro pin extrusion were discussed.

MECHANISMS OF LOAD REDUCTION BY ULTRASONIC VIBRATION IN FORMING

The load reduction caused by ultrasonic vibration in macro-scale forming has usually been explained by three different mechanisms or combination of them: stress superposition [9], acoustic softening [17] and the friction decrease at the interface [18].

The mechanism of stress superposition effect is explained by Figure 1 [9]. Different stages labeled from 1 to 8 in idealized stress-strain curve and strain-time curve represents material states during oscillation. When ultrasound is applied, the unloading and loading occurs thousands of times per second. Then, the average load will be reduced, which is shown as line ‘AA’ in the diagram. Therefore, the load reduction by stress superposition occurs due to the elastic-plastic property of materials.

![Figure 1 - The Mechanism of Stress Superposition of Ultrasonic Vibration](image)

Acoustic softening is the only mechanism which really changes the material properties among the three typical mechanisms. To achieve detectable material softening, secure coupling of acoustic energy is required [19]. In typical manufacturing setup, however, it is difficult to achieve such condition. Therefore, only few studies have reported a significant acoustic softening during ultrasonic assisted forming processes [7].

Friction reduction by ultrasonic vibration can decrease the forming load. Storck et al [20] explained friction reduction by periodic change in the direction of friction force using Coulomb’s law. They found that friction reduction only happens when the amplitude of harmonic velocity is larger than the forming velocity. There is no friction reduction for small magnitude of ultrasonic vibration.

When ultrasonic vibration is applied in micro/meso scale, with the size-reduction of dies and specimens, the characters of vibration coupling might be changed. Mixed with the scale effect in microforming processes, the effect of ultrasonic vibration on microforming become more complicated and is still an unclear area.

EXPERIMENTAL SETUP AND PROCEDURES

An experimental setup has been designed to study the effect of ultrasonic vibration on micro pin extrusion as shown in Figure 2 [21]. A DC motor (071-330-0058, Bison) was used to control extrusion speed and apply extrusion force. A magnetostrictive actuator (CU-18, Etrema Products Inc.) was used to apply ultrasonic oscillation during micro pin extrusion. A force sensor (9133B, Kistler) with frequency response of 180 kHz was used. The displacement of stage carrying the actuator was detected by a laser displacement sensor (optoNCDT 1401, Micro-Epsilon). All the sensor signals were supplied to xPC Target. The whole system was controlled by a system model built in Simulink.

![Figure 2 - Experimental Setup for Ultrasonic Microforming](image)

The die system for micro pin extrusion was designed and fabricated as shown in Figure 3. Pure aluminum (99.99%) specimens with a diameter of 2 mm were cut in 3.5 mm in length. All specimens have been annealed at 320°C for 1 hour before forming. The extrusion opening is 1.2 mm.

The magnetostrictive actuator can generate vibration up to 20 kHz supplying power up to 500 W. Vibration is amplified while travelling through the designed ultrasonic horn. In a typical design, the horn is usually mounted at a zero amplitude node via a nodal flange [10, 16]. This design can avoid the transmission of the vibration to the rest of structures.
In this study, various frequencies, however, were compared. A zero amplitude node for all different frequencies was then unavailable. Therefore, the horn was designed without any holding flange to avoid transmission of vibration to the rest of the structure. The amplitude of the vibration at the horn tip has been measured to be around 5 μm at off-resonant condition.

Series of tests for ultrasonic assisted micro pin extrusion were conducted. The extrusion speed was 80 μm/s. The tests were stopped at 1200 N to fully extrude samples. With this load limit, the duration of each test was around 40 s. Each condition was repeated at least three times to make sure that the observed phenomena were repeatable. Ultrasonic vibration was turned on and off during the micro pin extrusion. The voltage amplitude applied to the actuator was set to 50 V at various frequencies. Two configurations of micro pin extrusion [21] are investigated as shown in Figure 4. The resonant frequency of the system was obtained by a sweeping test. Then, the two frequencies were selected for comparison, one at resonant frequency and the other at off-resonant frequency.

