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Mechanics and full-field deformation study of the Ring Hoop Tension Test

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ABSTRACT

We investigate the mechanics of the Ring Hoop Tension Test (RHTT), as a means to assess the properties of anisotropic tubes in the hoop direction. This test involves placing a ring extracted from the tube over two close-fitting D-shaped mandrels that are then parted using a universal testing machine. Since the curvature of the ring does not change during loading, the ring undergoes only stretching. We determine the effects of contact pressure, radial stress, and friction between the tube and mandrels using FEA simulations. The effects of the pre-existing thickness eccentricity and of the specimen-making procedure on the recorded RHTT response are also assessed with a combination of experiments and analysis. We tested tubes from Al-6061-T4 with a diameter/thickness ratio of 20. We found that as the friction increases beyond 0.1–0.15, the state of uniaxial tension is deteriorated, indicating that care must be taken to minimize the tube-mandrel friction. We determined that although these tubes have a relatively large thickness eccentricity (±4% of the nominal thickness), this had no effect on the recorded results. We showed that the tubes should not be turned to remove that eccentricity, as the machining process induces damage that is noticeable in the results. We found that the contact pressure and the contact-induced radial stress cause limited deviations from uniaxial tension, comparable to the case of a tube under axial load and internal pressure which is often used for assessing the material properties in the hoop direction. Central in our analyses is the knowledge of the hoop strain field, which was assessed using 3D Digital Image Correlation. We propose a data reduction procedure for RHTT that accounts for all the above effects. Finally, with all effects accounted for, we establish the anisotropy of the extruded Al-6061-T4 tubes studied.

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1. Introduction

Reliable numerical simulations of material forming processes require accurate models of the material behavior, including plastic flow, anisotropy and failure. There is significant body of knowledge that indicates that accurate material models are imperative for numerical predictions of failure that match experimental observations (e.g., see Kuwabara et al., 2011). In the case of metal sheets, a large variety of experimental techniques have been devised to calibrate anisotropic material models (Kuwabara, 2007). However, when the workpiece is in tubular form, many of these techniques are inapplicable.

Fig. 1 shows a variety of testing techniques available for materials in tubular form (Kim et al., accepted for publication). The simplest way of assessing the hoop properties (plastic flow anisotropy and failure) is shown in Fig. 1a: an arc is extracted from the tube, flattened and then tested in uniaxial tension (see the ASTM E-8 standard, ASTM, 2008). Since the flattening introduces a prestrain on the specimen, this method can only be used for qualitative studies of the hoop response, or for assessing the weld strength of electric-resistance-welded (ERW) tubes. Another simple technique is tube-end flaring (Daxner et al., 2005), shown in Fig. 1b. In this method, a cone is driven coaxially with the tube, which expands to accommodate the cone movement. While at first approximation the end of the tube can be considered to experience uniaxial tension, the presence of the friction often leads to multiple necking in the circumference. Hence the failure limits determined from this test may not correspond to pure hoop tension. The classic experiment to assess the hoop properties is the inflation of a tube under axial load and internal pressure (Korkolis and Kyriakides, 2008, 2009; Korkolis et al., 2010; Kuwabara et al., 2005; Kuwabara and Sugawara, 2013), shown in Fig. 1c. While this experiment has been used extensively in plasticity, it requires relatively complex testing equipment. In contrast, the Ring Hoop Tension Test (RHTT) shown in Fig. 1d only requires a universal testing

