INFLUENCE OF ULTRASONIC VIBRATION ON MICROFORMING

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ABSTRACT

The influence of ultrasonic vibration on micro-extrusion of aluminum billets was investigated using a microforming tooling with the capacity to induce vibration at a frequency of 20 kHz. It was found that microforming load can be reduced by 23%, with substantial improvement in the surface quality of the formed part.

The percentage load reduction and surface improvement were found to be dependent on the type of extrusion process and the lubricant compositions. The processes investigated in this study were forward extrusion (FE), forward-backward extrusion (FBCE), and double cup extrusion(DCE).

INTRODUCTION

The emerging trend of miniaturization of a wide variety of mechanical devices and systems has resulted in high demand for microparts for applications in fields such as electronics, communication, biotechnology, medicine, optics, and environmental monitoring. Microforming is one of the miniaturization technologies with great potential for high production rates, due to minimum or zero material loss, and excellent mechanical properties. Despite the advantages of microforming, it is not yet robust enough to be fully utilized. In the past few years a lot of research in microforming has been carried out with focus on scale effect, lubrication, and effects of microstructure on material flow characteristics [Messner et al. 1994; Geiger et al. 1997; Tiesler et al. 1999; Cao et al. 2004; Krishnan et al. 2005; Wulfsberg et al. 2005]. The major differences between micro-scale and macro-scale arise due to the effect of various factors such as grain size and surface roughness that do not change when a process is scaled down geometrically.

However, several technical challenges need to be addressed before microforming can become a commercially viable manufacturing process. These includes severe tribological conditions caused by higher surface-to-volume ratio, difficulty in achieving desired tolerances, impracticality of using conventional metal-forming lubricants as the film-thickness of these types of lubricants reaches the order of part tolerances or part-size features, short tool life due to inability of available die materials to withstand the forces exerted on miniature dies and punches – particularly when microforming is done on carbon steel and stainless steel, and pronounced anisotropic behavior of metals at micro-scale. Other technical challenges confronting microforming include handling of micro billets, part ejection, transfer of billets between stations, and press accuracy. Some of the above-mentioned problems can be mitigated by the use of ultrasonic microforming processes.

Material-related challenges occur when a process is scaled down from conventional size to micro-scale. Engel et al. (2002) studied the size effect in microforming through a series of experiments on double-cup extrusion, forward rod - backward can extrusion, and bending tests performed on CuZn15 brass alloy. They observed that large grains showed a tendency to deform inhomogeneously, causing an irregular-shaped rim for the back-extruded can. Krishna et al. (2005) studied the influence of grain size on material flow, finding that the micro pin extruded from brass material of grain size 211 μm exhibited a bent curvature, while the micro pin extruded from grain size of 32 μm did not. The material characteristics anisotropy, inhomogeneity, and grain size present a challenge in making microforming processes cost-effective for miniature manufacturing.

Studies on tribology of miniature manufacturing have shown that tribological conditions become severe with miniaturization as compared to conventional manufacturing of macro parts subjected to the same lubrication conditions. Engel et al. (2002) scaled down the double cup extrusion test from 4 mm to 0.5 mm. The latter led to higher cup-height ratio, which implies higher friction. The frictional behavior observed from these tests can be explained by the model of "open and closed lubricant pockets," also called "dynamic and static lubricant pockets" [Pfestort et al. 1998]. When a forming load is applied to a lubricated workpiece surface, the asperities (roughness peaks) start to deform plastically, thus increasing the pressure of the lubricant, which is either trapped in the roughness valleys or squeezed out. Roughness valleys that have a connection to the edge of the surface cannot retain the lubricant. Thus, under the same surface roughness, the smaller specimen will develop unfavorable lubrication conditions.

A comparative analysis between deformation in macroforming and microforming can be drawn by considering the deformation energy associated with metal forming as expressed by

$$\Pi = I_1 + I_2 - I_3 = \int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}\,dV + k\int_V \dot{\varepsilon}_V\,\dot{\varepsilon}_V\,dV - \int_{SF} F_i\,\delta u_i\,ds$$

where k is a penalty constant, $\dot{\varepsilon}_V$ the volumetric strain rate, $\bar{\sigma}$ effective stress, $\bar{\varepsilon}$ effective strain, $\dot{\bar{\varepsilon}}$ effective strain rate, and F_i, traction. The 1st term represents the energy due to deformation, the 2nd term volumetric strain energy, and the 3rd term energy due to friction at the tool/workpiece interface. In the presence of good lubrication (i.e., shear friction factor m from 0.1 to 0.15), which could result to non-defective parts, the ratio between frictional energy and deformation energy ($R_{macro}=I_3/I_1$) associated with classic macroforming is usually of the order of 0.1 or less. With microforming, however, this ratio increases significantly [Figure 1].

