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On the influence of workpiece material on friction in microforming and lubricant effectiveness

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ABSTRACT

The frictional behaviors between metal forming tool and three different metallic materials were evaluated using the microforming T-shape test. A mathematical function is proposed to describe the calibration curves for different friction coefficients. Round bars of copper, aluminum and silver of diameter 1 mm and length 5 mm were used as the workpieces to study the material influence on friction factor, *m*, during unlubricated microforming process through comparison between simulation and experimental results. Furthermore, various lubricants were used with the aluminum and copper to examine their performance in microforming. The results have shown that the workpiece materials not only determine the friction factor, *m*, during unlubricated microforming, but also influence the performance of lubricants. Lubricant can be completely ineffective and may not produce discernible friction reduction in microforming, unlike in conventional metal forming. By considering the influence of contact pressure on lubricant effectiveness, a novel pressure dependent frictional model and a lubricant evaluation method are proposed.

1. Introduction

Development of miniaturization techniques has been a major contributor to new technologies in many segments of manufacturing industry. Industries such as IT, technology hardware and process automation for micro-processes have been boosted tremendously by the ever-developing techniques of miniaturization. As in the case of metallic micro-parts, their production at the present is dominated by micro-machining and MEMS-based processes. For general manufacturing, Altan et al. (2005) suggested that forming technology with its high productivity and low waste is generally preferred. Due to the demand to mass produce micro-parts, the boundary of metal forming processes has been steadily pushed to improve the general capability of forming at the smaller scale.

However, Geiger et al. (2001) revealed that the know-how in metal forming processes starts to break down when it is applied to microforming. Consequently, investigations on the mechanisms for the shift of material behaviors during miniaturization, or so-called the size effect, have become extensive in recent years. Among which, the shift of material mechanical properties and the change in frictional behaviors have been predominantly studied as summarized by Jeswiet et al. (2008). Microforming system is considered as a convolution of four individual aspects by Geiger et al. (2001): material, processes, tools and machine and the sources of size effects were categorized to physical (i.e. size effects influenced by the surface to volume size effect and relation of forces) and structural (i.e. size effects influenced by the grain distribution and surface roughness) by Vollertsen (2008).

Jeswiet et al. (2008) concluded that several past friction investigations in microforming have shown a significant size effect in lubricated contact, i.e. friction is increased with miniaturization. Geiger et al. (2001) presented a mechanical–rheological model based on the distribution of lubricant pockets on contacting surfaces. In such surfaces, the surface roughness naturally forms craters which subsequently become microscopic lubricant reservoirs. It was explained that the lubricant stored in craters closer to the edges of the surface is more likely to escape from the craters during contact making the lubrication ineffective in this region. Hence, as the components produced are miniaturized and the surface roughness remains relatively constant, the overall lubrication becomes less effective. This model has also been used in one of the investigations in Chan et al. (2011) to explain similar experimental findings of increased friction with miniaturization. Peng et al. (2010) used the lubricant pocket model further in a simulation to explain that friction behavior in microforming lies between conventional lubrication friction (low friction) and dry friction (high friction).

Prior microforming friction investigations used generic friction tests such as double cup extrusion test as reported by Geiger et al.

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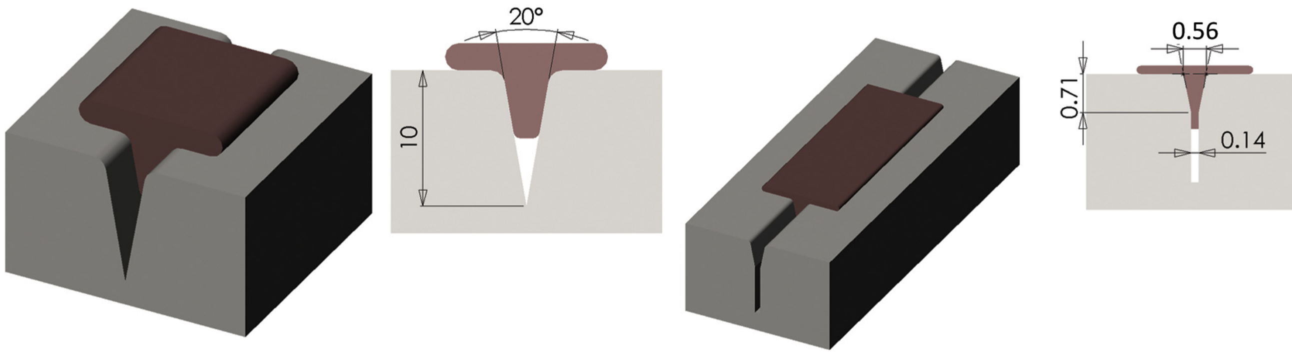

Fig. 1. (Left) Original and (right) microforming T-Shape test.

