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Multiple instability-constrained tube bending limits

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ABSTRACT

Understanding the bending limits is critical to extract the forming potential and to achieve precision tube bending. The most challenging task is the development of the tube bending limits in the presence of unequal deformation induced multiple instabilities and multi-factor coupling effects. Using analytical and 3D-FE methods as well as experiments, a comprehensive map of the tube bending limits during rotary draw bending is provided under a wide range of tube sizes, material types and processing parameters. The major results show: (1) For each instability, the intrinsic factors (tube geometrical parameters, D and t, and mechanical properties, m) dependent bending limits are clarified, and evident interactive or even conflicting effects are observed. (2) Under mandrel bending, the significant effects of the intrinsic factors on the wrinkling limit are reduced, the neglected effects of D/t on the thinning limit are magnified; the significant influences of D/t on the flattening limit even become contrary, and the effects of m on wrinkling and thinning limit are opposite to that on the flattening limit. (3) Taking D/t as the basic design parameter, a conceptual multiple defect-constrained bending limit diagram (BLD) is constructed, and a knowledge-based stepwise method for determining and improving tube bending limits is proposed, considering coupling effects of multiple forming parameters, e.g., intrinsic factors, tooling/processing parameters and uncertainties. (4) The method is experimentally verified by several practical bending scenarios for different kinds of tubular materials with extreme size.

1. Introduction

As one type of lightweight components for 'blood transfusion' or structural weight-bearing, bent tubular parts have been increasingly used in applications requiring diverse geometrical specifications and different quality tolerances for various industries, such as the aerospace, automobile, shipbuilding, energy and health care ones. Knowledge regarding the bending limit, i.e., the maximum deformation a tube can experience without bending failures, is a crucial issue in the exploration of the forming potential and the optimal design for precision tube bending (SAE Aerospace, 2004). However, upon bending, unequal tension and compression deformation inevitably occurs (shown in Fig. 1) at the extrados and intrados of the bend tube. Several inelastic instabilities may be induced, such as wrinkling, flattening (distortion) and over-thinning or even necking (cracking). Thus, different mechanisms causing these defects may exert coupling or even conflicting effects of various forming parameters on tube bending limits. A method for reducing one type of instabilities may probably cause another one to be much more severe (Li et al., 2007a,b). The co-existence of multiple defects and their interactions make determination and improvement of tube bending limit a challenge.

Currently, to improve the performance, the precision bending of advanced tubular materials with extreme geometrical specifications is urgently needed in practice. The materials such as Ti-alloy, Mg-alloy, and high-strength steel tubes are generally hard to deform with low ductility. The extreme structures are characterized by large diameters ($D > 40$ mm), small diameters ($D < 10$ mm), thin wall thicknesses ($D/t > 30$ mm), small bending radii ($R_d/D < 3$) and large bending angles ($\varphi > 90^\circ$). Bending tubes with these features may undergo larger/unequal strain conditions and thus encounter higher risks of multiple defects co-occurring. Meanwhile, as shown in Table 1, the requirements for the bending quality with respect to the maximum wrinkling height, δ_w, thinning, δ_t, and flattening, δ_D, have become much more strict and diverse in many industries (SAE Aerospace, 2007). This sharpens the difficulty in determining and improving the bending limits of tubes. Due to lack of knowledge on multiple defects-constrained bendability, for the bent tubes with small R_d, the welding of several pieces of deep drawn parts has to be used, which not only causes high cost and weight, but also reduces the fluid