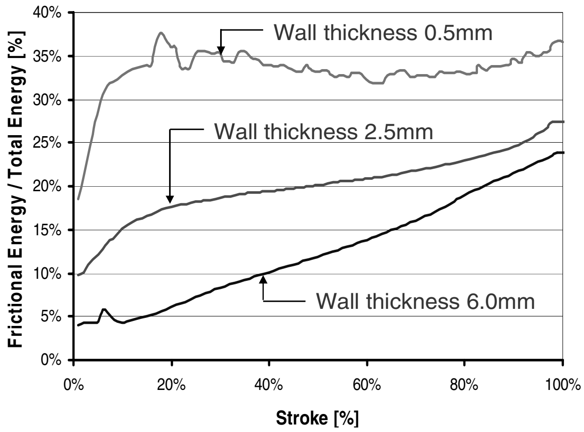

FIGURE 1. FRICTIONAL ENERGY TO TOTAL ENERGY RATIO FOR BACKWARD CUP EXTRUSION (FEA) [Bunget 2006].

This dramatic increase implies that much better lubrication is imperative in microforming than in macroforming. Furthermore, the typical lubricants used in cold macroforming, such as zinc phosphate + metal soap, become ineffective for microforming because the lubricant film thickness (e.g., 20 μm) may exceed the tolerance level of the micro part. Effective microforming systems may require innovative techniques such as the imposition of ultrasonic vibration during microforming.

The application of ultrasonic vibration in classic macro metal forming has been discussed for many years. Blaha et al. (1955) superimposed high-frequency vibrations onto the static load during tensile testing of a zinc single-crystal specimen and found a substantial reduction in the yield stress. When the experiments were extended to polycrystalline materials, the same effects were observed. The flow stress was considerably reduced by the ultrasonic oscillations superimposed on the compressive forming process [Hung et al. 2005]. Wire-drawing experiments under ultrasonic oscillations have shown that drawing forces can be reduced by 50% [Winsper et al. 1969]. The force reduction is attributed to vibration-induced effects of stress, velocity, and acceleration, and to thermal effects due to heat generation. Another observation was that all these factors are dependent on the amplitude of vibrations. It was found that as amplitude increases, load greatly decreases and heat generation increases. Experiments have shown that amplitude of 10 εm can cause the local temperature of the workpiece to reach about 300°C. However, the extent of temperature increase has been reported to be a function of the types of material used. Mollers et al. (1975) investigated the influence of ultrasonic waves on the deep-drawing process. They found that the ultrasonic effect can be maximized by optimizing the angle between the drawing direction and the direction of vibration. Jimma et al. (1998) found that the limiting drawing ratio (LDR) in the deep-drawing process increased 15-25%, depending on the material used. Many experiments have shown that forming load and friction force can be reduced significantly in the presence of ultrasonic vibrations [Izumi et al. 1966; Winsper et al. 1969, 1970; Dawson et al. 1970; Young et al. 1970, 1971; Eaves et al. 1975; Cheers 1995; Jimma et al. 1998].

The literature shows no prior investigation of the effect of ultrasonic vibration on microforming (microextrusion, microforging, microrolling, or microstamping). Yet for miniature parts that currently cannot be microformed due to part complexity, low formability, inhomogeneity, etc., there is great potential to be successfully microformed by ultrasonic microforming. Inducing ultrasonic vibrations at selective workpiece-interface locations in time and in space has potential for (a) lowering the forming load that is critical for microforming/ microextrusion of carbon steel, stainless steel, and other hard-to-form materials such as titanium and tantalum, (b) enhancing lubrication due to elastic relaxation of the deforming material at the tool-workpiece interface, thus creating favorable conditions for hydrostatic and hydrodynamic lubrication to occur, and (c) exploiting the temperature generation due to ultrasonic vibration to enhance material flow (pseudo-warm microforming).

