INFLUENCE OF ULTRASONIC VIBRATION ON MICRO-EXTRUSION

Cristina Bunget[1] and Gracious Ngaile[1]
[1]Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh, NC, USA

INTRODUCTION

The production of micro-parts has become more important in fields such as electronics, computers, communication, biotechnology, medicine, optics and environmental monitoring. Typical example for such parts are pins for IC-carriers, fasteners, micro-screws, lead frames, sockets, and any kind of connecting element (Figure 1). Traditionally these precision mechanical parts are fabricated by machining. The net shape or near net shape processes, such as metal forming processes, are best suited for miniaturization because of the higher productivity and accuracy.

FIGURE 1. Extruded micro-parts [1].

Despite the advantages of micro-forming, full utilization of this process has not been realized. Besides the problems that appear in conventional forming processes, like tool design and wear, there are also specific problems related with the miniaturization itself, such as material behavior, higher friction and tools fabrication. When the process is scaled down, the microstructure and the surface topography remain unchanged resulting in different material flow as compared to conventional process. A series of tests in sheet micro-forming has shown that flow stress of material decreases with miniaturization and also tribological conditions are more severe at micro-scale level. The influence of size on flow stress has thoroughly been investigated and well understood [2, 3]. The tribological effects are, however, not well understood. The double cup extrusion test was used to study lubrication conditions for different specimen sizes ranging from 4 to 0.5 mm diameter. The results showed an increase in apparent friction factor by a factor of 20 when the specimen size decreased to 0.5 mm diameter [4]. An analytical model to explain this behavior was proposed, but there is no any means yet to overcome this effect. The investigations have also shown an increase in scattering with miniaturization [3], and therefore difficulty in achieving desired tolerances. Other problems that appear in micro-forming are the fabrication of the tools, which need to be very small with very close tolerances and a good surface quality. The fact that micro-forming tools are also subjected to forces that may exceed the capacity of available die materials presents a great challenge as these tools are prone to short tool life. New manufacturing methods have been developed, such as micro-electrical discharging machining: micro-wire EDM, micro die sinking, electrical discharge drilling, micro-electrical discharge milling and grinding, but the problem of the high forces exerted on the tools still needs to be resolved [5].

There is a great potential to overcome some of the drawbacks of the miniaturization by applying the ultrasonic vibration during micro-forming process. The application of ultrasonic vibration in metal forming at macro-scale has been discussed for many years and some benefits were observed, such as a reduction in the flow stress and a considerable reduction of the external friction between tool and workpiece. The flow stress was observed experimentally to be considerably lowered by the ultrasonic oscillations superimposed on the compressive forming process [6]. This phenomenon was attributed to dynamical effects of stress, velocity and acceleration due to vibration, and also thermal effects due to heat generation, which was directly related with the amplitude of the vibration. Studies of the effects of the longitudinal oscillations imposed on the wire drawing found two possible effects of the ultrasonic oscillations superimposed on the forming process: volume effects and surface effects [7, 8]. The volume effects are related with a decrease in the flow stress. The surface effects are related with the changing of the frictional conditions at the die/specimen interface. Longitudinal, radial and torsional oscillations were applied during the rolling process, and the results indicated changes in the apparent friction coefficient, as a result of the pumping of the lubricant, softening or melting the asperities, separation of the surfaces, allowing a re-distribution of the lubricant [9]. Investigations done by superimposing ultrasonic oscillations on the tube drawing are reported in [10]. Their experiments showed a reduction in the flow stress, a greater reduction in the diameters and a surface finish superior to that obtained without ultrasonic, particularly on the inside surface. Other investigations were done to study the effect of the shape and length of the concentrator, or the tool attachment, an important part in the ultrasonic system [11]. The shapes found to be appropriate were conical, stepped and exponential, and the optimal length was found to be equal to a multiple of half of the wavelength. All the studies and experiments reached the same conclusions regarding the effect of the ultrasonic oscillations on the metal forming process: reduction of the forming forces, reduction of the flow stress, reduction of the friction between die and workpiece and production of better surface qualities and higher precision.

