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Characterization of the Effects of High-Frequency Vibration on Aluminum and Copper Upsetting

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Research Program: Micromanufaturing

Introduction

Micromanufacturing is a topic of growing importance, with applications in medical devices, MEMS, electronics, and many other fields. Several new challenges become apparent as parts reach the sub-millimeter level, including material size effects, geometric tolerance and surface finish, friction, and repeatability [1]. Tool wear is also a very important consideration, as it is currently very expensive to make tooling at this scale.

Ultrasonic vibration shows great promise to address many of the current limitations in microforming and has been used in wire-drawing since the 1950s [2] with marked reduction in flow stress, friction, and increases in repeatability and surface finish [3]. Similar results have also been observed in current research on microforming [4].

The focus of this paper is to identify and characterize the effects of high-frequency vibration to the simple upsetting of aluminum and copper. With this information it will be possible to develop a finite element model that will assist in ultrasonic forming die design.

Vibration Assisted Forming Background

There are several identified benefits of ultrasonic softening, although they can primarily be reduced to surface effects and volume effects [5, 6, 7]. The surface effect is dominated by a reduction in friction, and occurs by the moving surfaces making and breaking contact [8, 9]. The volume effect is marked by both superposition and acoustic softening. Stress superposition is caused by the "unloading" effect on a material under vibration, which reduces the average load [10, 11]. Acoustic softening can be attributed to the absorption of acoustic energy by internal defects such as grain boundaries, dislocations, and voids [2, 12]. An acoustic hardening effect has also been identified, which acts similarly to work hardening and is not present until vibration is removed [2].

Perhaps the most critical factor in designing dies for ultrasonic forming is their resonant response [4, 13]. The particular resonant mode is critical as well, and research shows that transverse vibration is most effective at reducing forming stress [13].

The following mathematical model was used to estimate stress reduction as a function of vibration amplitude:

$$\Delta\lambda = -\beta(E/\hat{\tau})^{m} \tag{1}$$

where ß and m are material-dependent parameters determined by experiment and assumed constant in this application, and the mechanical threshold, $\hat{\tau}$ is a material property based on dislocation density that is the theoretical equivalent to the shear strength of a metal at 0 K. *E* is the acoustic energy density, which for this experiment is defined on the following relationship:

$$E = \xi_{Ti}{}^{2}\omega^{2}\rho_{Ti}\alpha_{t} \tag{2}$$

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where ξ_{Ti} is the vibration amplitude at the titanium horn tip used in the study, ω is the angular frequency, ρ_{Ti} is the density of titanium and α_t is the coefficient of transmissibility [14].

Experimental Setup

Fig. 1 shows the apparatus used for vibration assisted forming. A Kistler force transducer is mounted between the die system and the system's frame. The ultrasonic generator is a Terfenol-D transducer from Etrema products, and includes a titanium horn tuned for a transverse resonance of 9.6 kHz. The ultrasonic generator is mounted to a sled that is moved by a DC motor attached to a screw drive. A laser displacement transducer measures the displacement of the sled. Transverse vibration of the horn tip is measured with a capacitive displacement sensor.

The system is automatically controlled through a Matlab Simulink model, which handles force and displacement-based control, as well as vibration frequency control with feedback from a lock-in amplifier. The vibration frequency control system also compensates for the nonlinear output of the Terfenol-D transducer for nearly constant vibration amplitude across a range of 5-10 kHz.

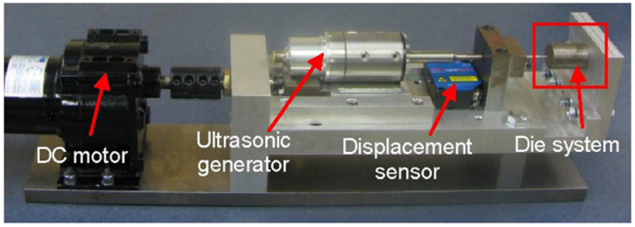

Fig. 1: Experimental setup for vibration assisted microforming

Results and Discussion

A COMSOL simulation was developed that consists of a vibration analysis which is used to determine the magnitude of ultrasonic vibration, which is then used with equations (1) and (2) to modify the material flow stress in a linked plastic strain FEM of the forming process. An elasto-plastic material model is used, and friction is neglected. Figures 2 and 3 show a comparison of the FEM with experimental data for Al and Cu.

The FEM matches the experimental data fairly well, although a better fit can be created by also including the effects of work hardening, as seen by the fact that throughout the ultrasonic portion of forming acoustic hardening causes the mean stress level to increase in the experimental data as compared to the FEM.

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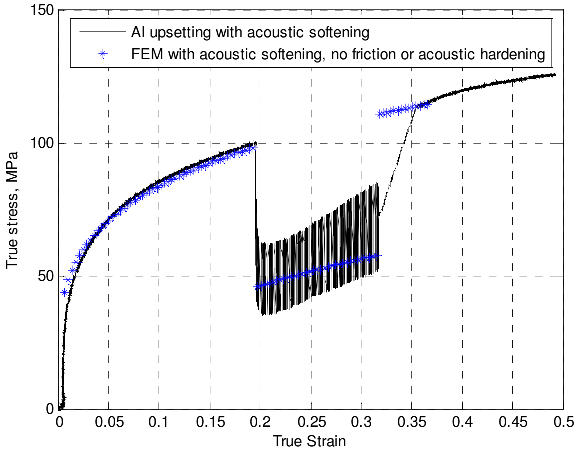

Fig. 2: Upsetting experiment vs. FEM for annealed Al 1100

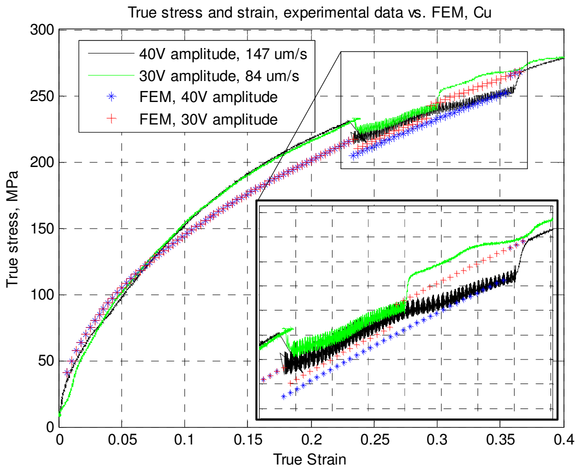

Fig. 3: Upsetting experiment vs. FEM for annealed Copper

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