Journal of Materials Processing Technology 212 (2012) 1916–1924

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Study on formability of tube hydroforming through elliptical die inserts

Shuhui Li[a,*], Xianfeng Chen[a], Qingshuai Kong[a], Zhongqi Yu[a], Zhongqin Lin[a,b]

[a] *Shanghai Key Laboratory of Digital Autobody Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *State Key Laboratory of Mechanical System and Vibration, Shanghai 200240, China*

ARTICLE INFO

Article history:
Received 21 November 2011
Received in revised form 23 March 2012
Accepted 21 April 2012
Available online 27 April 2012

Keywords:
Formability
Tube hydroforming
Biaxial stretching
Elliptical bulging
Forming limit curve (FLC)
Elliptical die inserts

ABSTRACT

This paper proposes a novel experimental approach to evaluate the formability for tube hydroforming under biaxial stretching through elliptical bulging. The idea comes from the hydraulic stretch-drawing tests with elliptical dies for the right hand side of forming limit curve (FLC). Based on the deformation theory and the classical Hosford yield criterion, an analytical model is constructed for the elliptical bulging of tube hydroforming. Then the novel experimental device is designed with five upper elliptical die inserts and one lower die insert used to produce ellipsoidal bulged domes and some experiments are performed. The linear strain paths in different strain states are verified and the right hand side of FLC for roll-formed QSTE340 seamed tube is determined through the proposed experimental approaches. Finally, a comparison between the theoretical results and experimental data is performed. The theoretical predictions show good agreement with the experimental results.

1. Introduction

Due to increasing demands for lightweight parts, tube hydroforming has been widely used to manufacture parts in various fields, such as automobile, aircraft, aerospace, and ship building industries (Dohmann and Hartl, 1996). During tube hydroforming, several forming parameters, including the loading path, material properties, die design, and friction at the tube-die interface, significantly influence the results. So the finite element method (FEM) has been widely used to predict and estimate the formability of the tube hydroforming process recently (Kang et al., 2005). The forming limit curve (FLC) or the forming limit diagram (FLD), which introduced by Keeler and Backofen (Keeler and Backofen, 1963) in the 1960s, is an important input for FEM simulation of parts. The experimental measurement of FLC has become common practice in the process of evaluating the formability of sheet metal. Test methods like Nakazima and Marciniak are frequently used as standardized test methods. But now there are not standardized and authoritative test methods used for the FLC of tube hydroforming in the whole forming modes. Therefore it is important to investigate the experimental approaches to obtain the curve.

The important problems of establishing the FLC are the determination of various linear strain paths and the suitable apparatus. In sheet metal tests, various strain states are achieved by adjusting different parameters like the lubrication conditions between the sheet metal and the punch and the sheet width, and a hemispherical punch or a cylindrical punch is used. In tube hydroforming, several research studies have been reported concerning the loading paths or the forming limit of tubes. Asnafi (1999) constructed analytical models to determine the loading paths for force-controlled tube free hydroforming. Asnafi and Skogsgardh (2000) also studied stroke-controlled tube free hydroforming theoretically for the linear strain paths. Chu and Xu (2008) investigated the prediction of FLD for tube hydroforming from the perspective various combinations of loading paths based on plastic instability. Davies et al. (2000) proposed a tooling and experimental apparatus to establish the FLC for AA6061 tube based on the free-expansion tube hydroforming with axial compression and internal pressure. Hwang et al. (2009) carried out bulge tests to establish the FLC of tubular material AA6011. A self-designed free bulge forming apparatus of fixed bulge length and a hydraulic test machine with axial feeding were used to carry out the bulge tests. Kim et al. (2005) performed a series of free bulge tests to evaluate the forming limit of the hydroforming process. The test tube is supported between a lower and an upper die. The lower part of the tube is fixed in movement, while the other is free to be able to move in the axial direction for providing axial feeding. Song et al. (2010) also executed a series of free bulge tests to the forming limit curve for tubular material in the tube hydroforming process with the same experimental apparatus.

All the investigations known in literature so far are concentrated on the free bulge tests with axial compression and internal pressure. So only the left hand side ($\beta < 0$) of FLC could be obtained from experiments. To obtain the right hand side ($\beta > 0$) of FLC, both ends of tube are subjected to different loading histories

---

* Corresponding author. Tel.: +86 21 34206304; fax: +86 21 34206304.
E-mail address: lishuhui@sjtu.edu.cn (S. Li).

0924-0136/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jmatprotec.2012.04.016

involving axial tension and internal pressure. The difficulty is to clamp both ends of tube with internal pressure. Yoshida and Kuwabara (2007) constructed the FLC for a steel tube from uniaxial to equibiaxial tension regions using a self-designed servo-controlled tension/compression-internal pressure testing machine. Korkolis and Kyriakides (2008) investigated the inflation and burst of Al-6260-T4 tubes under combined internal pressure and axial tension/compression load through a combination of experiments and modeling and observed that localized wall thinning and burst can be very sensitive to the constitutive description employed for the material. Chen et al. (2011) designed a novel device requiring the simultaneous application of lateral compression force and internal pressure to control the material flow under tension–tension strain states. But the suitable loading paths for the right hand side of FLC are calculated by FEM simulations and the accuracy is not high.

