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Axial crack resistance of cladding tubes for fast reactors

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ABSTRACT

Structural integrity of the core components of the nuclear reactors is vital for steady economical operation and avoidance of unwanted disasters. Two new test methods have been developed for quantifying the resistance to axial cracking of thin-walled tubular specimens. The specimens are fabricated from cladding tubes made of austenitic stainless steel for Indian fast breeder reactors. The reproducibility of the fracture toughness test results using the developed setups yields promising insights about acceptability of the new methods over the earlier through critical discussion about their relative advantages and precision in predicting the crack resistance data within the range for similar alloys.

1. Introduction

Cladding tube in a nuclear reactor core acts as a containment of the nuclear fuel for physically isolating the radioactive fuel and the fission products from spreading harmful radioactive contamination to the coolant and in turn to the environment (Corradini et al., 1988; Yang et al., 2007; Hofmann, 1999; Walters, 1999). Assurance of its structural integrity during service inside reactor and storage of spent fuel is thus important for safety of both reactor and ecology. Although during stable operation, instances of failure of such tubes are rare, operational transients such as sudden power surge or reactivity initiated or loss of coolant accident (RIA or LOCA) may impart shocking load, through large temperature variation over a tiny time on such tubes through a massive surge in biaxial stress, pellet-clad mechanical and chemical interaction and may lead to sudden failure (Cox, 1990; Fuketa et al., 2001; Shimada et al., 2004; Mardon and Dunn, 2007; Meyer et al., 1996). Also, during long term storage, for dying down of the radioactivity to a safe level, corrosion or hydrogen degradation may lead to leakage of the tubes (Daum et al., 2006; Terrani et al., 2014; Zieliński and Sobieszczyk, 2011; Kim, 2008; Peehs and Fleisch, 1986), resulting in radioactive contamination of the storage area with surroundings. Since past a few decades, many researches regarding the durability issues of the cladding tubes and other similar thin-walled tubular components such as steam generator tubes have been reported by evaluating their mechanical properties with a number of offbeat methods. As the mechanical response of the component is completely different from the bulk parent material before fabrication, due to difference in history and metallurgical attributes, design of the components must be done on the basis of their mechanical properties instead of that of the ingot. The length of such thin-walled tubular components in many cases is incomparably greater than their diameter and the diameter is about 10–20 times the wall thickness. Thus, experimental simulation for those entire components having dimensions of different orders of magnitude, for actual service condition is cost intensive and in many cases, such as in presence of radioactivity, high temperature and highly corrosive environment similar to a nuclear reactor core, it involves enormous safety risks. Thus, in-laboratory tests of a reasonably and suitably sized part of the component are much more convenient for extracting critical information about the mechanical response of the reduced representative part as a specimen. Although extrapolation of the laboratory test data for application to the actual service condition is challengingly difficult and involves analytical or numerical modeling with computer simulation (Ideriah, 1980; Takahashi et al., 2008; Hamman and Berry, 2010; Sauzay et al., 2004; Jones and Lewis, 1996) which again requires experimental validation before actual application, if the laboratory test condition is made relatively more severe than the actual service situation, it is always possible to predict the behavior of the component in a safe manner on the basis of the laboratory test data.

Depending on the mode of loading, and considering all sorts of possible stress state, a categorized literature review of the in-laboratory methods for mechanical testing of thin-walled tubular components has been presented in Table 1. As can be seen there, a host of researches has been done with the burst test (Mishima

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Table 1
Researches for structural integrity evaluation of thin-walled tubes with different test methods.

