MECHANICAL DESIGN OF STEEL TUBING FOR USE IN BLACK LIQUOR RECOVERY BOILERS

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ABSTRACT

Finite element models were developed for thermal-mechanical analysis of black liquor recovery boiler floor tubes. Residual stresses in boiler floors due to various manufacturing processes were analyzed. The modeling results were verified by X-ray and neutron diffraction measurements at room temperature on as-manufactured tubes as well as tubes after service. The established finite element models were then used to evaluate stress conditions during boiler operation.

Using these finite element models, a parametric response surface study was performed to investigate the influence of material properties of the clad layer on stresses in the floor tubes during various boiler operating conditions, which yielded a generalized solution of stresses in the composite tube floors.

The results of the study are useful for identifying the mechanisms of cracking experienced by recovery boilers. Based on the results of the response surface study, a recommendation was made for more suitable materials in terms of the analyzed mechanical properties.

INTRODUCTION

A black liquor recovery boiler (BLRB) is an essential component in kraft pulp and paper mills. It is used to recover certain chemicals used in the paper-making process and to generate process steam by burning the black liquor. Heat generated by burning the black liquor in the recovery furnace is transferred to pressurized water running through the tubes which form the floor and walls of the furnace. The chemicals, known collectively as smelt, are collected from the recovery boiler in a molten state. Some of the smelt which is deposited on the furnace floor can form a thick layer, which significantly affects the heat transfer and temperature of the floor tubes. The smelt layer adjacent to the floor tubes is normally frozen. The frozen smelt is a reasonably good insulator. The molten smelt sometimes penetrates through the frozen layer to the tube surface. This phenomenon is not well understood, but may occur due to chemical reactions in the smelt or due to cracking of the frozen smelt. Temperature measurements on some boiler floors confirm the expected temperatures at normal operation, but in some cases also show considerable temperature fluctuations.

In this study the coextruded composite tubes, SS304L clad on SA210 base tube, that are widely used in recovery boiler floors were analyzed. There are several reports of extensive cracking in the stainless steel layer. To determine the cause of the cracking phenomenon, a multidisciplinary research program has been initiated by ORNL [1, 2]. The present study is a part of the multidisciplinary study and aims to predict the stress state in the boiler floor before service, at different service conditions, and after service. A combination of numerical (finite element (FE) analyses performed with ABAQUS code [3]) and experimental (neutron diffraction (ND) and X-ray measurements) methods was used in determining the stress state. The results can be used to gain understanding of failure mechanisms in composite tubes.

Alternative materials and manufacturing processes are being considered to improve the resistance to cracking and the in-service life of composite tubes. To avoid numerous FE stress-strain analyses of composite tubes made of different material combinations, a response surface study was performed that considered two essential mechanical properties of the clad material - coefficient of thermal expansion and yield stress - as independent variables. The response surface study provided a generalized solution of stresses in the floor in terms of the two selected parameters.

THERMAL-MECHANICAL ANALYSIS

The thermal-mechanical analysis was performed for the SS304L/SA210 composite floor using different 2D and 3D FE models. The analyzed composite floor was made of tubes with the inside diameter of 49.0 mm and the thickness of 7.1 mm (5.2 mm SA210 base and 1.9 mm SS304L cladding), with 12.7 mm wide membranes between the tubes. The thermal and mechanical analyses were performed sequentially.

Thermal Analysis

A 2D FE model for thermal analysis of the smelt-tube-fluid system was developed to determine the temperature distribution in the composite tubes at normal operation and during temperature excursions. To determine the temperature distribution in the tube at normal operating conditions, a steady-state analysis was performed, assuming the floor is covered by a layer of frozen smelt, 25.4 mm thick (measured from the tube crown), with the molten smelt at 800°C on top. The tube is cooled inside by cooling water at 285°C. At steady state the temperature gradient through the tube thickness reaches about 30°C at the tube crown. A typical temperature excursion with the peak temperature of 550°C at the fireside surface at the tube crown was simulated to determine the temperature distribution in the tube during the excursion.