The objective of this study is therefore to investigate the influence of ultrasonic vibrations on forming-load characteristic, material flow, and tribological conditions pertaining to microextrusions.

Some Aspects of the Mechanics of Ultrasonic Microextrusion

The superimposing of the ultrasonic oscillations on the forming process and the creation of the openings is illustrated in Figure 2 for the forward extrusion (FE) process.

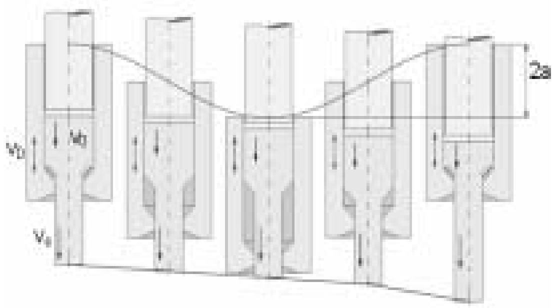

FIGURE 2. DIE PUNCH MOTIONS IN ONE CYCLE OF OSCILLATION (FBCE).

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. Because of the relative velocity between the die and material, the opening between them is created and closed at every cycle of oscillation. The pressure applied on the asperities when the die touches the material will contribute to their elastic-plastic deformation. 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 and the flow characteristic of the material. 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 microforming system, tribological performance can be enhanced and material properties can be altered. As discussed earlier, coating based lubrication commonly used in cold forging may not be effective for microforming. On the other hand for liquid lubricant to be effective, hydrostatic and hydrodynamic conditions need to be achieved.

DEVELOPMENT OF THE TOOLING AND EXPERIMENTAL SETUP

Tooling Design

The concentrator is the most important part of the design. This part is 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. For this purpose, the design of the concentrator and the holding system must respect some constructive principles given by the following equation of the standing wave transmitted through the concentrator.

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

where u is the displacement, a the amplitude of vibration, x the position, λ the wavelength, f the frequency of 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 minimum when x is equal to $\lambda/4$. Figure 3 shows 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. With the aid of the finite element (FE) analysis the tooling was designed and optimized. It should be noted that a simplified FE model was used to mimic the concentrator and die assembly shown in Figure 3. Different mode shapes are shown in Figure 4. The displacement are within elastic range, however, for clarity a higher magnification was used. The mode shapes exhibit bending, expansion, translation etc. The amplitude response at the die tip in radial and longitudinal directions is shown in Figure 5. The FE analyses were carried using ANSYS commercial code. The FE models were discretized using 60,000 tetrahedral elements. All the nodes at the edge of the disc were fixed in all degrees of freedom. Details of the FE model can be found in Bunget [2006]. The analysis was carried out assuming an ultrasonic generator of 2 kW and a piezoelectric transducer that provides maximum amplitude of 20 µm. The longitudinal displacement received from the imposed vibration is amplified five times at a frequency of 20 kHz [Figure 5].

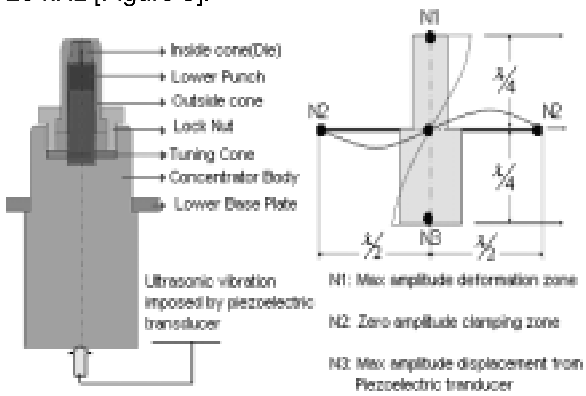

FIGURE 3. DESIGN CONSIDERATIONS.

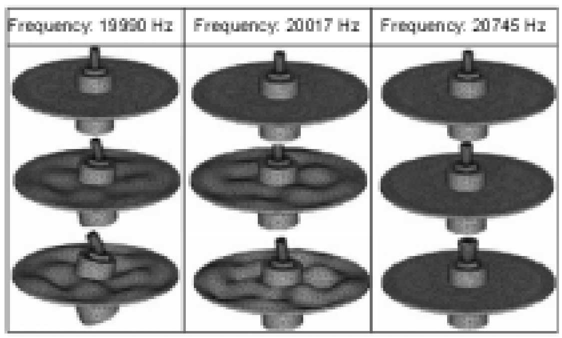

FIGURE 4. MODE SHAPES.