Researchers	Method adopted	Findings
Mishima et al. (1968), Hardy (1972), Maki and Ooyama (1975), Duncan (1978), Bauer et al. (1979), Yamanaka et al. (2002), Zhou et al. (2004), Nagase and Fuketa (2004), Kuwabara et al. (2005), Yagnik et al. (2005), Zhang and Ran (2005), Park et al. (2007), Alam and Hellwig (2008), Kim et al. (2008), Hermann et al. (2009), Bosch et al. (2011), Kuwabara et al. (2012), Khan et al. (2013), Alva et al. (2014), Lim et al. (2014), Hózer et al. (2015), Gussev et al. (2015), Yueh et al. (2016), Massey et al. (2016)	Burst test	Burst strength in terms of internal pressure and crack characteristics
Uchida et al. (1976), Onchi and Tanaka (1981), Arsene et al. (1996, 2002), Link et al. (1998), Daum et al. (2002), Wang et al. (2002), Hong et al. (2002), Desquines et al. (2005), Bae et al. (2006), Kim et al. (2006), Dosik et al. (2007), Alam and Hellwig (2008), Saux et al. (2008, 2010), Kim et al. (2009), Kim and Kim (2013), Lee and Hong (2012), Shulga (2013), Jeong et al. (2014), Hellouin de Menibus et al. (2014a, b), Dick and Korkolis (2014a,b, 2015), Eom and kim (2014), Jenkins and Salem (2014), Yan et al. (2015), Cha et al. (2015)	Ring tension test	Transverse tensile properties
Bradhurst and Heuer (1975), Kawasaki et al. (1975), Hobson and Rittenhouse (1972), Link et al. (1998), Daum et al. (2008), Busser et al. (2009), Martin-Rengel et al. (2013), Samal et al. (2013), Jeong and Hong (2013, 2014), Jeong et al. (2014), Nikulin et al. (2014), Kim et al. (2015a,b), Ruiz-Hervias et al. (2015), Saux et al. (2015), Hózer et al. (2015), Korinko et al. (2015)	Ring compression test	Extent of embrittlement
Daum et al. (2002, 2005), Wang et al. (2002), Yagnik et al. (2005), Desquines et al. (2005), Zhang et al. (2005, 2015), Dosik et al. (2007), Nishioka et al. (2008), Saux et al. (2008, 2010), Latha et al. (2014), Eom and Kim (2014)	Axial tension test	Tensile properties along axial direction
Ueda et al. (1982), Rawers (1984), Ortlieb et al. (1985), Cappelaere et al. (2002), Nam et al. (2002) Murty et al. (2002), Tsai et al. (2005), Zhang et al. (2005), Bae et al. (2006), Seok et al. (2006), Kim et al. (2007a,b), Seok et al. (2011), Latha et al. (2014), Mathew et al. (2014), Rautenberg et al. (2014)	Creep test	Lersen-Miller parameters, activation energy
Pandarinathan and Vasudevan (1980), Kim et al. (2007a, b), Jia et al. (2011), Wen et al. (2013), Cheng et al. (2015)	Low cycle fatigue test	Cyclic plastic response
Grigoriev et al. (1995, 1996, 2005), Dhia et al. (1997), Samal et al. (2010, 2011, 2012), Coleman et al. (2010), Sanyal et al. (2011), Sanyal and Samal (2012, 2013,2014), Grybėnas et al. (2014), Chen et al. (2014)	Pin loading tension (PLT) test	Axial fracture and fatigue crack growth behavior
Vingsbo et al. (1996), Sung et al. (2001), King et al. (2005), Tang et al. (2014), Lin et al. (2016)	Fretting test	Fretting behavior
Link et al. (1998), Daum et al. (2002a,b), Desquines et al. (2005), Le Saux et al. (2010), Hellouin de Menibus et al. (2014a,b)	Transverse plane strain tension (TPST) test	Limit strain for necking and fracture strain at separation
Edsinger et al. (2000)	Vallecitos Embedded Charpy (VEC) test	Axial fracture behavior
Hsu et al. (2002), Hsu and Tsay (2011, 2012), Hsu et al. (2014), Hsu (2006)	X-specimen test	Axial fracture behavior
Kim and Moon (2004)	C-ring stress corrosion test	Crack characteristics with advancement of corrosion under stress
Yagnik et al. (2005, 2015)	Slotted arc tension (SAT) test	Tensile properties along circumferential direction
Catherine et al. (2006), Dick and Korkolis (2014a,b)	Internal conical mandrel (ICM) test	Axial fracture behavior
Tomalin et al. (1979), Nobrega et al. (1985), Foster (1987), Nilsson et al. (2011, 2015)	Segmented expanding mandrel (SEM) test	Circumferential stress-strain relation
Theobald and Nurick (2007), Palanivelu et al. (2011), Rossiter et al. (2012)	Axial crushing test	Crushing behavior under blast loading
Tomiyasu et al. (2007), Lee Saux et al. (2007)	PCMI test	Simulation of cladding failure at RIA condition
Leclercq et al. (2008)	Electromagnetic forming test	Simulation of cladding failure at RIA condition
Ross and Hendrich (2006), Le Saux et al. (2010), Dick and Korkolis (2014), Hellouin de Menibus et al. (2014a,b), Abe et al. (2015), Shinozaki et al. (2016)	Expansion Due to Compression (EDC) testing	Transverse tensile properties
Bertsch and Hoffelner (2006)	Double edge notched, tension (DENT) test Central hole, tension (CHT) test Central notch, tension (CNT) test	Axial crack resistance
Desquines et al. (2013)	C-shaped sample Compression Test	Accurate determination of local stress
Kuwabara and Sugawara (2013)	Multiaxial tube expansion test	Deformation of thin metals from yielding to fracture