Chapter 4
Experiments on a Ring Tension Setup and FE Analysis to Evaluate Transverse Mechanical Properties of Tubular Components

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ABSTRACT

Determination of transverse mechanical properties from ring specimens machined from tubular components is not straightforward due to presence of combined tension and bending stresses. Zircaloy tubes as used in nuclear reactors are manufactured through a complicated process of pilgering and heat-treatment and hence, the properties need to be determined in the as-manufactured condition. In this work, the authors perform ring-tensile tests on specimens of Zircaloy pressure tubes of Indian pressurized heavy water reactor in order to carry out integrity assessment of these tubes. As the loading condition in this test imposes both membrane and bending stresses in the cross-section of the ring, 3-D finite element analysis of the test setup was carried out in order to determine material stress-strain curve using an iterative technique. The effect of the design of the loading mandrel on the experimental stress-strain data has been investigated in detail. To validate the methodology, miniature tensile specimens have been tested and the data has been compared to those of ring specimens.

INTRODUCTION

Pressure tubes act as channels of heat transfer in the pressurized water type of nuclear reactors and contain the fuel bundles. These tubes are subjected to high pressure, moderate temperature and high fluence of neutrons during the reactor operation. During service, the mechanical and fracture properties of these
tubes degrade due to various material ageing phenomena including those of irradiation. In order to have better mechanical and corrosion properties in the irradiated water environment and to ensure minimum absorption cross-section for neutrons, Zirconium based alloys are usually used for manufacturing of these tubes (Nikulina, 2003, 2004). The manufacturing route of these pressure tubes from the ingots is also complicated with several stages of mechanical working and heat-treatment procedures. For example, the pressure tubes of current Indian pressurized heavy water reactors (PHWRs) are manufactured from quadruple-melted ingots of Zr-2.5Nb alloys (Deshmukh et al., 2010). Similarly, the fuel-clad tubes are also manufactured from different types of Zirconium alloys through a series of mechanical working and heat-treatment processes. Due to the long term exposure to aggressive environments in the reactor, significant degradation in properties of the fuel-clad tubes has also been reported by various researchers in the literature (Edsinger et al., 2000; Murty, 1999, 2002; Wang & Murty, 1998; Leclercq et al., 2008).

For design and safety analysis of the pressure tubes as well as of the fuel-clad tubes, it is essential to evaluate the mechanical properties in the as-manufactured as well as in the in-service conditions. Due to the complex mechanical working and heat-treatment conditions experienced by these tubes during their manufacture, the mechanical properties of the pressure tubes are highly anisotropic. It is not possible to evaluate the transverse mechanical properties from the standard tensile tests as standard specimens with sufficient dimensions cannot be machined from the pressure tubes in the circumferential direction (the radius of curvature is too small for this purpose). Similar problem is also faced by the engineers in the mechanical property evaluation of fuel-clad tubes (Arsene & Bai, 1996; Bae et al., 2008; Seok et al., 2006; Lee & Hong, 2002; Bertolino et al. 2003; Fukuda et al., 2003; Videm & Lunde, 1979; Lee et al., 2001; Grigoriev et al. 1995, 1996, 1997; Grigoriev & Jakobsson, 2000, 2005; Nakatsuka et al., 1991; Yoshitake et al., 2004; Hsu et al., 2001; Josefsson & Grigoriev, 1996; Sainte Catherine et al. 2006; Yagnik et al., 2008; Samal et al., 2010a,b, 2012, 2013, 2014, 2015; Balakrishnan et al., 2014; Rashid et al., 2000; Bertsch & Hoffelner, 2006; O’ Brien & Ferguson, 1983; Martín-Rengel et al., 2009, 2012; Shah et al., 2011).

Several types of geometry of specimens and the loading-mandrels were designed by various researchers the world-over in order to determine the mechanical and fracture properties of these tubes satisfactorily. A pin-loading tension (PLT) test was designed by Grigoriev et al. (1995) to evaluate the fracture toughness of Zicaloy-2 fuel claddings. Axially notched ring specimens cut from the fuel cladding section have been tested in a way similar to that used to test compact-tension specimens. Hsu et al. (2001) have designed an X-shaped specimen and have used it to determine the fracture toughness of the thin-walled tubular materials. In this method, two curved axially-cracked semi-cylindrical specimens (machined from the fuel-clad tubes) were glued together by epoxy adhesive to make an X-shaped specimen so as to minimize the bending effects of the loading. A modified ring tension test was carried out by Jossefson and Grigoriev (1996) for fracture toughness testing of cladding where flattening of the ring is prevented by means of a central piece which is inserted into the ring. The central piece has almost the same dimension as that of the ring’s internal diameter. An internal conical mandrel technique has been used in Sainte Catherine et al. (2006) for evaluation of fracture toughness of fuel-clad tubes. A compilation of different types of specimens used by various researchers is presented in Yagnik et al. (2008).

In the recent years, specimens have been machined from the fuel-clad tubes in the form of rings of small width and tested with special types of loading mandrels. In this work, a similar technique is followed for the specimens machined from the pressure tubes, which has not received much attention in literature. However, the results from these tests cannot be used directly to evaluate the material stress-strain curve. The complexities lie in: