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Path-dependent failure of inflated aluminum tubes

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A B S T R A C T

Our recent investigation on the formability of Al alloy tubes under combined internal pressure and axial load is expanded by examining the effect of the loading path traced. A set of Al-6260-T4 tubes were loaded along orthogonal stress paths to failure and the results are compared to those of the corresponding radial paths. It is confirmed that failure strains are path-dependent, but also is demonstrated that failure stresses become path-dependent if the prestrain is significant. The experiments are simulated using the previously developed finite element models and the calibration of the Yld2000-2D [Barlat, F., Brem, J.C., Yoon, J.W., Chung, K., Dick, R.E., Lege, D.J., Pourboghrat, F., Choi, S.-H., Chu, E., 2003. Plane stress yield function for aluminum alloy sheets-part I: theory. Int. J. Plasticity 19, 1297–1319] anisotropic yield function shown in [Korkolis, Y.P., Kyriakides, S., 2008b. Inflation and burst of anisotropic aluminum tubes. Part II: an advanced yield function including deformation-induced anisotropy. Int. J. Plasticity 24, 1625–1637] to yield accurate predictions of rupture for nine radial paths. The models are shown to reproduce the path dependence of the failure stresses and strains quite well. A group of additional radial and corner paths are subsequently examined numerically to enrich the existing data on path-dependence of failure. It is again shown that the amount of plastic prestraining in either of the two directions influences the difference of the failure stresses and strains between the radial and the corner stress paths.

1. Introduction

We recently reported results from a series of experiments, conducted in support of a larger project on tube hydroforming, that involved inflation of relatively thin-walled Al-6260-T4 tubes under

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combined internal pressure and axial load (Korkolis and Kyriakides – K-K – 2008a). The tubes were loaded to failure along radial paths in the engineering stress space. The specimens developed localized axisymmetric bulging associated with a limit load, that lead to localized failure. In axial tension dominant loading paths, the tubes failed by circumferential rupture whereas for hoop stress dominant paths the rupture was along a tube generator (see also Kuwabara et al., 2005; Davies et al., 2000). The experiments were then simulated with finite element models (FE) in which three different anisotropic yield functions were employed, using isotropic hardening plasticity: Hosford (1979), Karafillis and Boyce (1993), and Barlat et al. (2003). The added flexibility provided by the eight anisotropy parameters of the last model, coupled with the incorporation of some deformation-induced anisotropy observed in the experiments were found to produce the most accurate predictions of the strain paths traced in the experiments (K-K, 2008b). On the other hand, optimal prediction of the strains at rupture for the whole set of experiments required additional small amendments to the anisotropy parameters. The most successful scheme was based on a hybrid procedure that also included adjustments of the yield function variables based on the structural performance of the FE models.

A significant body of work dealing with strain-based *forming limit diagrams* (FLDs) has shown experimentally that such failure limits are path-dependent and consequently are only applicable to forming operations with loading paths similar to the ones used to construct them. For example, the path dependence of FLDs was demonstrated for a wide range of materials and loading paths that typically involved prestraining, unloading and reloading in a variety of failure strain combinations by Muschenborn and Sonne (1975), Kleemola and Pelkkikangas (1977), Lloyd and Sang (1979), McCandless and Bahrani (1979), Wagoner and Laukonis (1983) and others. In more recent investigations, Graf and Hosford (1993, 1994), Hosford and Caddell (1993), and Korhonen and Manninen (2008), among others, confirmed and expanded these earlier observations.

In an effort to develop a more general failure framework for metal forming, it has been postulated that despite the failure strains being path-dependent, the associated failure stresses are not (or at least much less so; e.g., Gronostajski (1984), Arrieux (1995) and more recently Stoughton (2000), Wu et al. (2005), and others). Some experimental support for this proposal appears in Yoshida et al. (2005) although later work by the same group (Yoshida and Kuwabara, 2006, 2007) points to limitations of this concept.

The present work presents results from a number of new biaxial experiments involving axial loading and internal pressure of tubes of the same Al alloy as that used in K-K (2008a) but now using non-proportional stress paths. The aim is to establish the extent of path dependence of limit states in strain space and simultaneously test the extent of validity of path independence of the corresponding limit stresses. This is accomplished by prescribing rather extreme non-proportional corner paths is the σ_x–σ_θ plane. The experiments are subsequently simulated numerically using the FE models developed in K-K (2008a) along with the specially calibrated anisotropic yield function of Barlat et al. (2003) which successfully predicted the onset of failure for the radial paths in K-K (2008b). One of the objectives is to determine if the thus calibrated constitutive models are also capable of predicting with accuracy the onset of failure under the more demanding non-proportional stress paths.

2. Experimental

2.1. Experimental setup and procedure

The experimental program involved testing seamless Al-6260-T4 tubes under combined axial tension and internal pressure. The experiments were conducted in the custom biaxial testing facility shown schematically in Fig. 1. The facility consists of a 50 kip (222 kN) servo-hydraulic testing machine that can operate in conjunction with a 10,000 psi (690 bar) pressurizing unit with an independent closed-loop control system (inside the dashed boundary). By connecting the two systems through feedback, the axial and pressure modes of loading can be related, in order to generate various paths in the engineering stress plane σ_x–σ_θ (x and θ are the axial and circumferential directions, respectively).