The calculated temperature profile of normal operation was applied to a 3D model of the boiler floor to analyze the stress state at service conditions. To calculate the stresses during a temperature excursion, the calculated time- dependent temperature profile of a temperature excursion was superimposed on the temperature profile of normal operation.

Mechanical Analysis

Stresses in the boiler structure at service conditions are a combination of stresses due to in-service loading and residual stresses from manufacturing. The most important in-service loading is the high, often fluctuating, operating temperature and the internal tube pressurization. The boiler structure undergoes a sequence of manufacturing processes, which means that it has built-in stresses even before it sees service.

These stresses may be collectively termed residual stresses from manufacturing. Neutron diffraction (ND) and X-ray techniques were used to measure the residual stresses from the tube manufacturing. These residual stress results were used in the FE simulation of the assembly welding and the total residual stresses from the panel manufacturing were predicted. The calculated residual stresses were then used to define the initial stress conditions in the analysis of in-service loading, performed by a 3D model.

Experimental

Apart from supplying initial residual stress values due to the fabrication of composite tubes, neutron and X-ray diffraction have been used to validate the results of finite element calculations. The ND experiments were carried out at the High Flux Isotope Reactor of Oak Ridge National Laboratory using a modified triple-axis spectrometer [4]. This method [5] uses one or several diffraction peaks as a strain sensor. From the measured residual strains, residual stresses are derived using Hooke's law and appropriate elastic constants.

The X-ray experiments were carried out using a portable instrument (TEC, Inc., Knoxville, Tennessee, USA). Due to the fabrication process, the clad layer of the composite tubes is textured. As a consequence, a special X-ray technique, based on the measurement of the fcc (3 1 1) reflection using Cr K_β radiation, had to be developed [6] in order to allow precise determination of surface residual stresses in the textured clad layer. With this technique, an experimental precision of ±10-20 MPa was achieved.

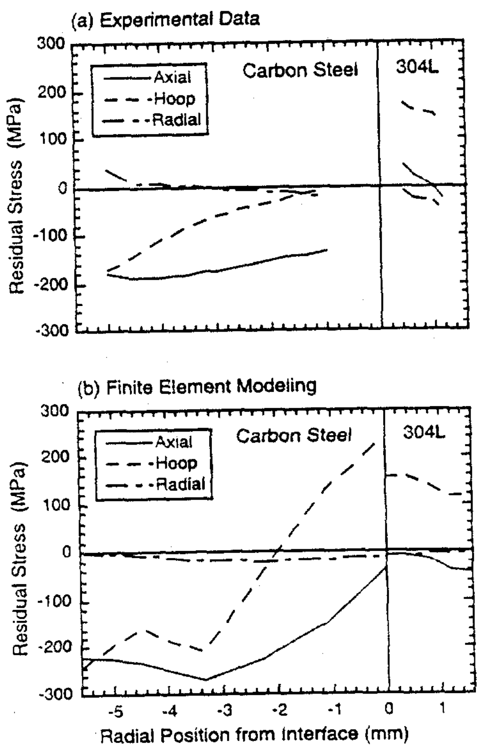
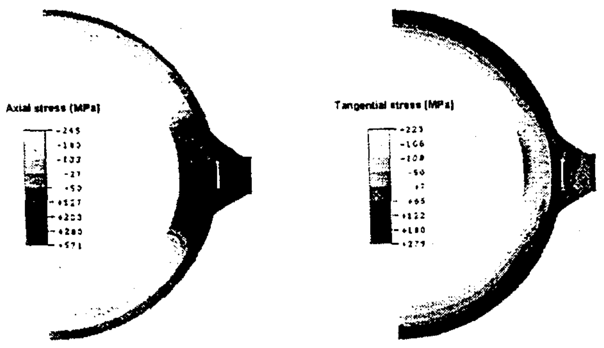


Figure 1. A comparison of through-thickness residual stress profile at the crown of a composite tube panel as determined with neutron diffraction and calculated by finite element modeling.