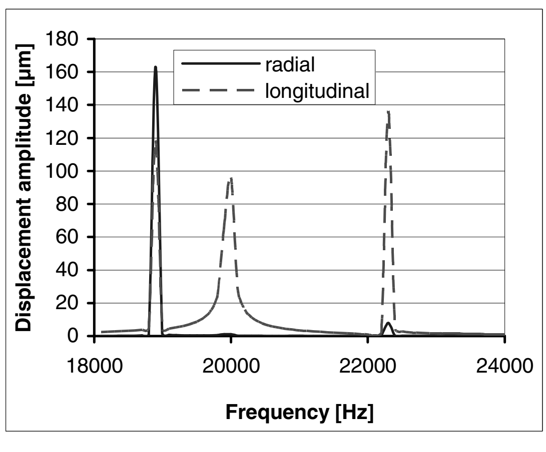

FIGURE 5. THE RADIAL AND LONGITUDINAL DISPLACEMENT AMPLITUDE RESPONSE.

Test Setup and Test Procedures

The setup used for conducting the ultrasonic microforming tests is shown in Figure 6. The main parts of the system include upper and lower die/punch assemblies, ultrasonic piezoelectric transducer, ultrasonic concentrator, and 20-kHz generator. A scale is attached to the lever for recording the forming load. It should be noted that the forming load is applied through the upper punch assembly which is isolated from ultrasonic vibrations. The tooling has been designed such that most of the vibrational energy goes to the die assembly. However, it should be expected that a certain percent of energy will be transmitted to the deforming material. Three different micro-extrusion techniques were investigated: FE, FBCE, and DCE. The specimens were prepared from a 2-mm-diameter aluminum wire (1100) and cut to the length of 3 mm for DCE, 4 mm for FE, and 5 mm for FBCE. Some residual stresses may have remained in the specimens as the original aluminum wire was taken from a spool, however, we considered the effect of residual stress to be insignificant. The specimens were polished by sand papers and measured by a micrometer.

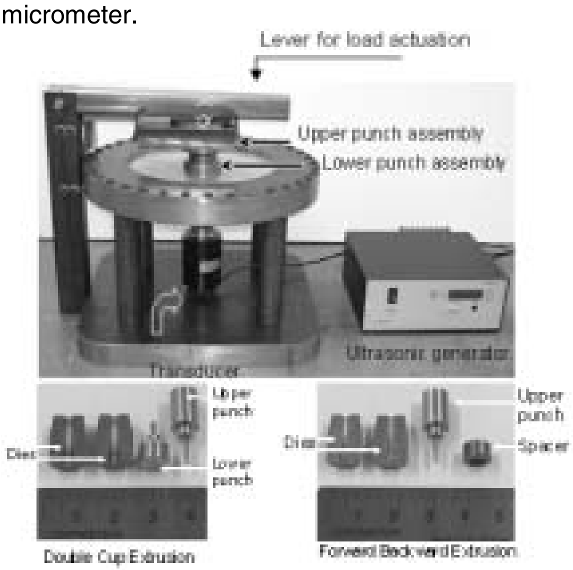

FIGURE 6. ULTRASONIC TOOLING SETUP AND DIE SETS.

Figure 7 presents the micro-parts obtained from the experiments. Micro-extrusion tests with and without ultrasonic vibration were conducted. For each test three specimens were used. Three different lubricants were tested: a polymeric based lubricant (Lub 1) [Ngaile 2006], 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 investigated.

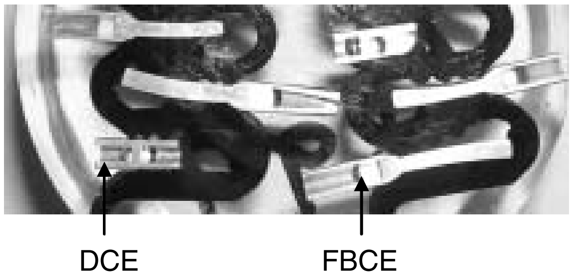

FIGURE 7. CROSS-SECTION OF MICRO-EXTRUDED PARTS.