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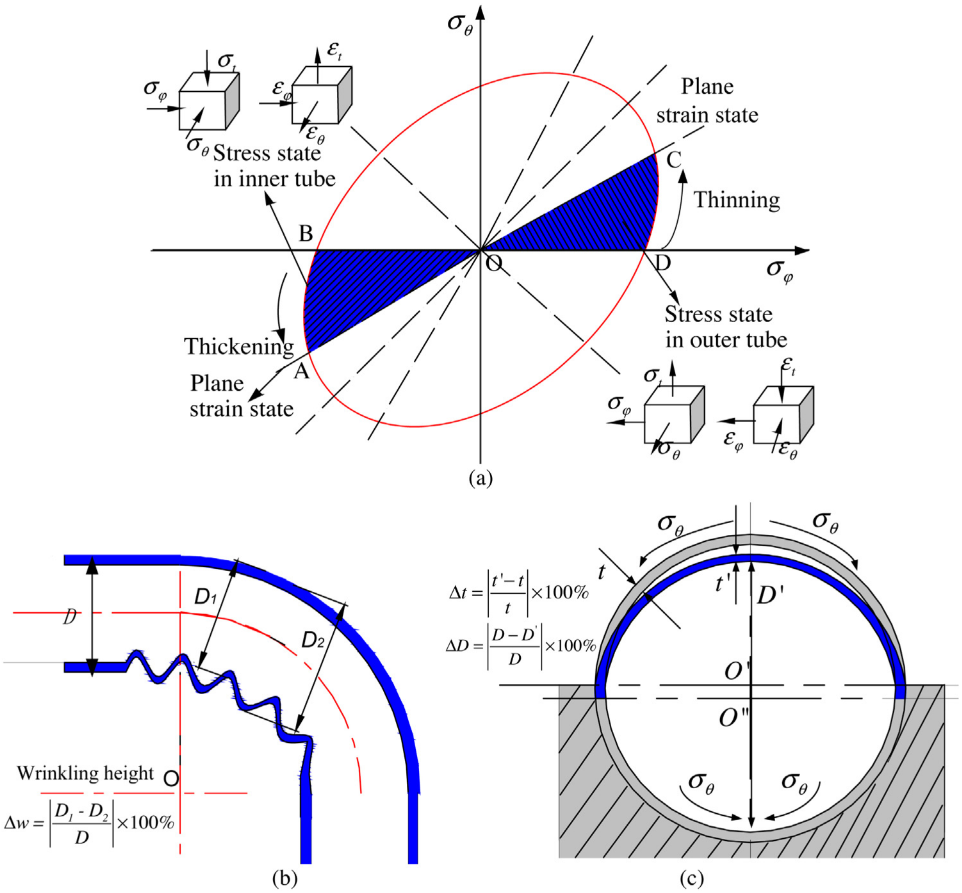

(a)

(b)

(c)

Fig. 1. Unequal stress/strain distributions and multiple instabilities in tube bending: (a) stress/strain states; (b) wrinkling; (c) thinning and flattening.

flow volume and flow rate. Thus, good insight into the multiple instability-constrained bending limits of tubes should be obtained to find a logical way to improve the bending formability in the presence of the coupling effects of multiple factors, e.g., intrinsic factors (tube geometrical parameters, *D* and *t*, and mechanical properties, *m*), tooling/processing parameters and uncertainties in bending.

Great efforts have been taken to explore the formability of various materials using analytical, experimental or numerical approaches. The bending limits of tubular materials were extensively investigated under different bending operations. However, few reports considered multiple bending instabilities and the coupling effects of the various forming parameters to investigate multiple instability-related limits. Zeng and Li (2002) experimentally achieved difficult push bending of an Al-alloy tube with R_d equal to *D* using reasonable internal pressure and lubricant conditions. Goodarzi et al. (2005) experimentally proved that shear bending can produce Al-alloy bent tubes with small R_d via combining shear and bending modes. Using the minimum energy principle, Wang and Cao (2001) analytically calculated the wrinkling limit (minimum R_d without wrinkling) in tube bending. By introducing a new wrinkling wave function, Yang and Lin (2004) analytically obtained the effects of material properties on the wrinkling limit. With respect to thinning, Khodayari (2008) experimentally and analytically established the bending limit curve (BLC) of tube in Rotary Draw Bending (RDB) for various steel tubes and verified that the BLC provided more accurate prediction of the thinning limit than the standard FLC (forming limit diagram). Okude et al. (2012) showed that the usage of a wiper die and axial tension can improve the wrinkling limit of a square section tube in RDB. With respect to flattening, Lee et al. (2003) studied the bending limit of a square Al-alloy tube in rubber pad bending via experiments and FE simulation. Regarding a non-dimensional shape degradation factor, Lee et al. (2005) numerically obtained a hoop-buckle limit of oval tube bending. The mandrel roles in preventing the wrinkling and flattening of Al-alloy tubes and copper tubes in RDB were studied by Li et al. (2007a,b). Regarding thinning and flattening, Wu et al. (2008) explored the effects of temperature, bending velocity and grain size on the bendability of Mg-alloy AM30 tubes. For mandrel-free RDB (without internal supports) of small diameter tubes, the relationship between tube geometrical variables was correlated with cross-ovalization by Mentella and Strano (2012). These studies provide beneficial understanding on bending limits of various types of tubes. While, since the interactions between multiple instabilities and the coupling effects of overall parameters on these defects have not yet been identified, how to determine and improve

Table 1
Diverse bending tolerances with respect to the three major defects (SAE Aerospace, 2007).

Working pressure	Tube materials	Maximum wrinkling height δ_w (%)	Thinning δ_t (%)	Flattening δ_D (%)
Under 3.45 MPa	Al-alloy, steel	2	30	10
	Ti-alloy	2	30	5
Over 3.45 MPa	Al-alloy, steel	1	25	5
	Ti-alloy	No visible wrinkling	25	3