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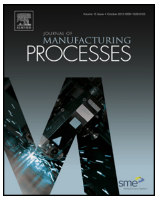

Technical Paper

The development of a microscale strain measurement system applied to sheet bulge hydroforming

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ABSTRACT

Micro and multiscale sheet metal forming processes represent new and attractive solutions to many manufacturing problems. However, evaluating the strains in these products is a difficult endeavor. Larger organizations are utilizing commercially available microscale digital image correlation systems to measure the strains in microscale parts or on macroscale parts with critical microscale features. The cost of these strain measurement systems is preventing smaller research and development organizations from entering this challenging area or they are forgoing the ability to determine strains. The present paper describes the development of a method for creating microscale grids and measuring strains on microscale parts or microscale locations on larger parts. The method developed was able to measure true strains up to 0.618 for square grids that are 127 μm measured from center-to-center. Microscale strains resulting from sheet bulge hydroforming experiments using 11 mm, 5 mm, and 1 mm diameter dies were evaluated and material properties of the sheet metal were estimated based upon the strains measured in conjunction with FEA simulations and compared to analytical solutions and microscale tension tests. The material properties determined using the strains and FEM approach were consistent with the other methods.

1. Introduction

Researchers focusing on macroscale sheet metal forming frequently need to determine the strains in the sheet. This may be achieved analytically, using finite element analysis (FEA), or direct measurement of the strains using either digital image correlation (DIC) or grid measurement techniques. Recently, researchers have begun to develop microscale sheet metal forming processes by modifying macroscale approaches in order to produce microscale features. Developing these processes is complicated by not just the small size of the parts but also by the reduced number of grains though the thickness of the part which results in material properties that differ significantly from published macroscale material properties. Hence, testing is required in order to determine material properties as well as validating new designs. A key requirement for evaluating part compliance and material performance is the ability to measure strains and strain fields in critical regions. For researchers and product developers; determining evaluating features and measuring microscale strains represents an added challenge.

One of the growing areas in multiscale sheet metal forming is the use of microscale hydroforming parts or microscale features on macroscale parts. One example of a macroscale part with microscale features is a bipolar plate for fuel cells. These are formed either using one or two dies, a sealing system, and hydraulic or pneumatic pressure. The pressure required to form microscale parts that have small part diameter to thickness ratios can be extremely high, exceeding 350 MPa. As a result, the tooling and equipment must be designed to withstand high pressures. The cost of the equipment may be partially offset by reduced tooling wear due to low friction between the sheet and the tooling and the processes ability to force sheet metal into sharp corners compared to stamp forming processes [1]. For fuel cells, the reduction in tooling costs and wear are extremely favorable because of the complex geometries of the microchannels in bipolar plates which have sharp corners.

As with macroscale sheet metal forming, microscale hydroforming tests may be used to determine the material properties of

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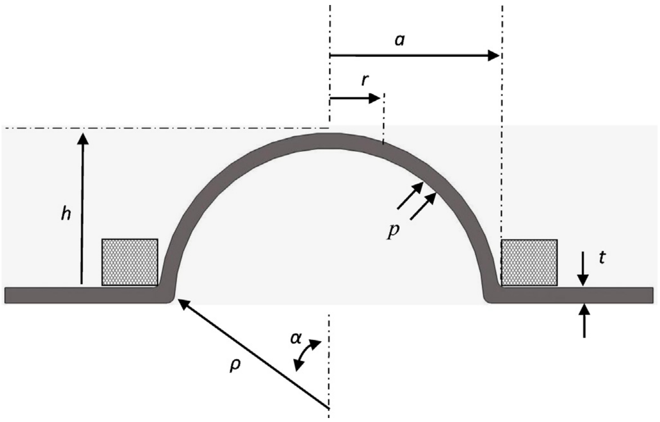

Fig. 1. Schematic of open die sheet hydroforming.

the sheet metal, either for determining forming limits, or biaxial material properties, assuming that the plastic deformation may be modeled using a power law relationship. At the pole of a bulged sheet, the sheet is in biaxial tension. Several researchers have developed methods for estimating the material properties based upon the bulge height and forming pressure. Marciniak et al. developed an analytical method for determining the stress and strain at the pole of the bulge. For macroscale sheet hydroforming the Marciniak analytical approach (Eqs. (1)–(3)), provide satisfactory results [1]. If the material properties are to be determined, a least squares fit can be then used to determine the power law relationship for deformation after yielding occurs.