Figure 1 compares the through-thickness residual stress profile at the crown of a composite tube panel determined with ND with the results of FE calculations. As can be seen, the main features of FE calculations are confirmed by the experimental data. Note that the axial stress is compressive at the outer surface. Upon cooling from operating temperature, the axial stress should become tensile, according to the FE model. This prediction was verified by X-ray and ND measurements of tube panels removed from operating mills [7], where a tensile residual stress was found at the crown of the panel. These experimental results show that the essential physics describing the thermal-mechanical behavior of the boiler panel under study has been adequately covered in the present FE model. Therefore, it is justified to use this model to evaluate stress conditions during boiler operation and for the mechanical design of new boiler tubing.

Finite Element Modeling

A 2D model of the tube-weld-membrane radial cross-section based on an uncoupled thermal-mechanical FE formulation was developed to perform the simulation of assembly welding (for details see [8, 9]). The simulation was performed such that the weld was made on one side first, the tube was cooled to room temperature, and then the weld was made on the other side. The properties of type 312 stainless steel were used for the weld filler metal. Figure 2(a) shows the axial stresses and Fig. 2(b) the tangential stresses in the tube-membrane assembly that result from the panel manufacturing processes. Particularly high axial tensile stresses develop in the weld joint region, whereas the stresses are compressive in the rest of the tube. Tangential stresses are tensile in the clad material and in the outer part of the carbon steel base, but are compressive at the inner tube surface.



(a) (b)

Figure 2. Calculated residual stresses in as-manufactured composite tube panels: (a) axial stress distribution; (b) tangential stress distribution.

The 3D FE model, 5 tubes wide and 1270 mm long, built by shell finite elements and the consideration of dual geometric symmetry, was developed to analyze the stress state in the tubes at normal operating conditions and at temperature excursions (for details see [9]). In addition to the calculated residual stresses from manufacturing, thermal loading and internal pressurization were applied. Figure 3 shows the imposed temperature cycle of a normal operation and the corresponding stress results for a point at the fireside surface of the tube crown. The results show that the compressive stresses in the SS304L clad layer exceed the yield stress at operating conditions. Stresses at room temperature after service are tensile and considerably higher than the residual stresses from manufacturing. The performed analysis is a sequence of steady state thermal analyses, which means that transient stresses during cooling were not calculated (for the complete transient analysis see [9]). The results of the transient analysis show that stresses in the SS304L clad become tensile at about 270°C and reach the yield stress at the temperature of approximately 220°C. This is important in considering failure mechanisms during the shut-down event of a boiler.

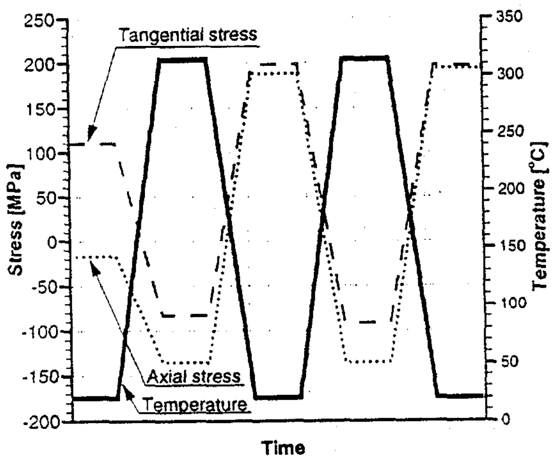


Figure 3. Axial and tangential stresses for a normal operating cycle.