The objectives of this study are to investigate the possibility of applying the ultrasonic vibrations in the micro-forming process and to investigate their influence on material flow, forming load and tribological characteristics. It is anticipated that ultrasonic technology can overcome some of the difficulties brought by miniaturization.

METHODOLOGY

Three micro-extrusion processes are investigated in this study. These processes are: double cup extrusion (DCE), forward extrusion (FE) and forward-backward cup extrusion (FBCE). These processes were selected as being representative for forging micro-parts.

Physics of the Process

The superimposing of the ultrasonic oscillations on the forming process and the creation of the openings is illustrated in Figure 2 for Forward extrusion (FE) process. The punch has the velocity v_0. The material will enter with velocity v_0, but will exit with a different velocity, v_e. The die will vibrate with an oscillatory velocity v_D. This velocity is larger than the velocity of the material to be deformed. Because of the relative velocity between the die and material, the opening between die and material is created and closed at every cycle of oscillation. The pressure applied on the asperities when the die touches the material will contribute to elastic-plastic deformation of the asperities. Because of the deformation and the friction at the tool – workpiece interface heat will be generated. The increase in the temperature at the die-specimen interface will influence the behavior of the lubricant. It can be observed that under ultrasonic oscillations the direction of the friction force reverses for every period of oscillation, thus changing the friction characteristic at the tool-workpiece interface. Therefore, with proper design of an ultrasonic micro-forming system, tribological performance can be enhanced.

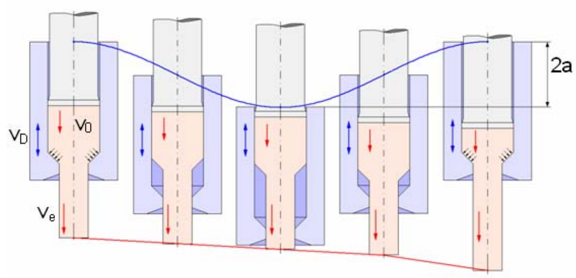


FIGURE 2. Superimposing ultrasonic oscillations on the forward extrusion process.

Design of the Tooling

A set of tooling capable to superimpose the ultrasonic vibrations on the micro-extrusion process was designed. The concentrator is the most important part for the design. This part will be connected to the transducer, and for this purpose had to be designed to resonate at the same frequency. The concentrator also holds the tools for the micro-extrusion process (dies and punches). The objective of the design is to obtain a tooling with the natural frequency of the system as close as possible to the imposed frequency; otherwise the energy will be lost and the vibration will be transmitted to the rest of the structure, limiting the efficiency and causing damage. For this purpose, the design of the concentrator and the holding system must respect some constructive principles given by the equation of the standing wave transmitted through concentrator (Eq.1) [9]:

$$u = a \cdot \cos\frac{2\pi x}{\lambda} \cdot \sin 2\pi f t \qquad (1)$$

Where u is the displacement, a the amplitude of vibration (given peak-to-peak), x the position, λ the wavelength, f the frequency of the vibration and t the time. From this equation, it can be concluded that the displacement is maximum when x is 0 or $\lambda/2$, and 0 for $\lambda/4$.

Figure 3 illustrates the two waves transmitted into the concentrator system: (a) a longitudinal wave that comes directly from the piezoelectric transducer and (b) a wave transmitted into the disc that holds the concentrator. The length of the concentrator is half of the wavelength of the transmitted wave, with a maximum at the transducer/concentrator interface and another maximum at the other end, were the micro-forming tooling and the deformation zone will be. At the middle, there is a zero amplitude node, used for holding the concentrator. Even if the disc is in the zero amplitude zone, there is still the possibility that the wave will be transmitted into the disc, and from the disc to the entire tooling. In order to obtain zero amplitude in the clamping zone the diameter of the disc needs to be equal with the wavelength.

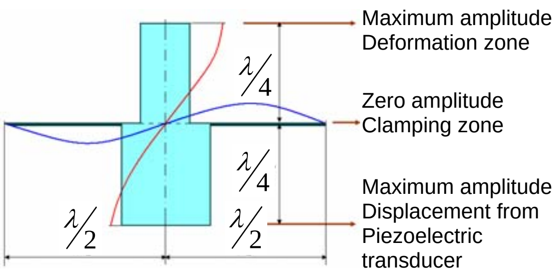


FIGURE 3. Design considerations.

