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Abstract

Micro hydroforming has an ability to manufacture complex 3D micro parts at a high production rate and has drawn increasing attentions. Brief understanding of macro hydroforming, for instance, deep drawing, is necessary to understand the principle of micro hydroforming. Then, special phenomena, such as size effects, occurred at micro scale are discussed and the related theories explaining these phenomena are introduced. Based on the similarities and differences between micro and macro hydroforming, experiments and simulation which consider the size effects are reviewed.

Keywords

micro hydroforming, micro hydromechanical deep drawing, size effects, numerical simulation

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Study on Micro Hydroforming of Metals

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Abstract. Micro hydroforming owns ability to manufacture complex 3D micro parts at a high production rate and draws increasing attentions. Brief understanding of macro hydroforming, for instance, deep drawing, is necessary. Then, special phenomena, such as size effects, occurred at micro scale are discussed and relating theories explaining these phenomena are introduced. Based on the similarities and differences between micro and macro hydroforming, experiments and simulation which considers the size effects are reviewed.

Introduction

With micro electromechanical systems (MEMS) presenting deep and comprehensive influences on our lives, there is an urgent demand on developing new methods for manufacturing truly 3D micro parts with complicated geometries and non-silicon materials at a high machining speed [1, 2]. Micro forming, especially micro hydroforming, is a potential technology with promising superiors over other micro processing methods, such as LIGA, silicon based technologies and ultra-precise micromachining methods [3-5].

Hydromechanical deep drawing, a typical hydroforming process, has been employed in industry while micro hydromechanical deep drawing, though exhibiting similarities to normal drawing process, is a budding technology. That is because that, when scaling down normal drawing, material behaves differently from that at the macro level. Phenomena, such as an increased flow stress, a data scatter and a different frictional property in micro drawing process, have been investigated and proved bearing close relation to sizes. Accordingly, these phenomena are labelled as size effects and then some theories are publicized as explanations for these phenomena.

Due to the similarities between macro and micro hydromechanical deep drawing, research results of macro hydromechanical deep drawing are reviewed at first. Subsequently, theories explaining material's different behaviours at the micro level are introduced. Experiments on micro hydroforming and numerical simulation that employs size based models are discussed at the end of this paper.

Macro Hydroforming

Micro hydroforming has some similarities to macro hydroforming, therefore the research methods and key factors in macro hydroforming can be drawn on for study of micro hydroforming.

Generally, hydroforming performs better than forming without hydraulic assistance in terms of achievable forming limit, surface finish and shape accuracy. For hydromechanical deep drawing, a suitable hydraulic pressure path is one key factor as it provides frictional holding effect, overflow effect and beneficial stress state. During the drawing process, there are four stages for hydraulic pressure. A proper prebulging before actual drawing benefits formability and resistance of wrinkling. Then the hydraulic pressure increases from a low value to a high level gradually in the second stage. Next, the hydraulic pressure remains at a high degree to offer frictional holding effect

and overflow effect. At the end of drawing process, a decreasing pressure is beneficial to drawing and resistance of springback [6]. Further, FEM results show that an increased hydraulic pressure changes local thinning position and improves shape accuracy. Moreover, an over pressure leads to fracture and an inadequate pressure results in wrinkling.

According to the hydraulic pressure, the blank holding force should also be changeable. Small forces at beginning and end and a large force at middle stage of drawing process are suitable. However, neither a constant gap between blank holder and die nor a constant blank holding force, which are commonly utilised in deep drawing, is suitable for prevention of fracture and wrinkling.

