Journal of Materials Processing Technology 211 (2011) 2012–2021

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

A theoretical and experimental study on forming limit diagram for a seamed tube hydroforming

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ARTICLE INFO

Article history:
Received 24 February 2011
Received in revised form 21 June 2011
Accepted 26 June 2011
Available online 1 July 2011

Keywords:
Forming limit diagram (FLD)
Seamed tube
Tube hydroforming
Theoretical model
Loading paths

ABSTRACT

The purpose of this work is to establish the forming limit diagram (FLD) for a seamed tube hydroforming. A new theoretical model is developed to predict the FLD for a seamed tube hydroforming. Based on this theoretical model, the FLD for a seamed tube made of QSTE340 sheet metal is calculated by using the Hosford yield criterion. Some forming limit experiments are performed. A classical free hydroforming tool set is used for obtaining the left hand side forming limit strains, and a novel hydroforming tool set is designed for the right hand side of FLD. The novel device required the simultaneous application of lateral compression force and internal pressure to control the material flow under tension–tension strain states. Furthermore, the suitable loading paths for the left hand side of FLD by theoretical formulas and for the right hand side of FLD by finite element (FE) simulations are calculated. Finally, a comparison between the theoretical results and experimental data is performed. The theoretical predicting results show good agreement with the experimental results.

1. Introduction

In recent years, the automotive industry has shown a growing interest in tube hydroforming. The process has some considerable advantages compared to conventional forming processes like stamping. It allows weight reduction, part consolidation, reduced tooling cost, fewer operations and improved structural stiffness of the hydroformed part. Due to its low cost, high productivity, high quality and varieties in products, seamed tubes have been widely used to manufacture hydroformed parts. However, bursting for seamless and seamed tube is different under free hydroforming, as illustrated in Fig. 1. The cracking position is located at the base metal near the weld zone for a seamed tube. The main cause of such defects is the constraint of the weld zone in a seamed tube hydroforming.

Bursting is generally classified as an irrecoverable failure mode. Hence in order to obtain the sound hydroformed parts, it is necessary to predict the bursting behavior and to analyze the effects of process parameters and weld metal on this failure condition in hydroforming processes. The forming limit diagram (FLD) can be used as a measure of the maximum formability of the material.

Some experimental and theoretical methods have been applied to study the FLD for tube hydroforming. Davies et al. (2000) proposed a tooling and experimental apparatus to establish FLD for AA6061 tube based on the free-expansion tube hydroforming. These experimental results were compared to the theoretical FLD calculated via the Marciniak–Kuczynski (M–K) method. Varma et al. (2007) and Varma and Narasimhan (2008) analyzed the localized necking in aluminum tubes free hydroforming using the M–K method along with an anisotropic version of the Gurson model. They also studies the influence of loading conditions, such as prescribed fluid pressure or volume flow rate in conjunction with axial end feed. Kulkarni et al. (2004) studied the localized necking initiation in aluminum alloy tubes during hydroforming by an experimental and numerical method. In addition, approximate analytical approach has been adopted to obtain the peak internal pressure and M–K analyses have been conducted to predict the limit strains corresponding to onset of necking of the tube wall. Hashemi et al. (2009) obtained a theoretical forming limit stress diagram (FLSD) to predict necking initiation in tube hydroforming via the M–K model. Hwang et al. (2009) used bugle tests to establish the FLD of tubular material AA6011. These experimental results were compared to the theoretical FLD calculated via the Swift's diffused necking criterion and Hill's localized necking. In these studies, only the left hand side ($\beta<0$) of FLD could be obtained from experiments for the difficulty to clamp both ends of tube in free hydroforming for the right hand side ($\beta>0$) of FLD. The difference between the theoretical methods for sheet forming and for tube hydroforming could not be considered. So it is questionable whether a direct application of the concept of FLD obtained in sheet metal forming to tube hydroforming is a physically possible solution.

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doi:10.1016/j.jmatprotec.2011.06.023