RESULTS AND DISCUSSION

Influence of Ultrasonic Vibration on Forming Load

During the experiment the load was recorded for each sample. Figure 8 shows the forming load for each type of extrusion process and each lubricant, with and without ultrasonic vibration. 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.

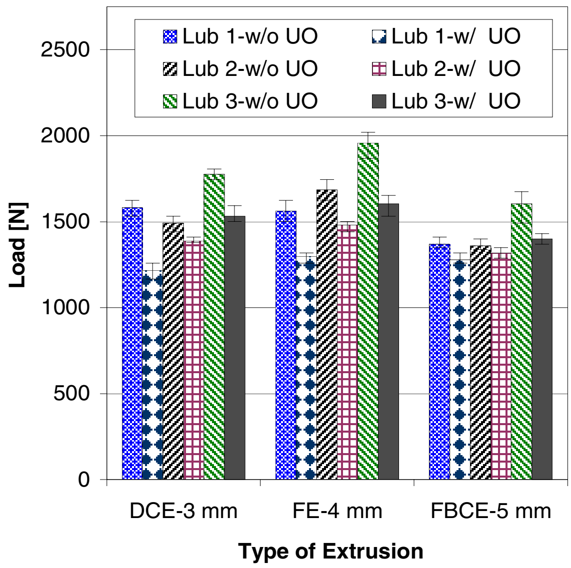

FIGURE 8. INFLUENCE OF THE ULTRASONIC VIBRATION ON THE FORMING LOAD.

Figure 8 shows that the percentage load reduction varies with extrusion process and type of lubricant used. Among the three lubricants tested, lubricant 1 exhibited the lowest forming load. Detailed chemical analysis was not carried out in this study to determine why Lub 1 was the best.

Influence of Ultrasonic Vibration on Surface Finish

Micrographs were taken for all types of tests and for all lubricants. The surface quality was observed to be improved in all ultrasonic tests, as shown in Figures 9 and 10. The differences between the surface finish obtained for the classic double cup micro-extrusion test and the ultrasonic test are presented in Figure 10. Micrographs were taken in different zones: (1) the lower cup zone, the middle zone, characterized by high pressure at the interface, and (2) the upper cup zone.

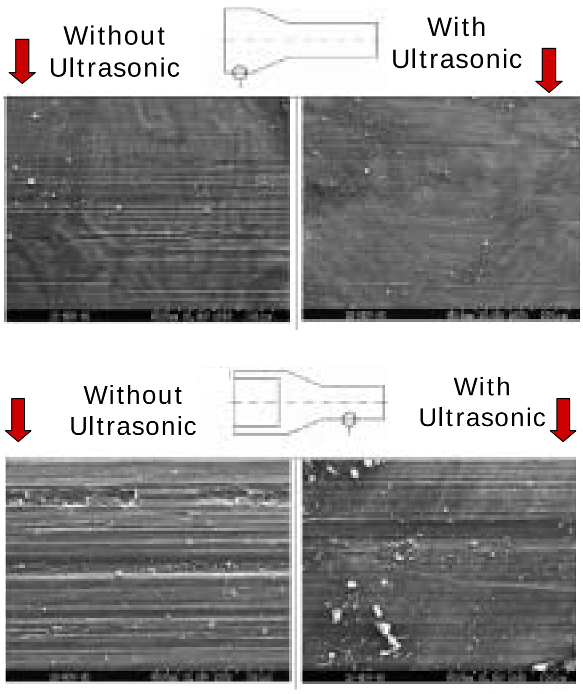

FIGURE 9. MICROGRAPHS TAKEN AT DIFFERENT LOCATIONS FOR FE AND FBCE TESTS, USING LUB 1.

