International Journal of Plasticity 38 (2012) 27–46

Contents lists available at SciVerse ScienceDirect

International Journal of Plasticity

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

A sheet tension/compression test for elevated temperature

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ARTICLE INFO

Article history:
Received 14 June 2011
Received in final revised form 5 March 2012
Available online 25 April 2012

Keywords:
A. Buckling
A. Twinning
C. Mechanical testing
C. Finite elements
B. Plates

ABSTRACT

An apparatus was designed, simulated, optimized, and constructed to enable the large-strain, continuous tension/compression testing of sheet materials at elevated temperature. Thermal and mechanical FE analyses were used to locate cartridge heaters, thus enabling the attainment of temperatures up to 350 °C within 15 min of start-up, and ensuring temperature uniformity throughout the gage length within 8 °C. The low-cost device also makes isothermal testing possible at strain rates higher than corresponding tests in air.

Analysis was carried out to predict the attainable compressive strains using novel finite element (FE) modeling and a single parameter characteristic of the machine and fixtures. The limits of compressive strain vary primarily with the material thickness and the applied-side-force-to-material-strength ratio. Predictions for a range of sheet alloys with measured buckling strains from −0.04 to −0.17 agreed within a standard deviation of 0.025 (0.015 excluding one material that was not initially flat).

In order to demonstrate the utility of the new method, several sheet materials were tested over a range of temperatures. Some of the data obtained is the first of its kind. Magnesium AZ31B sheets were tested at temperatures up to 250 °C with a strain rate of 0.001/s. The inflected stress–strain curve observed in compression at room temperature disappeared between 125 and 150 °C, corresponding to the suppression of twinning, and suggesting a simple method for identifying the deformation mechanism transition temperature. The temperature-dependent behaviors of selected advanced high strength steels (TWIP and DP) were revealed by preliminary tests at room temperature, 150 and 250 °C.

1. Introduction

The room-temperature testing of bulk materials under uniaxial tension (ASTM-E8-00, 2000) and compression (ASTM-E9-89a, 2000) are well established. However, methods for large-strain compression testing in the plane of sheet materials remain more challenging and specialized; they require suppression of buckling.

Two basic approaches have been presented, as reviewed elsewhere (Boger et al., 2005). The first method relies on a small specimen with specific length-to-thickness ratio in a range of 16 to 2 corresponding to a limit compressive strain from −0.01

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0749-6419/$ - see front matter
http://dx.doi.org/10.1016/j.ijplas.2012.03.009

to −0.15 (Abel and Ham, 1966; Bate and Wilson, 1986; Karman et al., 2001). The specimen geometry precludes accurate strain measurement, particularly for higher strain limits, because of the inhomogeneity of stress and strain.

The second method uses side force to stabilize compressive deformation of a typical tensile specimen. (Tan et al., 1994; Kuwabara et al., 1995; Balakrishnan, 1999; Geng and Wagoner, 2002; Yoshida et al., 2002; Boger et al., 2005; Lee et al., 2005). One such device (Kuwabara et al., 2001) uses comb-shaped "fingers" to reduce the size of the unsupported regions of specimen. Alternatively, sliding blocks can be used to clamp the specimen (Cheng et al., 2007) rigidly, thus permitting compressive strains around −0.1. The clamping force cannot be controlled, thus making the biaxial stress correction and friction correction problematic (Cao et al., 2009).

Boger et al. (2005) extended the second method to test sheet metals in continuous large-strain tension/compression tests at room temperature using a standard tensile testing machine. In the Boger method, two solid support plates sandwiched the specimen with a constant restraining side force generated by a hydraulic cylinder. An exaggerated dog-bone specimen was optimized by FEA simulations in order to suppress buckling in the thickness direction (T-buckling), in the unsupported gap (L-buckling), and in the width direction (W-buckling). A maximum compressive strain of −0.08 was achieved in cyclic tests, and homogeneous strains were accurately measured using a laser extensometer. Biaxial stress and friction corrections were introduced to obtain equivalent uniaxial plastic behavior (Balakrishnan, 1999). The current work focuses on developing an improved method and device capable of extending the temperature range of the technique to above room temperature.

Elevated-temperature methods for monotonic testing of metals in tension (ASTM-E21-92, 1998) and compression (ASTM-E209-00, 2005) are also standard. For compression testing, springs or screws are usually used to provide constraint lateral pressure without control or measurement. Various methods to reduce friction have been used: grooves (Gerard, 1961; King, 1961), balls (Hyler, 1956; Gerard, 1961; King, 1961), leaf springs (Breindel et al., 1961; Gerard, 1961), rollers (Bernett and Gerberich, 1961), or solid blocks with lubricants (Fenn, 1960; Gerard, 1961; ASTM-E209-00, 2005).

Heat sources for elevated temperature testing include convection (Hyler, 1956; Gerard, 1961; King, 1961), radiation (Macdougall, 1998; Yang et al., 2001), specimen resistance (Fenn, 1960; Bernett and Gerberich, 1961; Fenn, 1961), induction (Rosenberg et al., 1986), and embedded electrical resistance cartridges (Hyler, 1956). Enclosing atmospheric furnaces are most common (Zhao, 2000), but have drawbacks in terms of the extensometry, mechanical pass-through, slow heating rates, and limited isothermality at high testing rates (Hyler, 1956; Gerard, 1961; King, 1961). Radiant heating offers rapid heating but requires placement of multiple thermocouples to insure accuracy and uniformity (Macdougall, 1998; Yang et al., 2001), and can make laser extensometer difficult depending on the wavelength of the radiant energy. Electrical self-resistance heating (Fenn, 1960; Bernett and Gerberich, 1961; Fenn, 1961; Sladik and Longauerova, 1992) is attractive, but requires electrical isolation of the specimen.

The present work was aimed at providing a low-cost and readily-reproduced device and method for elevated temperature tension/compression testing, with a particular goal of testing Mg alloys between 25 and 350 °C. The following attributes of such a device and method were sought:

- Continuous, uninterrupted tension and compression cycling.
- Uniform strain throughout the gage length, similar to that of room-temperature tensile testing.
- Direct, accurate strain measurement from within the specimen gage length (thereby avoiding machine compliance issues).
- Use with standard tensile machine; self aligning for low capital cost and simplicity.
- Heating from 25 to 250 °C in less than 10 min.
- Temperature uniformity in the gage length, less than 5 °C variation at 250 °C.
- Controlled, constant side force to enable accurate compensation for biaxial stresses and friction.

2. Design and optimization for elevated-temperature tension/compression test

The Boger fixture design was modified (see summary of Boger's design in the Introduction section of this paper) by developing an integrated heating system to meet the objectives listed above, then performing thermal and mechanical finite element (FE) simulations to optimize it. The alignment principle and specimen design were retained in order to maintain the advantages of large compressive limit strains and a simple, low-cost device to be used with standard tensile testing machines.

2.1. Design overview

In order to describe the design and optimization process concretely and briefly, Fig. 1 shows the final design. The heating plates are equivalent to what were called "support side plates" in the Boger room-temperature device (Boger et al., 2005). They provide both the means for applying the anti-buckling side force to the specimen and for heating the specimen. Fig. 1 shows 12 holes where cartridge heaters are installed in the heating plates, which are adjacent to wooden "insulating plates" that abut tool steel "backing plates." These sets of three plates replace the side plates in the room-temperature Boger design.