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Review

Influences of generalized loading parameters on FLD predictions for aluminum tube hydroforming

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ABSTRACT

The present study intends to investigate the prediction of forming limit diagrams (FLDs) for tube hydroforming from the perspective of selecting various combinations of loading parameters based on plastic instability. From this perspective, certain related research efforts on plastic instability of thin-walled tubes subjected to internal fluid pressure and axial force are reviewed and six combinations of loading parameters have been identified. There are nine combinations of loading parameters, including six found in the literature, being employed to determine forming limit curves (FLCs) for tube hydroforming in the present study. The predicted FLCs are compared with experimental data obtained in a well-controlled laboratory condition. Comparisons indicate that the combination of the internal pressure p and the resultant axial force $F_z + \pi r^2 p$ provides the best predicted right side of FLC among the nine combinations and a reasonably well-predicted left-hand side of FLC. In addition, comparison also demonstrated that the combination of p and the applied axial stress $F_z/2\pi rt$ can also give a reasonable predicted left-hand side of FLC.

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1. Introduction

The tube hydroforming process is used commercially to form a wide variety of automotive components, such as camshafts, radiator frames, front and rear axial parts, engine cradles, crankshafts, seat frames, space frames, roof rails, etc. Mass production of these components using advanced hydroforming machinery is a reality today in the automotive industry (Dohmann and Hartl, 1996; Bartley and Evert, 2000; Chu and Xu, 2004a,b). Application of this process is driven mainly by the need for weight reduction, part consolidation, and for improving dimensional tolerances. Components produced by this method offer economical benefits and allow design flexibility.

Tube hydroforming is a metal forming process during which a cylindrical tube is deformed into the desired shape through simultaneous applications of an axial compressive force and an internal fluid pressure. The final shape of the tube is determined by a die against which the tube is deformed and by how well the operating parameters are being controlled throughout the process. The major failure modes in tube hydroforming are bursting, localized wrinkling, global buckling and folding of tubes, as illustrated in Fig. 1.

Motivated by the needs to develop mathematical tools for better designing and optimizing aluminum tube hydroforming components, the current authors (Chu and Xu, 2004a,b) have previously formulated the process window diagram (PWD) theoretically. The "Process Window" predicts the required process conditions within which an aluminum tube can operate safely without failure under a free-expansion tube hydroforming process. Theoretically, the PWD is bounded by the aforementioned failure modes such as buckling, wrinkling and bursting. This new development enables process engineers to better design and develop a hydroforming process that maximizes part performance.

For practical industrial applications on the shop floor, FLD has been a convenient way of describing the incipient localized necking condition. The deformation having strain distributions below the FLC is considered safe from necking and tearing. While the region above the FLC is regarded as unsafe during the forming operation. This provides a system whereby the onset of incipient localized failure of a formed part could be readily determined without the part actually showing signs of fracture in a plant environment. Though the development of FLCs for sheet metal forming has been established on a solid experimental foundation, the application and determination of the FLCs for tube hydroforming remain unsettled. It is a topic of ongoing research in the industry.

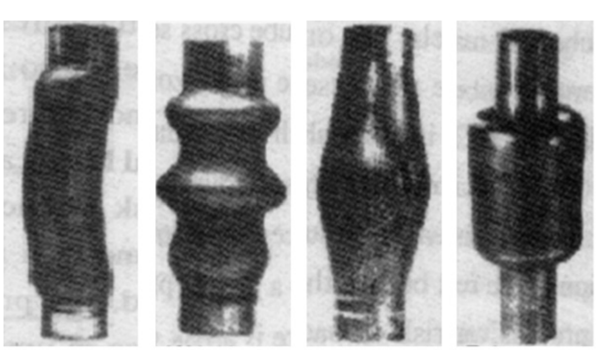

Fig. 1 – Diagram showing various failure modes in tube hydroforming (cited from Dohmann (Dohmann and Hartl, 1996)).

Recently, an attempt was made by Levy (2000), who presented evidence to show that, if properly applied, the standard North America FLC is applicable to tube hydroforming. Levy suggested that a proper inclusion of the strain path and the use of a terminal n-value be incorporated into the FLC for tube hydroforming applications. Such an approach appears to be a first logic step to predict FLC for tube hydroforming. However, it lacks both experimental as well as theoretical justifications. It is questionable whether a direct application of the concept of FLC obtained in sheet metal forming to tube hydroforming is a physically possible solution (Xu, 2001; Xu and Chu, 2005; Chu et al., 2006). Research works have shown that the FLC for tube hydroforming may be different from that for sheet metal forming. The existence of two plastic instability criteria, one for sheets and one for tubes, was highlighted by Nefussi and Comescure (Nefussi and Combescure, 2002). Some of the physical as well as theoretical differences have been examined in Refs. Xu (2001), Xu and Chu (2005), and Chu et al. (2006).

To predict FLCs for tube hydroforming based on plastic instability, one must study the loading system and the possibility of using various combinations of generalized loading parameters (Nefussi and Combescure, 2002; Hill, 1996). For bi-axially stretched sheets, the loading parameters are relatively obvious in that they are either the total forces acting on the edges (Swift, 1952) or the principal tensions through the sheet (Marciniak et al., 2002); however, they are not as obvious for tube hydroforming although the internal fluid pressure and the external axial force are commonly considered as the basic loading parameters. Hill (1996) presented a general theoretical framework of plastic deformation and instability in thin-walled tubes using a combination of generalized loading parameters. He subsequently proposed four possible combinations of generalized loading parameters. Based on plastic instability, Nefussi and Combescure (2002) obtained two separate forming limits, one for tube hydroforming and one for sheet metal forming, by using two combinations of generalized loading parameters.

Reviewing all research efforts in the analysis of the plastic instability of thin-walled tubes, including the possibility of using stress-based FLC, is far beyond the scope of the present study. The present study intends to re-categorize a number of research works from the perspective of selecting a combination of generalized loading parameters to predict the forming limits in the strain space for tube hydroforming. In this re-categorization, it is assumed that the tube is subjected to an internal pressure p and an external axial force F_z with an instantaneous radius r, thickness t and length l. Mellor (1962) used p for the case when the circumferential strain $\varepsilon_\theta > 0$ and $F_z + \pi r^2 p$ for the case when $\varepsilon_\theta < 0$, respectively. Hillier (1962) combined prl ($2\pi rlp$) and $F_z + \pi r^2 p$ together to formulate his model. Yamada and Aoki (1966) derived the sub-tangent from Hill's uniqueness principle; however the same formula can be derived by employing p and F_z simultaneously. Xing and Makinouchi (2001) directly applied the formula derived by Yamada and Aoki (1966). Nefussi and Combescure (2002) used