In sheet metal forming, the right hand side of FLC can be obtained by hydraulic stretch-drawing tests with elliptical dies. Rees (1999) outlined a theory of diffuse instability for ellipsoidal bulging of oriented, orthotropic rolled sheet metals under biaxial tension. Comparisons are made with the limiting strains and the peak pressure is observed from experimental pole failures. Giuliano et al. (2005) performed bulge tests using elliptical shape dies with different aspect ratios to predict the limit strains of PbSn60 alloy under biaxial stress at the room temperature and at constant gas pressure. Altan et al. (2006) used biaxial bulge tests to determine the material properties (flow stress, anisotropy and formability) over a large strain/deformation range. Abu-Farha et al. (2008) presented a detailed systematic methodology for assessing formability and limiting strains by pneumatic sheet metal stretching. The proposed approach is demonstratively applied to the AZ31 magnesium alloy at elevated temperatures. Since the biaxial bulge test for sheet metal has not been standardized yet, the biaxial bulge test has its own specific field of application due to biaxial tension strain paths.

In this study, it is attempted to propose a novel approach to study the formability of tube hydroforming under biaxial stretching from the biaxial bulge test for sheet metal. The principle is described and an analytical model is developed for the elliptical bulging of tube hydroforming. An experimental setup is designed with five upper elliptical die inserts and one lower die insert used to produce ellipsoidal bulged domes with different biaxial strain ratios. Then some experiments are performed. The linear strain paths in different strain states are verified and the right hand side of FLC for seamed tube is determined. Finally, a comparison between the theoretical results and experimental data is performed. Good correlation is observed between the theoretical results and experimental data.

2. Analysis for tube elliptical bulging

2.1. Principle description

In order to observe the material deformation behaviors of the simplest tube free bulge hydroforming, FEM simulation is performed with both tube ends fixed. The simulation results for the strain ratio of the node with the lowest thickness value at the top of the bulge are shown in Fig. 1. In order to achieve the tension–tension strain states, the free expansion length is relatively short.

The simulation results show that the materials are difficult to be strained under tension states in longitudinal direction. The plastic deformation is primarily under plane strain state at the initial stage. So in order to study the formability of tube hydroforming under biaxial stretching, an approach must be proposed to improve the deformation in longitudinal direction under tension–tension strain states.

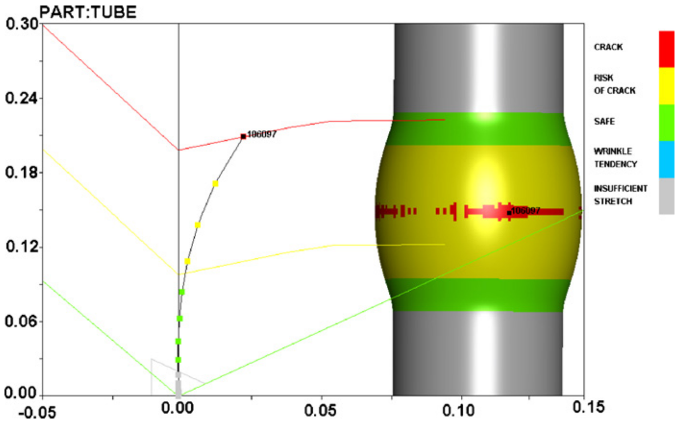

Fig. 1. Simulation results for tube free bulge test.

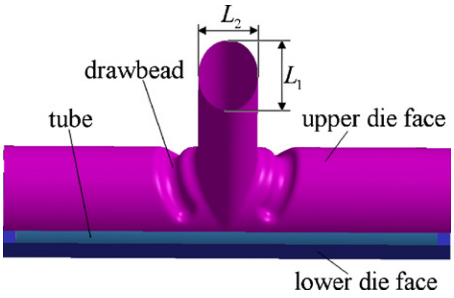

Fig. 2. Principle diagram for tube hydrofroming under biaxial stretching.

In sheet metal bulge test, different elliptical aspect ratios inserts are used to produce ellipsoidal bulged domes with different strain ratios. These geometrical aspect ratios represent the ratios between the minor and major axes of the elliptical die inserts, and do not necessarily equal the biaxial strain ratio at the apex of the bulged ellipsoidal dome.

So in tube hydroforming, different elliptical aspect ratios ($\gamma = L_2/L_1$) die cavities are used for different biaxial strain ratios ($\beta = \varepsilon_2/\varepsilon_1$). In tube elliptical bulging, both ends of tube are fixed. And as shown in Fig. 2 L_1 is the major axis in circumferential direction and L_2 is the minor axis in longitudinal direction. The decrease of L_2 is benefit for the deformation in longitudinal direction under tension–tension strain states. The upper die faces are designed with drawbead and without drawbead. The use of the drawbead is to control the material flow along larger biaxial strain ratios with the same elliptical aspect ratio.

In order to verify the principle for tube hydroforming under biaxial stretching, FEM simulation is used before the experimental setup manufactured. The test seamed tube with 58 mm outside diameter, 2.5 mm wall thickness and 210 mm long, is produced by roll forming and welding the QSTE340 sheet metal. Micro-hardness profile (Chen et al., 2011) indicates that a seamed tube is composed of weld metal, heat affected zone (HAZ) and base metal, and the weld metal and HAZ width is approximately 4 and 6 mm. The stress-strain relations for three parts of seamed tube are fitted to the flow curve as $\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon})^n$. Material properties for each part are listed in Table 1.

The FEM model of tube hydroforming is set up in FEM program LS-DYNA, which is composed of a rigid upper die, a rigid lower die and a deformable seamed tube. The deformable seamed tube is modeled using the 4-noded Belytschko–Tsay shell elements with 7 integration points through the shell thickness, and the MAT 036-model of LS-DYNA “Mat_3-Parameter_Barlat” is used. The contact