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Residual strain distribution in bent composite boiler tubes

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Abstract

Kraft recovery boilers are typically constructed of carbon steel boiler tubes clad with a corrosion resistant layer, and these composite tubes are bent and welded together to form air port panels which enable the combustion air to enter the boiler. In this paper, the through-thickness residual strain in the carbon steel layer of non-heat-treated and heat-treated composite bent tubes were measured by neutron diffraction techniques and modeled by finite element modeling. The results can be used to optimize material selection and manufacturing processes to prevent stress corrosion and corrosion fatigue cracking in the boiler tubes.

Keywords: Residual stresses; Neutron diffraction; Heat treatment

1. Introduction

Co-extruded 304L stainless steel/SA210 carbon steel tubes were first used to make recovery boiler walls in Nordic countries in the early 1970s, and by the end of the decade, application of the composite tubes had been extended to service in many boilers in North America as floor tubes and wall tubes due to improved resistance to environments that caused severe thinning of carbon steel tubes [1]. But later experience gained with composite tubes in kraft recovery boiler tubes led to the realization that these tubes could be subject to different corrosion problems and failure mechanisms than the carbon steel tubes they replaced. These include accelerated preferential corrosion of the stainless steel outer layer in recesses around port openings, and cracking of the stainless layer in tubes that formed spout openings in some boilers. As the widespread nature of the cracking problem in composite tubes became apparent in North American and Nordic countries' boilers [2], a study funded by the U.S. Department of Energy was undertaken to try to identify the cracking mechanism and to recommend solutions.

Residual stresses on the outer surface of alloy 825/carbon steel composite bent tubes with or without heat-treatment were measured by X-ray diffraction technique in a previous study [3]. The results showed the surface residual stresses are compressive on the as-received non-heat-treated bent tubes, and change to tensile after heat-treated at either 615 or 920 °C. Previous observations of cracked floor tubes also revealed that some cracks initiated in the outer layer can continue to propagate into the inner carbon steel (CS) layer. Most cracks were circumferential and hence their growth would be aided by axial tensile stresses [4]. For preventing cracks growing across the CS/825 interface, compressive residual stresses in the CS layer can be very beneficial.

In this paper, room temperature axial residual strain in the carbon steel (CS) layer of alloy 825/carbon steel composite bent tubes were measured by neutron diffraction. Three types of composite bent tubes were investigated: a non-heat-treated tube; a tube heat-treated at 615 °C; and a tube heat-treated at 920 °C. These residual strain measurements are intended for validation of stress modeling to predict stress evolution in the CS layer of bent tubes and welded air ports during normal operation at high temperatures or with some localized thermal excursions. The study also assesses if heat-treatment procedures can be optimized or alternate materials selection can be used to avoid large tensile axial stress during operation or upon return to room temperature to prevent crack propagation into CS tube.

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2. Materials and experimental procedure

2.1. Materials

Three bent tube samples are all of the Kaevener design [5], where the bend is less extreme than with air ports from other sources. The extruded bent tube consists of a clad out-layer (825 steel) 2 mm thick and a carbon steel layer 5 mm thick (Fig. 1). The locations of neutron strain measurements in the CS layer are shown in Table 1 and Figs. 2 and 3. The distance between adjacent measurement locations is about 50 mm. For the neutron residual strain measurement, 9 locations on Kaevener tube, 13 locations on GPKV2 tube, and 11 locations on GPKV5 tube on the bent side with relatively high residual stresses were selected for study. Because previous observation shows crack growth was mainly aided by axial tensile stresses, only axial residual strain were measured on the Kaevener and GPKV2 bent tubes, while both axial and radial residual strain were measured on GPKV5 bent tube.

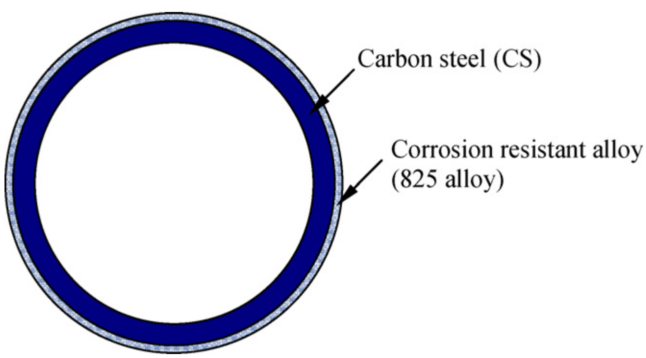

Fig. 1. Cross-section of a bent tube. Clad 825 steel layer thickness is 2 mm and the carbon steel core is 5 mm thick.