These constructive principles were verified through harmonic response analysis. A varying load is applied and the amplitude of vibration at a point corresponding to the deformation zone are obtained. The amplitude response in radial and longitudinal (vertical) directions is shown in Figure 4. The finite element analysis was carried out assuming an ultrasonic generator of 2 kW and a piezoelectric transducer which provides maximum amplitude of 20 microns. The longitudinal displacement received from the imposed vibration is amplified five times for the frequency of 20 kHz.

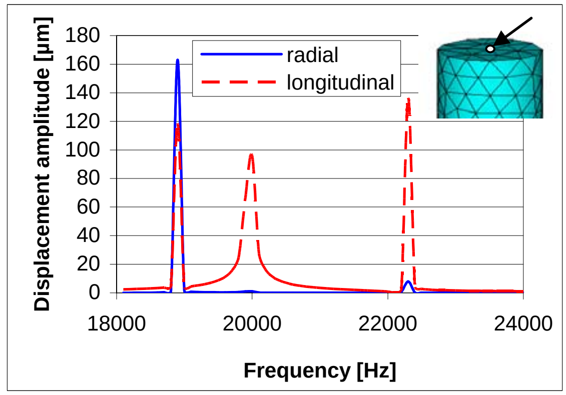


FIGURE 4. The radial and longitudinal displacement amplitude response.

Assisted by finite element analysis, the tooling was designed and optimized. Figure 5 presents the components of the concentrator system. The deformation zone is in the upper part of the concentrator, where the die and punch are placed. There are two possibilities to tune the frequency of the system by modifying the dimensions, after this has been manufactured: the tuning cone and the disc.

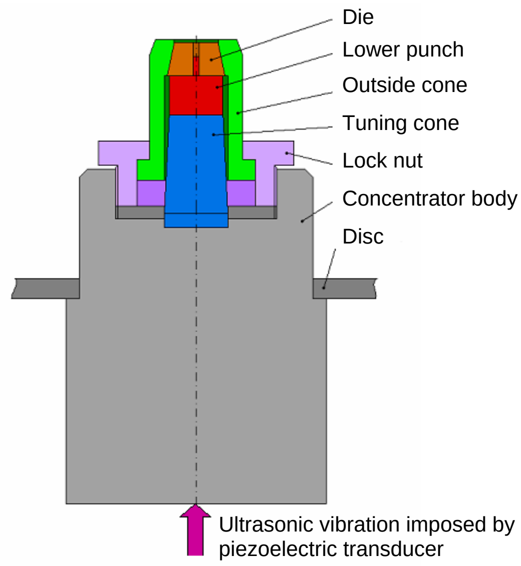


FIGURE 5. The concentrator system.

Test Set-up

The set-up used for conducting the ultrasonic microforming tests is shown in Figure 6. The assembly consists of common parts for both microforming and ultrasonic microforming. The first category includes the lower punch and die assembly, upper punch assembly and a lever. A scale is attached to the lever for recording the forming load. The ultrasonic system includes three parts: ultrasonic generator which gives an electric signal of 20 kHz frequency at amplitude of 22-23 µm, with the possibility of variation between 50 % and 100% of this value, the ultrasonic piezoelectric transducer used to transmit the ultrasonic oscillations to the lower punch assembly, and the ultrasonic concentrator. The dies and the punches are presented in Figure 7 for forward extrusion (FE) and for double cup extrusion (DCE). Note that for forward-backward cup extrusion test, the tools are a combination of those used in the other two tests.