(2001). Qin et al. (2008) outlined the importance of considering the tool-fabrication capabilities and tool cost when designing microforming process. Microforming designers need to consider the available technologies and processes which can be used to produce certain components for a new machine. It also includes the accuracy each technology or process can achieve and its respective cost. Thus in miniaturized tooling fabrication, intricate geometry is generally avoided to minimize the possibility of: (a) imprecise fabrication, or (b) expensive tool cost. Therefore, the use of conventional size friction test was deemed undesirable.

In addition, although it has been well understood that the magnitude of friction can be reflected by the forming load during metal forming process as investigated by Isogawa et al. (1992) through the use of spike test, the same may not apply in microforming due to the presence of size effects on material mechanical properties. Yun et al. (2010) presented an example of the size-dependent deviation of the mechanical properties in microforming and established the need to provide a novel constitutive material model to represent the workpiece in microforming process.

Various friction tests for metal forming processes such as the ring compression test (by Male and Cockroft (1964)), double cup extrusion (by Buschhausen et al. (1992)) and spike test (by Isogawa et al. (1992)) have been proposed and they were designed to identify the influence of contact properties, e.g. contacting materials, surface finish of the tooling and lubricant, to study frictional behavior during macro metal forming processes. As such, the typical characteristics of metal forming processes of high contact pressure and large amount of plastic deformation need to be imitated in these friction tests. For adaptation to microforming friction investigation, there are added considerations of the tool-fabrication capabilities and tool cost, handling and characterization methodology.

Upon reviewing nine notable friction tests for metal forming, a modification to the T-Shape test was proposed by Taureza et al. (2012) as a friction test for microforming, referred to in this study as the microforming T-Shape test. The original T-Shape test was introduced by Zhang et al. (2009) to recreate the high contact pressure and plastic deformation which are characteristics of cold forging processes for macro size. The test produces co-existence of extrusion and upsetting metal flow similar to the process of micro-forging/extrusion process as performed by Ghassemali et al. (2013) which contributes to its friction-sensitive finished workpiece geometry. At macro size, the test has also been used to investigate high temperature forming behavior of magnesium alloys and the test showed repeatability of results by Fereshteh-Saniee et al. (2011). The modifications proposed by Taureza et al. (2012) include the higher length to diameter ratio and change in the characterization approach (both to ease material handling) as well as the change in die geometry for improved friction sensitivity. Fig. 1 illustrates the construction of the original T-Shape test die with workpiece initial diameter of 7 mm and length of 7 mm alongside the modified geometry for initial diameter of 1 mm and length of 5 mm.

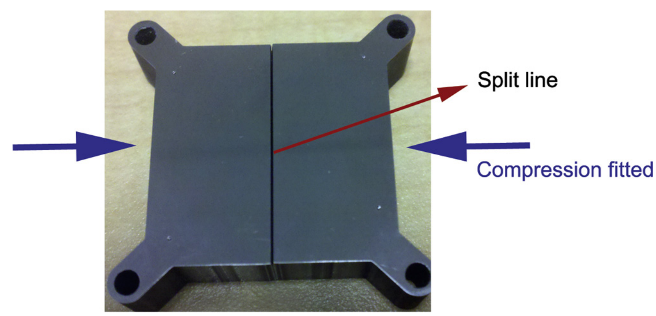

Fig. 2. Microforming T-Shape dies used in experiment.

This paper presents the results on the influence of materials in contact to frictional behavior using the microforming T-Shape die setup. Three workpiece materials (copper, aluminum and silver) were selected as they are considered materials of interest in many industrial applications. All three materials possess face-centered cubic (FCC) crystal structures, hence such selection filters out the influence of crystal structures in the current investigation. The frictional behavior during the microforming friction test was evaluated through benchmarking with simulation results using friction factor, *m*.

2. Experimental setup

The Schmidt Servo Press 420 was used to perform the experiments. The punch-die assembly was fabricated from heat treated Hitachi SLD Magic steel with the surfaces polished to a surface roughness of Ra 0.08–0.12 μm. The microforming T-Shape split dies used in the experiments are presented in Fig. 2. Split dies were used in microforming T-Shape test to allow post-test examination of tooling surface to inspect galling and defects on tooling surface.

The workpiece materials chosen were 1 mm diameter aluminum wire with 99.5% purity and as drawn condition, 1 mm diameter silver wire with 99.99% purity and annealed condition as well as 1 mm diameter ETP copper wire. The miniature round bars for the experiment were prepared by cutting from a stock reel to 5 ± 0.5 mm length.

Alongside the experiments, implicit finite element (FE) simulation using Deform 3D and quarter-workpiece simulation domain (with approximately 30,000 elements, Fig. 3) was conducted in order to produce friction calibration curves. Symmetry boundary conditions as illustrated in Fig. 3 were prescribed on the symmetry planes as the four quarters of the workpiece are assumed to deform uniformly and the resource saved can be used to allow finer meshing to capture higher deformation details. During the simulation,