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Deformation analysis of double-sided tube hydroforming in square-section die

Xiao-Lei Cui, Xiao-Song Wang*, Shi-Jian Yuan

National Key Laboratory of Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, Heilongjiang, PR China

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ABSTRACT

In this paper, in order to explore the deformation behavior of double-sided tube hydroforming in square-section die, effect of external pressure on the critical effective strain was theoretically analyzed firstly. And then a special experimental setup was designed for double-sided tube hydroforming in which the difficulty of simultaneous loading was overcome using two independent intensifiers and servo controlling while the sealing of external pressure was guaranteed by the O rings assembled in the interfaces of mandrel/base plate and outer cylinder/base plate. Furthermore, 5A02-O aluminum alloy tubes with outer diameter of 63 mm and thickness of 2 mm were investigated under different external pressures varying from 0 to 80 MPa. At the same time, numerical simulation was conducted using the Abaqus/Explicit software. It is shown that increasing of external pressure has an effect on the fraction of grain boundaries, the number and size of the microvoids and the microhardness in the transition zone, and thus increases the critical effective strain in the transition zone. It can be concluded that the deformation ability of the transition zone is improved by the external pressure in double-sided tube hydroforming of square-section. This investigation shows that double-sided tube hydroforming is a potential forming method for the fabrication of lightweight hollow structures using the tubes with low ductility.

1. Introduction

With the urgent requirement of energy conservation and emission reduction in the fields of automobile and aerospace, lightweight alloys, such as aluminum alloy and magnesium alloy, were proven to be the preferred alternative to traditional steel materials (Hirsch and Al-Samman, 2013). The structural members with different cross-sections have been widely used in aerospace and automobile industry due to their excellent bending performance and high stability of assembly (Lang et al., 2004). However, the onset of plastic instability is more likely to happen in the transition zone because of the too large hoop stress in the process of corner filling for tubes with poor formability such as aluminum alloy tubes and magnesium alloy tubes (Liu et al., 2006). Tube hydroforming process is one of the most important forming technology in which the formability of the tube can be improved obviously by the combined action of axial force and internal pressure. Nevertheless, the stress state applied on the tube can be simplified as plane stress state due to the negligible internal pressure compared with the in-plane stress (Dohmann and Hartl, 1996).

As is known, material's formability is not only related to its inherent properties, but also has a strong dependence on the imposed stress state when it is undergoing plastic deformation (Lewandowski and Lowhaphandu, 1998). Motivated by such theories, double-sided tube hydroforming is proposed, where hydraulic pressure is introduced on both sides of the tube and/or the axial force is applied on the tube ends simultaneously, and then the tube is formed into the required shape under the pressure difference and/or the axial force (Jain, 2003). Nucleation, growth and coalescence of micro voids in the tube materials can be suppressed effectively by applying external pressure on the outside surface, which could change the stress state and increase the hydrostatic pressure in the deformation zone, thus the forming limit of the tube is improved.

In 1966, Fuchs et al. (1966) found that the forming limit of tube can be improved remarkably by applying liquid pressure to the inside and outside of the tube simultaneously. Since then both domestic and international scholars started to study the effect of through-thickness normal stress on the sheet metal formability. Forming limit model considering through-thickness normal stress were proposed on the basis of the classical theory of plastic instability. Smith et al. (2003a) studied six different formability models for suitability for finite element modeling of the double-sided high-pressure tubular hydroforming process. Smith et al. (2003b) also

* Corresponding author. Tel.: +86 451 86417917; fax: +86 451 86417917.
E-mail addresses: cuixiaolei2005@163.com (X.-L. Cui), hitxswang@hit.edn.cn (X.-S. Wang), syuan@hit.edn.cn (S.-J. Yuan).

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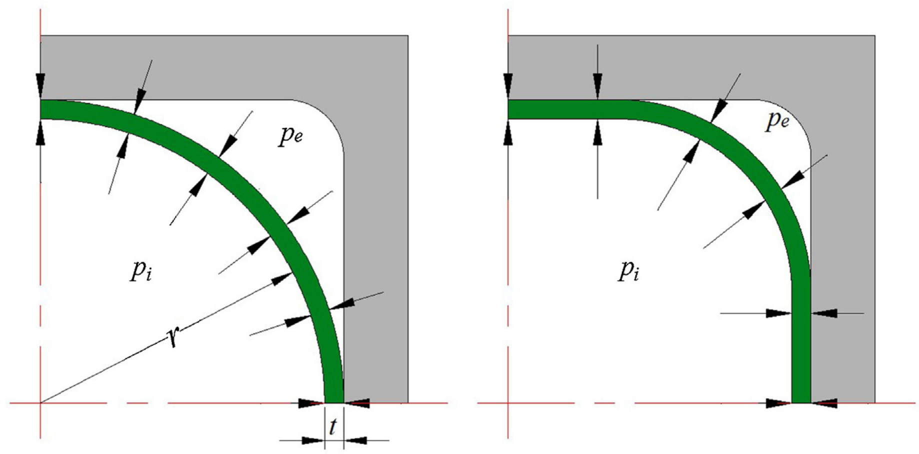