Table 1
Bent tube samples and measurement locations

Bent tube sample name	Heat-treatment	Locations measured by neutron in carbon steel layer
Kaevener	As-received, non-heat-treated	#1 to #9
GPKV2	920 °C heat-treated	#1 to #13
GPKV5	615 °C heat-treated	#1 to #6, #8 to #12

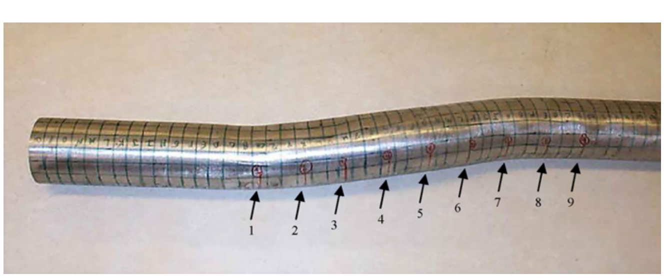

Fig. 2. As-received Kaevener bent tube and measurement locations #1 to #9 along bent side. There is about 50 mm between each measurement location.

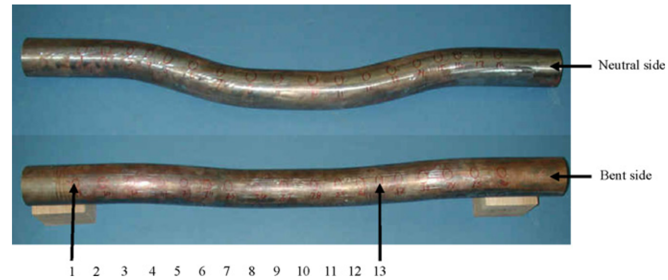

Fig. 3. Photos of GPKV5 bent tube showing the neutral and bent sides. Circles on the tube indicate the locations (approximately 50 mm apart) where surface stress and internal carbon steel strain were measured.

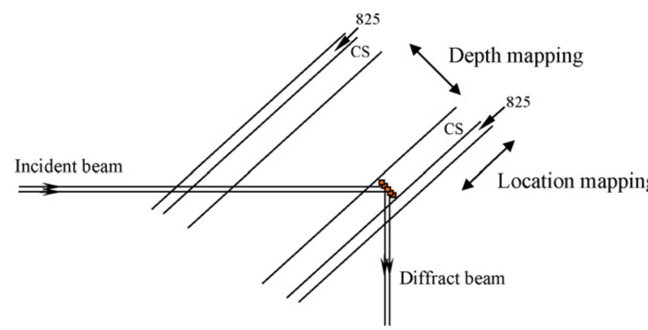

Fig. 4. Neutron strain measurement locations in the carbon steel layer as a function of depth. The measurement volume is shown schematically by the shaded diamond. With translation of the tube, multiple depths within the CS were sampled.

2.2. Strain measurement by neutron diffraction

The strain as a function of depth in the carbon steel layer (as shown in Fig. 4) was measured at the neutron residual stress facility (NRSF2) at the High Flux Isotope Reactor (HFIR) of Oak Ridge National Laboratory [6]. The bent tubes were mounted horizontally and residual strains were measured using the computer controlled goniometer with a single position sensitive detector (PSD). The diffraction peak of Fe (2 1 1) and neutron wavelength of 0.173 nm was used. Nominal gauge volume of 1 mm × 1 mm ×5 mm for the neutron measurement is defined by slits close to the specimen. A small steel bar (2 mm × 2 mm × 20 mm) was cut from the bent tube and used as the stress-free d0 standard for strain calculation. As shown schematically in Fig. 4, translation stages move the specimen relative to the gauge volume which is fixed in space. Effectively the gauge volume of the neutron beam moved through the carbon steel layer from the CS/825 interface to the inner (ID) free surface with a step size of 1 mm.

3. Results

3.1. Strain measurement results

The measurement results of axial residual strain at nine different locations along the length and through the thickness of the CS in the Kaevener bent tube are shown in Fig. 5. For a given