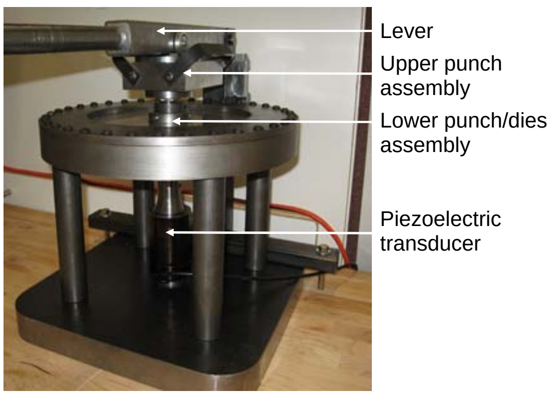
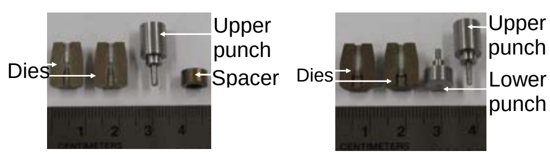


FIGURE 6. Microforming and ultrasonic tooling.



(a) (b)

FIGURE 7. Dies and punches for (a) FE and (b) DCE.

Test Procedures

The tooling presented in Figure 6 was used to test the influence of the ultrasonic vibration on micro-extrusion. The material used for the specimen is aluminum (1100), obtained from wire of 2 mm diameter, and cut to the length of 3 mm for DCE, 4 mm for FE and 5 mm for FBCE. Figure 8 presents the micro-parts obtained through our experiments.

Micro-extrusion tests with and without ultrasonic vibration were conducted. Three different lubricants were tested: a polymeric based lubricant (Lub 1), an oil based lubricant (Lub 2) and a water based lubricant (Lub 3). The forming load, the surface finish and the lubricant distribution after deformation were some of the aspects investigated. The forming load was recorded for all tests. Scanning electron microscopy (HITACHI S 3200 NSEM) was used in studying the influence of the ultrasonic oscillations on the surface quality.

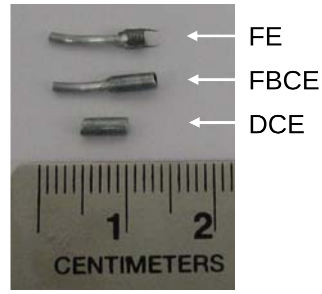


FIGURE 8. Micro-extruded parts obtained.

RESULTS AND DISCUSSION

Influence of the Ultrasonic Vibration on the Forming Load

During the experiment the load was recorded for each sample. Figure 9 shows the forming load for each type of extrusion process and each lubricant, with and without ultrasonic vibration.

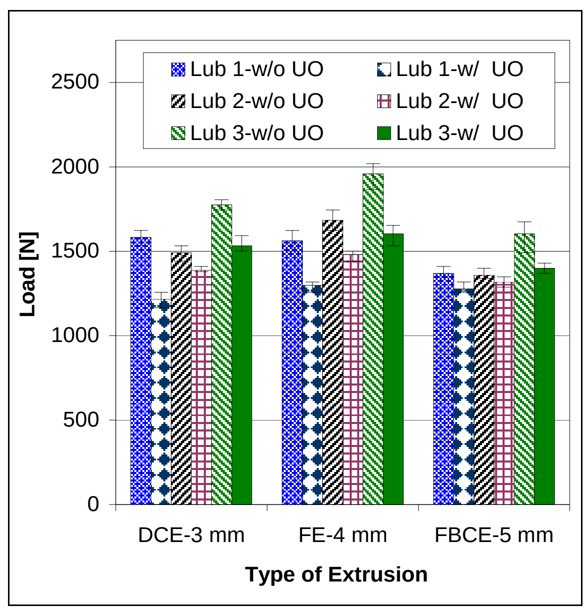


FIGURE 9. Influence of the ultrasonic vibration on the forming load.

The reduction in the forming load as compared to non-ultrasonic process was 12-18% for forward extrusion, 7-23% for double cup extrusion, and 3-13% for forward-backward cup extrusion, the forming load was also reduced, by 3%-13%. The percent of load reduction depends on the process and on the type of lubricant used. Among the three lubricants tested, lubricant 1 had a smaller forming load, and lubricant 2, an oil based lubricant, was found to be the most effective under ultrasonic vibrations.

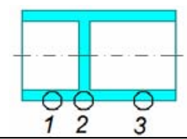
Influence of the Ultrasonic Vibration on the Surface Finish

The surface obtained after the tests with and without ultrasonic oscillations was analyzed, this being a key in understanding the lubrication mechanism. Micrographs were taken for all types of tests and all lubricants, and compared. The surface quality was observed to be improved in all ultrasonic tests, more significantly for lubricant 3.