To improve the drawability and formability, investigations into parameters of both drawing machine and drawing process have been conducted and modifications of drawing machine have been tried. The hydraulic pressure has been introduced to controlling the blank holding force and offering a peripheral push on the blank. A limit drawing ratio (LDR) of 2.77 was obtained by this method [7]. The die and punch are also modified. A stepped punch with a re-entrant feature was developed to improve drawability [8]. A tractrix die was built to research the drawing process and optimisation of parameters improves LDR [9]. A conical die with a square aperture at the end was introduced to form square cups. Through this design the blank holder is omitted and square cups can be produced at a small peak punch force in one stroke [10]. Square cups were also manufactured by a square punch and a round die, as shown in fig. 1, which provide a local constraint [11]. An angular die was introduced into drawing process for investigating influences of radii of punch nose and die fillet on the drawability. A large angle of die and great radii of punch nose and die fillet benefit the LDR [12]. Elliptic and irregular cups were produced by hydromechanical deep drawing. Properly increasing the punch nose roughness enhances frictional holding effect which improves cup thickness uniformity [13].

Fig. 1 Scheme of hydromechanical deep drawing with a square punch and a round die

At the macro level, hydromechanical deep drawing generally performs better than deep drawing, if well adjusting the hydraulic pressure path and the blank holding force. Parameters of both drawing machine and drawing process have been investigated. Further, modifications on drawing machine have also been tried and studied. All these attempts to improve drawing performances can be drawn on in micro hydromechanical deep drawing process.

Micro Deformation Phenomena

At micro level, material behaves differently from that at macro level and presents size effects. Therefore, understanding of material behaviours is indispensable for micro hydroforming process.

An increase of flow stress with decrease of specimen size was observed. Consequently, a surface layer model was developed to explain this phenomenon from a dislocation viewpoint. Grains on the surface are less restricted than inner grains due to dislocation cannot pile up at surface [14]. As scaling down the specimen sizes, the ratio of surface area to volume increases and the weaken effect introduced by the surface layer becomes significant. Further, a transitional layer was inserted

between surface layer and inner layer for accuracy calculation [15]. If reducing the sample size further to a grain size level, an increase of flow stress can be observed. That is because that at the grain size level each grain in the deformation zone participates into deformation while if specimen size is larger than grain size, grains in the deformation zone present selective deformation which lowers deformation resistance [16]. However, protective passivation oxidation layer generally has much higher deformation resistance than that of inner grains. Therefore, the flow stress increases with decrease of specimen sizes.

As there are only a few grains in the deformation zone, and each grain has different size, orientation and properties, randomness of grains' characteristics results in an increase of data scatter with a decrease of sample size.

In micro deep drawing, the proportion of friction force to total drawing force becomes significant. The constant frictional coefficient tribological theory is challenged by the observation of an increase of frictional coefficient in experiments, such as double-cup extrusion tests. Then an open and closed lubricant package theory was proposed [17]. Once scaled down to the micro level, the closed lubricant packages are reduced and cannot seal pressed lubricant, which increases real contact pressure shouldered by asperities on the surface and consequently the frictional coefficient. Furthermore, pool lubricant conditions lead to temperature rise and reduced oil viscosity and eventually, worsen lubrication effect [18].

A Tiffany structure was introduced to represent a sheet with only one grain in cross section direction while many grains along in-plan directions [18]. The Tiffany structure affects LDR and formability as it amplifies strain localisation. Additionally, the authors in literature [18] also found that grain sizes should be in correspondence with feature sizes as gains with smaller sizes than feature sizes can flow into and fulfil the features.

Temperature alters forming process at both macro and micro level. A high temperature improves formability of material due to it activates dislocation movement and consequently releases restriction of grains [14]. The high temperature also flattens the data scatter.

At micro scale, material behaves differently and some theories have been proposed as phenomenological explanations. However, mechanism of these phenomena is unclear. Moreover, ignorable factors at macro scale, such as surface tension and Van der Waals force, become significant and should be considered.

Simulation and Experiments

Based on the similarities and differences between macro and micro hydroforming, especially micro hydromechanical deep drawing, experiments and simulation with new models have been conducted.