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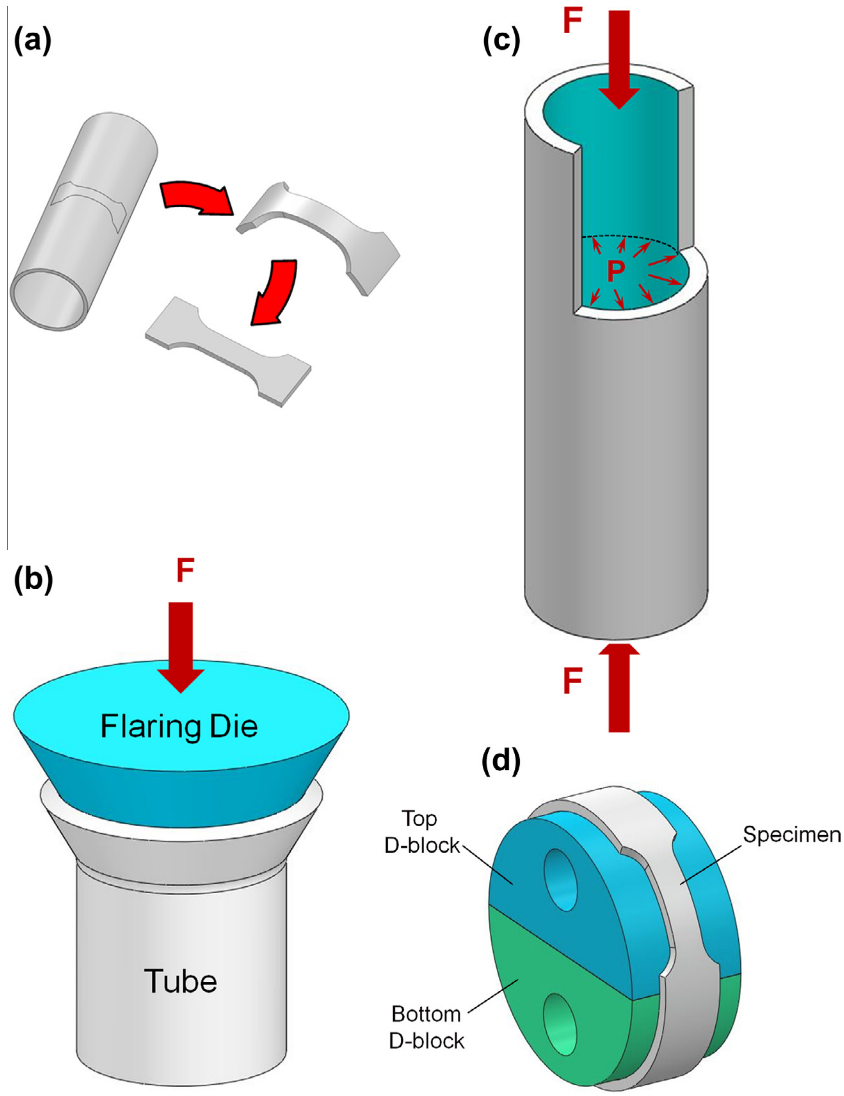

Fig. 1. Testing methods for assessing the plastic flow and failure properties of tubes in the hoop direction. (a) Flattening and tension test, (b) tube flaring, (c) tube inflation under axial load and internal pressure and, (d) Ring Hoop Tension Test (RHTT).

machine. In that test, a dogbone specimen geometry is machined on a ring extracted from the tube. The ring is then placed over two closely-fitting D-shaped mandrels that are parted with the use of a testing machine. Since the curvature of the ring does not change during testing, the specimen undergoes only stretching and no bending.

The RHTT technique was proposed about 15 years ago. Arsene and Bai (1996, 1998) used various combinations of internal mandrels to stretch a ring without inducing bending. They used finite element analysis to investigate certain factors of this test such as the effect of friction on the response and compared the analysis to their experiments. Their work was directed towards nuclear fuel cladding applications and the materials examined were an Al–Si alloy and Zircalloy. Wang et al. (2002) examined the RHTT of a steel tube for hydroforming applications. The average hoop strain was measured with an extensometer during the test. They also used circle-grid analysis for assessing the spatial distribution of the strains after the end of the test. He et al. (2010) used the RHTT to study the warm formability of AZ 31B magnesium tubes for hydroforming applications. Note that the RHTT readily lends itself to high-temperature testing due to its simplicity. Link et al. (1998) also looked at the effects of high temperature deformation along with strain-rate effects, but used a wider RHTT specimen to impose plane-strain conditions. They used that geometry to study the failure of Zircalloy cladding for nuclear fuel applications. Walsh and Adams (2008) used an arrangement of 4 internal quadrant mandrels to stretch composite rings, but found this fixture arrangement to be difficult to work properly. Finally, Korkolis et al. (2013) presented a preliminary experimental investigation of RHTT using a full-field Digital Image Correlation method to assess the evolution of the strain field during the RHTT.

In this paper, we examine the Ring Hoop Tension Test in an effort to establish its validity, as well as determine a standardized testing procedure that can yield reliable and repeatable results. We selected to study the behavior of a relatively thick-walled (diameter/thickness = 20) extruded tube, to accentuate the effects of wall thickness and its circumferential variation on the response. We begin with a simple analytical model, which illustrates the effect of friction on the performance of the test. A more complete, 3D finite element model of the RHTT is then considered. This model is probed to determine the effects of the contact pressure, the thickness eccentricity and the data reduction technique on the accuracy of the RHTT results. It is also used to help in determining the appropriate RHTT specimen geometry. Guided by these results,

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