The differences between the surface finish obtained after classic double cup micro-extrusion test and the ultrasonic test are presented in Figure 10. Micrographs were taken in different zones: the lower cup zone (1), the middle zone (2), characterized by high pressure at the interface, and the upper cup zone (3). The surfaces obtained in non-ultrasonic conditions presents scaring, indicating sticking conditions, and localized smearing indicating lubrication breakdown and metal-to-metal contact with subsequent shearing and smearing of the junctions, especially in zone 3. The surfaces obtained when ultrasonic oscillations were used show a significant improvement in the lubrication conditions. There are some isolated scaring in zones 1 and 2, indicating boundary lubrication. In zone 3, the absence of scaring and presence of roughening and formation of pits (lubricating pockets) indicates mixed-film lubrication, therefore a much more favorable lubrication regime.

The differences in the surface quality are attributed to various factors, some of which can be understood by studying the possible lubrication mechanisms in non-ultrasonic and ultrasonic test. Ultrasonic oscillation results in high instantaneous relative velocities at the tool-workpiece interface. This leads to reduction of adhesive bond formation and hence better lubrication condition.

At the same time, because of the change in the direction of the relative movement, there will be a change in the direction of the friction force that will help the material to flow downward easier than in the classic case. Also because of the relative velocity, the pockets formed by the surface roughness will trap the lubricant and will keep it in the deformation zone. The lubricant will be better distributed at the interface. Therefore the lubricant is helped to keep up with the expansion of the surface and the generation of the new surface due to deformation. Due to these changes, the lubrication regime will be improved and the effective friction coefficient will decrease.

Double Cup Extrusion (DCE) Lubricant 3		
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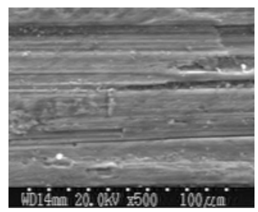
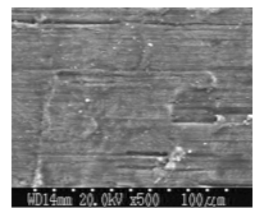
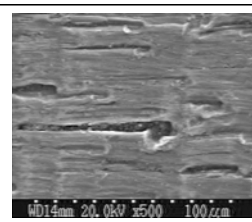
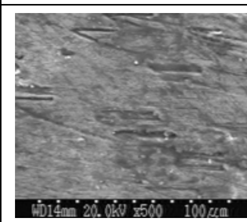
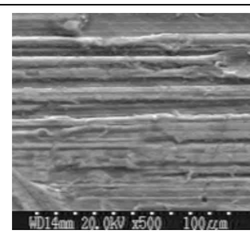
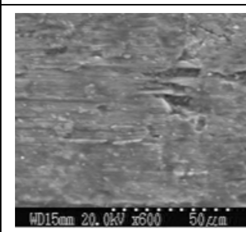
1		
2		
3		

FIGURE 10. Micrographs taken in different location for DCE test. Lubricant used: Lub 3.

CONCLUSIONS

In this paper the influence of ultrasonic vibration on micro-extrusion processes is investigated. An ultrasonic micro-forming tooling was developed and micro-extrusion experiments were conducted. The forming load and the surface finish were some of the aspects studied. Based on results of the tests, the following conclusions were reached:

- Ultrasonic oscillations influence significantly the friction and lubrication mechanism at the die/workpiece interface. Higher instantaneous sliding velocities help to shift a boundary lubrication regime to a mixed-film regime and sticking conditions to a boundary regime.
- Better lubrication conditions and better surface finish with ultrasonic oscillations suggest that ultrasonic micro-forming is a viable process for difficult-to-lubricate materials.
- The magnitude of the ultrasonic oscillations effects depends on the type of the extrusion process, but is also influenced by the lubricant composition.
- The reduction in friction will result in a reduction in load, thus in less energy consumption.

In conclusion, the study has demonstrated that there is high potential for using ultrasonic vibration as a way to overcome the difficulties brought by the miniaturization.

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