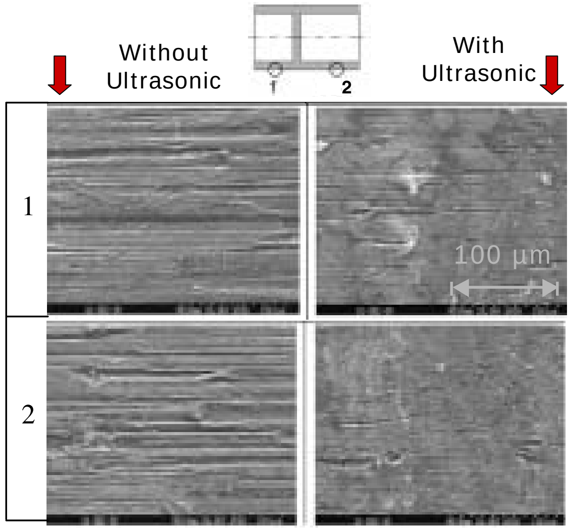

FIGURE 10. MICROGRAPHS TAKEN AT DIFFERENT LOCATIONS FOR DCE TEST, USING LUB 3.

The surfaces obtained in non-ultrasonic conditions exhibit scarring, indicating sticking conditions; localized smearing, indicating lubrication breakdown; metal-to-metal contact; and subsequent shearing and smearing of the junctions, especially in zone 2. The surfaces obtained when ultrasonic oscillations were used show a significant improvement in lubrication conditions. There is some isolated scarring in zones 1 indicating boundary lubrication. Formation of tiny lubricant pockets can be seen in zone 2, indicating a much more favorable lubrication condition.

To understand the impact of ultrasonic oscillations on the local material movement at the workpiece boundaries as deformation proceeds, numerical analysis using the finite element method was performed on several microextrusions: FE, DCE, and FBCE. Only DCE geometry will be discussed here. Through FEA, the local velocity profiles on the boundary were established

The surface velocity profiles obtained from FEA are given in Figure 11. With a punch velocity of 1 mm/s, a considerable gradient in the surface velocity in the surface region AB is observed. Region AX (bottom cup) exhibits about 300% higher surface velocity than does region XB (top cup). It should be noted that the difference in the velocities in the two regions is caused by the fact that during double cup extrusion process, the lower punch and the die remain stationary. As the upper punch travels forcing the deforming material to flow towards the upper and lower cup, different velocity patterns are encountered.

When ultrasonic oscillation is imposed on the die, causing high micro contact-sliding mean velocity, the surface region AB is expected to exhibit microplastic and/or hydrodynamic and hydrostatic lubrication conditions. However, since there are two distinct surface regions, one with high sliding velocity of 2 mm/s and the other with 0.5 mm/s, it is anticipated that the dominant mode of lubrication in region AX may differ from that in XB. This may explain the slight difference in surface quality between regions 1 and 2. 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. 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, enabling the material to flow downward easier than in the classic case.

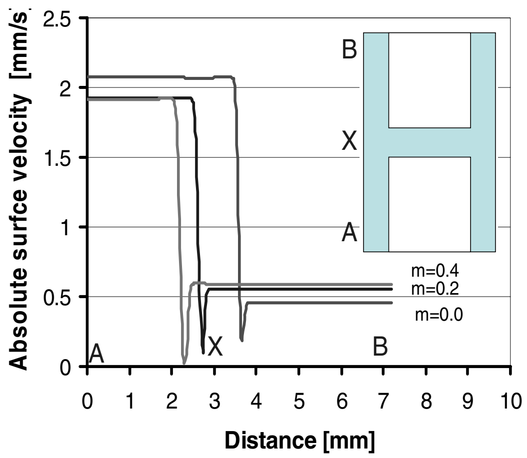

FIGURE 11. LOCAL SURFACE VELOCITY OBTAINED FROM FEA FOR DCE (AL 1100).

CONCLUSIONS

In this paper the influence of ultrasonic vibration on micro-extrusion processes is discussed. An ultrasonic microforming 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 can be drawn:

- Ultrasonic vibration can reduce forming load up to 23%. One of the reasons for load reduction is the improvement in tribological performance as a result of ultrasonic vibrations.
- Better lubrication conditions and better surface finish with ultrasonic oscillations suggest that ultrasonic vibrations can alleviate some of the tribological issues in microforming.
- The degree that ultrasonic oscillations influence load reduction depends on the type of the extrusion process as well as the composition of the lubricant.

In conclusion, the study has demonstrated that there is high potential for using ultrasonic vibration as a way to overcome some of the difficulties brought by miniaturization. Another attractive feature for economic implementation of ultrasonic systems for microforming is the fact that, microforming systems do not require large capacity ultrasonic generators.