Normalisation was utilised to represent and design micro forming tools' parameters [19]. For micro deep drawing process, parameters normalised by blank thickness were employed and optimised. Similarly, the blank holding force was thought to be a parabola in a dimensionless form [15]. Influences of punch velocity on micro deep drawing were studied. A high punch velocity results in a large peak blank holding force and a small frictional coefficient. Further, the processing window enlarged with a decrease of friction [20]. A two-step blanking-drawing process is employed for precisely positioning of the blank in the micro drawing process. Through micro deep drawing experiments, it is found that surface roughness is smoothed by tensile stress whereas roughened by compressive stress [21].

A dislocation based constitutive model that draws on surface layer model was built to simulate micro deep drawing of ultrafine grain copper [22]. Although considered surface layer model, only a weighted average flow stress was utilised in simulation. Then, a multi-region model was developed where three regions, namely inner polycrystalline region, grains interior of surface layer and grain-boundary layer on surface, were considered with different properties [23]. Simulation analysis that applies this model is in accordance with compress experimental results.

Given the inhomogeneity of material, twelve different regions were chosen to obtain the material properties. Then, these twelve material properties were applied in the FE model to represent randomness of grain characteristics. Size effects, such as the increase of flow stress and data scatter,

can be predicted by this model [24]. A rate-dependent slip model with the Kocks-type strain hardening expression for pure aluminium was developed. Then Voronoi tessellation was employed for representing microstructure, where each Voronoi cell stands for one grain with different properties [25]. The Ludwik's law was utilised to describe a flow stress curve in micro deep drawing process. Then, a 2D axisymmetric implicit simulation that takes transverse anisotropy into account and a 3D explicit case that considers planar anisotropy were conducted. Simulation results show that with a constant frictional coefficient simulation results cannot meet both maximum drawing force and ironing force simultaneously compared to experiments. Moreover, a few tens of microns' tolerance can lead to an over 10% deviation of the peak drawing force [26]. Modification of the Swift model via adding an extended function which introduces blank thickness and grain size, as shown in Eq. 1, has been tried to reflect size effects [27].

$$\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon})^n F(t, g) \dots\dots\dots (1)$$

where $\bar{\sigma}$ is the flow stress, ε_0 is the initial yield strain, $\bar{\varepsilon}$ is the equivalent strain, K is the strength coefficient, and n is the strain-hardening exponent. $F(t, g) = \frac{a_1 t^2 + b_1 t + c_1}{a_2 g + b_2}$, a_1 , b_1 , c_1 , a_2 and b_2 are material parameters, t and g stand for the thickness and the grain size of the blank, respectively.

Gong et al. confirmed the open and closed lubricant package theory by comparison of micro deep drawing with three lubricants [28]. PE film with high viscosity benefits drawing process due to it can be maintained during drawing process. An exponential function, shown in Eq. 2, was obtained through strip drawing experimental results and utilised as a contact pressure based frictional coefficient [29]. Then this function was introduced into rectangular deep drawing process successfully [30].

$$\mu = C_1 + C_2 \cdot \exp(-p \cdot C_4) + C_3 \cdot \exp(-p \cdot C_5) \dots\dots\dots (2)$$

where C_1 to C_5 are parameters with no physical meaning and measured from friction tests. P is normal pressure.

A laser beam was employed to heat the blank in micro deep drawing process, the LDR of low carbon steel with thickness of 0.1mm increased from 1.033 to 2.2 [31].

Research on micro hydroforming, especially micro hydromechanical deep drawing, has mixed both similar factors, such as punch force, punch velocity and blank holder force, and differences, for instances, size effects. However, as a new technology, fundamental mechanism is still undiscovered and versatility of simulation models and experimental methods is limited.

Conclusions

Micro and macro hydroforming have similarities and differences. A general knowledge on macro hydroforming, especially hydromechanical drawing, is reviewed. The special phenomena that are different from macro world are introduced and their explanations are discussed. At the end, current simulation and experimental work on micro hydroforming, for example micro hydromechanical deep drawing is discussed. As a budding technology, further efforts on investigation of micro hydroforming are needed.

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