$$p = \frac{2\sigma_\phi t}{\rho} = 4\bar{\sigma} t_0 \frac{h}{a^2} \frac{1}{\{1 + (h/a)^2\}^2} \tag{1}$$

where

$$\sigma_\phi = \bar{\sigma} = K\bar{\varepsilon}^n = K\left(\ln\frac{t_o}{t}\right)^n = K(2\phi_\phi)^n \tag{2}$$

and

$$\rho = \frac{(a^2 + h^2)}{2h} \tag{3}$$

For these equations, p is the forming pressure, $\bar{\sigma}, \bar{\varepsilon}, \sigma_\phi$, and ε_ϕ are the effective true stress effective true strain, membrane stress, and membrane strain at the pole of the bulge. The geometric variables are the bulge height h, measured at the pole; the half diameter of the die a; the radius of curvature of the deformed sheet ρ; and the original and instantaneous thickness of the sheet t_o and t, measured at the pole of the bulge. Fig. 1 is a pictorial representation of a sheet undergoing bulging. In addition, the circumferential strain ε_ϕ, can be measured at the pole of the bulge; the effective stress $\bar{\sigma}$ can be determined if the forming pressure and the bulge height is known. For Eqs. (1)–(3) it is assumed that the power law material relationship, $\sigma = K\varepsilon^n$, may be applied if the strength coefficient K and the strain hardening exponent n may be determined experimentally through tension tests.

Ekineev–Kruglov also developed an analytical approach between pressure, stress, and strain based upon the material deformation being modeled as a sine function. Their approach has been is documented as the more accurate method compared Marciniak et al.'s [2]. However Marciniak et al.'s approach is the most well-known and will be used in this research. Siegert and Wagner [3] reported an approach by Gologranc [4] for determining the flow stress while bulge testing and then summarized Panknin's method for determining the thickness stress [5]. However, it should be pointed out that Marciniak's sheet hydroforming equations as well as the Ekineev–Kruglov and Gologranc equations for hydroforming all assume a high diameter to thickness ratio, which may not be valid assumptions for some hydroforming operations such as when the diameter to thickness ratio is less than ten or if there is a significant variation in the bulge thickness at the pole compared to other locations of the dome. If material properties are to be determined from the bulge tests under these conditions, the researchers must then consider tensile test results or possibly iterative approaches based upon FEA in order to converge upon approximate material properties for the material. Also, analytical methods do not allow researchers to determine strains elsewhere on the bulge.

Extending hydroforming from the macroscale to the microscale, the size effect for scaling down the sheet from macroscale to microscale features is related to the size, location, and orientation of grains within the structure. Several drawbacks have been encountered when scaling down forming processes, primarily because of size effects including the impact of material grain behavior. The influence of grain behavior is extremely noticeable while working with materials that have thicknesses that are less than a micron and even less than one millimeter. Other notable size effects related to the grain structure occur as the number of grains is reduced through the thickness, resulting in a decrease in the yield stress and an increase in the strain hardening exponent. Gau et al. found materials hardness measurements to be contradictory to the Hall–Petch effect when compared to the macroscale effects [6]. These material hardness results, combined with other grain-size effects, make further micro-scale testing of material properties imperative. Kim et al. [7] described introducing two parameters, α and β into the Hall–Petch equation. Gau et al. [8] also examined size effect for flow stress. These results are significant when considering deep drawing applications and hydroforming. However, the experimental data have shown inconsistent process behavior. For example, Raulea et al. found no clear patterns have been observed that would define the strain hardening/yield stress phenomenon encountered while using CuZn15 (Brass) [9].

Issues related to strain have been considered for microscale forming. For example; Zhuang et al. have advocated the use of an integrated crystal-plasticity multi-crystal finite element (CPFE) approach to model tube microscale tube hydroforming [10]. They showed that for microscale tubes, which have only a few grains through the thickness of the wall, CPFE may predict localized necking where the tube section crosses the crystal axis. However, in order to predict localized necking, it is necessary to utilize material properties that are appropriate for microscale deformation processes.

2. Microscale strain measurement

Measuring strains on the microscale remains difficult. The most obvious method is to follow Marciniak et al.'s lead by either measuring the bulge height at the pole and use Eqs. (1)–(3) in order to determine the strains or measure the thickness strain by either by sectioning the deformed work piece in order to measure the thickness or by simultaneously using two LVDTs in order to measure the height of the bulged sheet from the bottom and top of the pole. The two direct measurement methods used for macroscale strains for sheet metal forming are DIC and strain grid deformation. There are several commercially available systems for both methods. Table 1 lists the published accuracy of a commercially available DIC system and a commercially available macroscale strain grid measurement system. It is clear from the table that the DIC system is both much more accurate and much more expensive than the strain grid measurement system. However, the cost of both systems can be prohibitive for entry level research and development projects where microscale strains need to be measured despite the need