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REFERENCES

Bunget, C. (2006). “Microforming and Ultrasonic Microforming.” MS Thesis, North Carolina State University.

Cao, J., N. Krishnan, Z. Wang, H. Lu. W. Liu, and A. Swanson (2004). “Microforming: Experimental Investigation of the Extrusion Process for Micropins and its Numerical Simulation Using RKEM.” *ASME Journal of Manufacturing Science and Engineering*, Vol. 126, pp. 642-652.

Cheers, C.F. (1995). “Design and optimization of an ultrasonic die system for forming metal cans.” PhD dissertation, Loughborough University of Technology.

Dawson, G.R., C.E. Winsper, and D.H. Sansome (1970) “Application of high- and low-frequency oscillations to the plastic deformation of metals – A complete appraisal of the development and potential.” *Metal Forming*, pp. 254-261.

Eaves, A.E., A.W. Smith, W.J. Waterhouse, and D.H. Sansome (1975). "Review of the application of ultrasonic vibrations to deforming metals." *Ultrasonics*, pp. 162-170.

Engel, U. and R. Eckstein (2002). "Microforming – from basic research to its realization." *Journal of Materials Processing Technology*, 125-126, pp. 35-44.

Geiger, M., A. Messner, and U. Engel (1997). "Production of microparts – size effects in bulk metal forming, similarity theory." *Production Engineering*, Vol. IV/1, pp. 55-58.

Hung, J.C. and C. Hung, (2005). "The influence of ultrasonic-vibration on hot upsetting of aluminum alloy." *Ultrasonics,* V43, pp. 692-698.

Izumi, O., K. Oyama, and Y. Suzuki (1966). "On the superimposing of ultrasonic vibration during compressive deformation of metals." *Transactions of the Japan Institute of Metals*, V7, pp. 158-162.

Izumi, O., K. Oyama, and Y. Suzuki (1966). "Effects of superimposed ultrasonic vibration on compressive deformation of metals." *Transactions of the Japan Institute of Metals*, V7, pp. 162-167.

Jimma, T., Y. Kasuga, N. Iwaki, O. Miyazawa, E. Mori, K. Ito, and H. Hatano (1998) "An application of ultrasonic vibration to the deep drawing process." *Journal of Materials Processing Technology*, 80-81, pp. 406-412.

Krishnan, N., J. Cao, B. Kinsey, S. Parasiz, M. Li, (2005)."Investigation of deformation characteristics of micropins fabricated using microextrusions." P*roceedings of IMECE.*

Messner, A., U. Engel, R. Kals, and F. Vollertsen(1994). "Size effect in the FE-simulation of micro-forming processes." *Journal of Materials Processing Technology,* V45: pp. 371-376.

Ngaile, G., J. Cochran, and D. Stark (2006). "Development of Polymeric Lubricant for Cold Forging Processes." *Transactions of NAMRI/SME*, Vol. 34, pp. 563-570.

Pfestorf, M., U. Engel, and M. Geiger (1998). "Three-dimensional characterization of surfaces for sheet metal forming." *Wear*, 216, pp. 244-250.

Tiesler, N., U. Engel, and M. Geiger (1999). "Forming of microparts – effects of miniaturization on friction." *Advanced Technology of Plasticity*, Vol. II, Proc. of 6th ICTP, Sept. 19-24, Forming of Microparts I, pp. 889-894.

Winsper, C.E. and D.H. Sansome (1969). "Fundamentals of 'ultrasonic' wire drawing." *Journal of the Institute of Metals*, 97, pp. 274-280.

Winsper, C.E., G.R. Dawson, and D.H. Sansome (1970). "An introduction to the mechanics of oscillatory metalworking." *Metals and Materials*, pp. 158-162.

Wulfsberg, J.P. and M. Terzi, (2005). Investigation and application of size effect sin the laser assisted forging of microparts with transparent tools. Proc. of International Conf. on Technology of Plasticity, Verona Italy.

Young, M.J.R., C.E. Winsper, and D.H. Sansome (1970). "Radial mode vibrators for oscillatory metal forming." *Applied Acoustics*, V3, pp. 299-308.

Young, M.J.R., C.E. Winsper, and D.H. Sansome (1971). "The design of high intensity radial vibrators for metal working applications." *Journal of Physics D: Applied Physics*, V4, pp. 212-216.