FIGURE 3 – DIE DESIGN OF ULTRASONIC MICRO PIN EXTRUSION

FIGURE 4 – TWO CONFIGURATIONS FOR MICRO PIN EXTRUSION
(A) VIBRATION OF THE DIE (B) VIBRATION OF THE PUNCH

RESULTS AND DISCUSSIONS

The sweeping tests were conducted at several different load values to obtain the resonant frequency. The results showed that there was a resonant frequency around 7.8 kHz. And this resonant frequency did not vary significantly under different loads. One sweeping result under a load of 1200 N is shown in Figure 5.

Typical results of micro pin extrusion with ultrasound of 9 kHz (off-resonance) are shown in Figures 6 and 7. The average load reduced immediately when ultrasonic vibration was applied. The load immediately returned to static force when ultrasonic vibration was stopped. When ultrasound was applied, the path of maximum oscillatory force was nearly consistent with the static force. This phenomenon can be explained by the stress superposition shown in Figure 1.

FIGURE 5 – SWEEPING TEST RESULT WITH A LOAD OF 1200 N

FIGURE 6 – LOAD-DISPLACEMENT CURVE OF ULTRASONIC MICRO PIN EXTRUSION (VIBRATION OF THE DIE, 9 KHZ)
(A) ORIGINAL DATA (B) PROCESSED DATA WITH AVERAGE LOAD

Figures 6 and 7 show the results with die vibration and punch vibration respectively. Vibration of the die is usually considered to have more significant effect on load reduction compared with vibration of the punch [22]. However, no significant difference could be detected between these two configurations for our setup.
FIGURE 7 - LOAD-DISPLACEMENT CURVE OF ULTRASONIC MICRO PIN EXTRUSION (VIBRATION OF THE PUNCH, 9 KHZ) 
(A) ORIGINAL DATA (B) PROCESSED DATA WITH AVERAGE LOAD

Result of micro pin extrusion with ultrasound of 7.8 kHz (in-resonance) is shown in Figure 8. Although the average load reduced when ultrasonic vibration was applied, the original oscillatory force exceeded the static force. This phenomenon was not found at off-resonant frequency (Figures 6 and 7). There was large amplitude of oscillation when ultrasonic vibration at resonant frequency was applied. We speculate that the whole die system was under resonance condition and resulted large force detection. Therefore, the oscillation of the force exceeded the static force, which is undesirable. Although designing the system at resonant condition is typical in ultrasonic assisted manufacturing [22], the response of the system may be different due to the size miniaturization of dies. When dies and samples become small, the whole die system is under resonant condition.

The mechanisms of load reduction by ultrasonic vibration in this study can be explained by stress superposition of ultrasonic vibration. For stress superposition, the magnitude of load reduction directly depends on the amplitude of ultrasonic vibration. Therefore, the reduction magnitude can be enhanced by increasing the input power of the ultrasonic actuator.

FIGURE 8 - LOAD-DISPLACEMENT CURVE OF ULTRASONIC MICRO PIN EXTRUSION (VIBRATION OF THE DIE, 7.8 KHZ) 
(A) ORIGINAL DATA (B) PROCESSED DATA WITH AVERAGE LOAD

Compared with acoustic softening effect reported in literatures [8, 23], there is no evidence of acoustic softening shown in this study. In micro pin extrusion, it is difficult to acquire secure coupling of acoustic energy. The temperature in the specimen may be increased by the high-frequency vibration; however, this heating effect may be negligible in current experimental conditions. Therefore, material softening induced by ultrasonic vibration is considered to be unlikely in the current setup.

Micro pin extrusion is a friction sensitive process [5]. The load will remarkably reduce with significant decrease of friction. Such a significant load reduction still has not been monitored based on current setup. Bunget et al [16] explained the load reduction in their experiments by the improvement in tribological condition. There may exist some critical conditions [20] that need to be satisfied to acquire significant friction reduction by ultrasonic vibration.

CONCLUSIONS AND FUTURE WORK

The effect of ultrasonic vibration on micro pin extrusion was investigated. Experiments showed that ultrasonic vibration reduced the average load in both off-resonant and resonant frequency. But the system at resonance has a dynamic impact which increased the oscillatory load. No significant differences
were detected between vibration of the die and vibration of the punch. The mechanism of load reduction was explained by stress superposition of ultrasound.

To acquire significant load decrease in micro pin extrusion, high relative motion between the die and the workpiece may be required for friction reduction. Therefore, improving vibration coupling of the current system is our next step work. Also the mechanism of friction reduction in micro pin extrusion process need to be further investigated.

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