Nomenclature

P_w	"w" zone internal pressure
P_b	"b" zone internal pressure
P_i	instantaneous internal pressure
F	axial force
F_{mixed}	total load on the mixed tensile specimen
A	cross-sectional area
t_0	initial tube wall thickness
t_i	instantaneous tube wall thickness
d_0	initial tube diameter
d_i	instantaneous tube diameter
$\bar{\sigma}$	equivalent stress
σ_1	circumferential stress
σ_2	longitudinal stress
FLD_0	limit strain under plane strain state
ε_0	initial equivalent strain
$\bar{\varepsilon}$	equivalent strain
ε_1	circumferential strain
ε_2	longitudinal strain
ε_3	radial strain
e_1	engineering circumferential strain
e_2	engineering longitudinal strain
$d\varepsilon_1$	circumferential strain increment
$d\varepsilon_2$	longitudinal strain increment
u_1	circumferential micro-displacement
u_2	longitudinal micro-displacement
u_3	radial micro-displacement
ρ_0	initial tube radius
ρ_1	instantaneous circumferential radius
ρ_2	instantaneous longitudinal radius
L_0	initial tube length
w	free tube length
r_d	die profile radius
s	stroke of punch
h	stroke of pressing block
c	width of pressing block
l_0	initial contact length
K	strength coefficient
E	elastic modulus
ν	Poisson's ratio
n	strain hardening exponent
m	stress exponent of crystal structure
R	anisotropy coefficient
φ	ratio of the equivalent stress and the major stress
α	stress ratio
β	strain ratio
f	constant of failure criterion
π	circumference ratio
r_{in}	instantaneous tube inner radius
r_{out}	instantaneous tube outer radius
μ	coefficient of friction

Some research works had shown that the FLD for tube hydroforming may be different from that for sheet metal forming (Chu and Xu, 2004a,b). Xing and Makinouchi (2001) concluded that the forming zone for tube hydroforming is narrower than for conventional sheet stamping. In the biaxial tensile stress zone, the forming limit for tubular hydroforming is significantly lower than that for sheet forming; while in the compression-tension stress zone, it is between those of the diffusion necking and the local necking for sheet forming. Nefussi and Combescure (2002) highlighted two Swift's diffuse criteria for sheet forming and for tube hydroforming to predict necking. Chu and Xu (2008) investigated the prediction of FLD for tube hydroforming from the perspective various combinations of loading parameters based on plastic instability. Kim et al. (2004a) predicted the bursting failure based on the Hill' quadratic plastic potential under combining internal pressure and axial feeding. Finally, the hydroforming strain and stress limit diagrams were obtained from the above approach. Kim et al. (2009) investigated the theoretical FLSD based on the local necking criterion to predict bursting failure in tube hydroforming. Then the proposed analytical approach based on the implementation of the FLSD was verified with a series of bulge tests.

In the above studies, all bursting failure predictions did not study the effects of the weld line of seamed tube. Kim et al. (2004b) investigated the forming limit and bursting pressure level for a seamed tube that comprised weld metal, heat affected zone (HAZ) and base material parts by means of the finite element method (FEM) combined with Oyane's ductile fracture criterion based on the Hill's quadratic plastic potential. Song et al. (2010) performed some experiments for seamed tube hydroforming. But the theoretical prediction for tube did not study the effects of the weld line. A seamed tube used in hydroforming is generally produced by high frequency electric resistance welding (HF-ERW) after a roll forming operation. For a steel seamed tube, the base metal has significantly lower yield strength and higher ductility than the weld metal. The quality of the weld in a tubular blank is critical for a successful forming operation. However, no previous theoretical study on the influence of the weld metal properties on the forming limit of bulge forming has been presented.

As discussed all above, the FLD for tube hydroforming is now receiving increasing attention. But current researches on the FLD for a seamed tube hydroforming are restricted in the application due to the experimental apparatus and the theoretical model. So it must be studied urgently that a special apparatus for the right hand

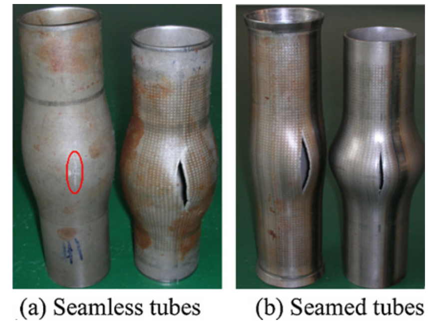

Fig. 1. Cracking position for seamless and seamed tubes in hydroforming.

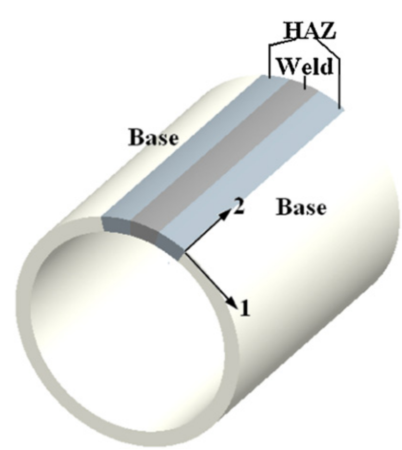

Fig. 2. Theoretical analysis model of FLD for a seamed tube.