Fig. 1. Principle of double-sided tube hydroforming in a square-section die: (a) initial stage; (b) corner filling stage.

adopted Stoughton's plane-stress model based on Hill's 48 yield criterion and proposed a new sheet metal formability model that takes the through-thickness normal stress into account. Matin and Smith (2005) improved their model proposed in 2003 by assuming that the in-plane strain ratio as constant according to the practical observation. Jain and Wang (2005) have made a theoretical analysis of plastic instability for the tube under different loading conditions, and then drawn a conclusion that the formability of the tube could be improved by imposing liquid pressure on the tube outside no matter how much axial feeding participated in the process. In the study of effect of external pressure on the plastic instability of the thin-wall tubes, Guven (2009) obtained the circumferential limit strain and axial limit strain considering the effect of through-thickness normal stress using three different necking criteria. Moreover, initial imperfection was assumed to be inevitable for the actual sheet materials and the influence of through-thickness normal stress on formability was discussed based on the M-K model. Allwood and Shouler (2009) proposed a generalized forming limit diagram (GFLD) accounting for the possibility that all six components of the stress and strain tensors in sheet forming may be non-zero. Assempour et al. (2010) modified the FLC based on the M-K model by using Hill48 3D yield criterion. Nurcheshmeh and Green (2012) did the similar work and obtained both the FLC and FLSD with the effect of a non-negligible through-thickness normal stress. The forming limit models mentioned above considered the influence of through-thickness normal stress by using three-dimensional yield criteria. However, Banabic and Soare (2008) used a general method to describe the effect of the normal pressure while maintaining the plane-stress characteristic of the model. In addition, Jain et al. (2004) established the merits of applying external counter pressure in tube hydroforming using the finite element simulation. Liu et al. (2012) simulated the effect of through-thickness normal stress on the sheet formability using the finite element software based on the ductile fracture criterion. Although Wang (2009) has investigated the role of through-thickness normal stress in viscous pressure bulging of overlapping sheets and double-sided viscous pressure bulging, the normal stress induced by the overlapping sheet or the viscous medium was uncontrollable and the shear stress also play an important role on the formability improvement for the target sheet. As the above mentioned issues are concerned, most investigations of influence of through-thickness normal stress on sheet formability are focused on the theoretical analysis and numerical simulation. The systematical experimental work about double-sided tube hydroforming, in which the through-thickness normal stress can be controlled artificially, has not appeared in the published academic papers.

In the present study, theoretical analysis of the effect of external pressure (through-thickness normal stress) on tube formability in a square-section die was carried out based on the classical theory of plastic instability. Then a special experimental setup for double-sided tube hydroforming was designed and 5A02-O aluminum alloy tubes were bulged in the experimental setup with a square-section die cavity under the combined action of internal pressure and external pressure. In addition, numerical simulation was conducted using the Abaqus/Explicit software. The thickness distribution and effective strain distribution were validated detailedly with experimental, theoretical and simulation study. Finally, the deformation mechanism in the transition zone under different external pressure is clarified by the electron back scattering diffraction (EBSD), fracture morphology and micro hardness.

2. Principle of double-sided tube hydroforming in a square-section die

The principle of double-sided tube hydroforming in a square-section die is shown in Fig. 1. Compared with the conventional tube hydroforming of square section in which the tube is deformed toward to the die corner only by the function of internal pressure, external pressure is introduced to the tube outside simultaneously in the double-sided tube hydroforming of square section and the tube is deformed under the hybrid effect of internal pressure and external pressure. The external pressure, as a supporting role to increase the normal compressive stress, could change the stress state and increase the hydrostatic pressure for the tube, thus improve its deformation ability.

The loading path for the double-sided tube hydroforming in a square-section die is shown in Fig. 2. It should be ensured that the internal pressure is greater than the external pressure for a certain value in the process of establishment for external pressure (T0–T1) owing to the shape feature of the tube. The specific relationship between internal pressure and external pressure is shown as follows according to the mechanical equilibrium condition.

$$p_i = p_e\left(1 + \frac{t}{r}\right) \tag{1}$$

where p_i is the internal pressure, p_e is the external pressure, t is the initial thickness of the tube and r is the inside radius of the tube. In the stage of establishment for external pressure (T0–T1), the internal pressure and external pressure are increased to their target values respectively according to Eq. (1). In the corner filling