A temperature loading scenario that consists of two temperature excursions to 550°C, one after another, superimposed to a normal operating cycle was constructed to analyze stresses in the tubes at temperature excursions. Figure 4 shows the temperature variation and the corresponding axial and tangential stress components for a point within the hot spot region at the fireside surface of the tube crown. The temperature excursion causes higher compressive stresses compared to those at normal operating conditions and considerable yielding. Returning to the operating temperature causes a stress reversal in the SS304L clad. Stresses at the hot spot remain tensile at normal operation after temperature excursions and exceed the yield stress of the material at normal operating temperature. Cooling to room temperature introduces additional yielding and further increases the tensile stresses. Additional analyses show that stresses at the hot spot location remain tensile throughout the current service period, but become compressive again after the shut-down and restart of the boiler. The mismatch in thermal expansion between the base and the clad material and the low yield strength of SS304L are the main reasons for the very high stress and yielding in the SS304L clad. As the analyses show, simply heating to the operating temperature causes the SS304L clad to yield. Very small temperature fluctuations, 40°C or higher, can cause the reversal of compressive to tensile stresses in the SS304L clad at operation.

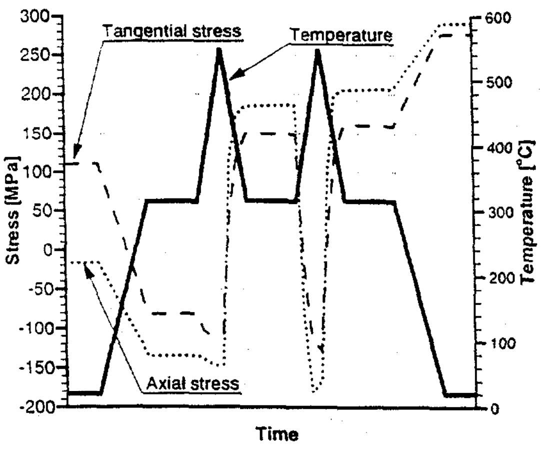


Figure 4. Axial and tangential stresses for a temperature excursion scenario.

PARAMETRIC STUDY OF CLAD MATERIALS

To obtain a generalized solution of stress state in composite boiler floor tubes made of SA210 carbon steel with various clad materials, a study combining the FE analyses and response surface technique was performed. Details of the response surface study performed can be found elsewhere [9]. Based on the results of this study a recommendation for clad materials with the most suitable mechanical properties was made.

Initially, two independent variables and two dependent parameters were selected. The independent variables are the yield stress of the clad material, σ_y, and its coefficient of thermal expansion (CTE) and the dependent parameters are the axial and tangential stresses. The selected range for σ_y is between 100 MPa and 700 MPa, whereas the range from 0.9×10^{-5} °C^{-1} to 2.1×10^{-5} °C^{-1} was selected for CTE. The selected range covers the presently used materials, as well as most of the alternative clad materials. The stresses or dependent parameters in the response surface analysis were evaluated at the fireside surface of the tube crown and at the fireside surface of the membrane. Figure 5 is a schematic of the three temperature scenarios analyzed, showing temperatures of the fireside surface of the tube crown. Scenario A is a transient from the unloaded state at room temperature to normal operating conditions and back to room temperature. The two other scenarios are designed to study the effects of temperature excursions on stresses in the tubes. In scenario B, a temperature excursion with the peak temperature of 550°C is superimposed on the operating temperature of the transient A. Scenario C is similar to B, except that its peak temperature is 380°C. According to temperature measurements on some recovery boiler floors, the temperature fluctuations with peak temperature of 380°C occur often, whereas 550°C is the highest temperature of recorded excursions [10].

Figures 6 and 7 show the calculated tangential stresses at the fireside surface of the tube crown at service, transient A, and at service after the temperature excursion, transient C. The calculated stresses are presented as functions of the two independent variables, CTE and σ_y. Positive numbers represent tensile stresses, whereas negative numbers denote compressive stresses. Note the axis at the right side that shows σ_y of the clad materials that corresponds to the plot temperature. Also note that the points representing the materials normally used in recovery boilers are adjusted according to the plot temperature.

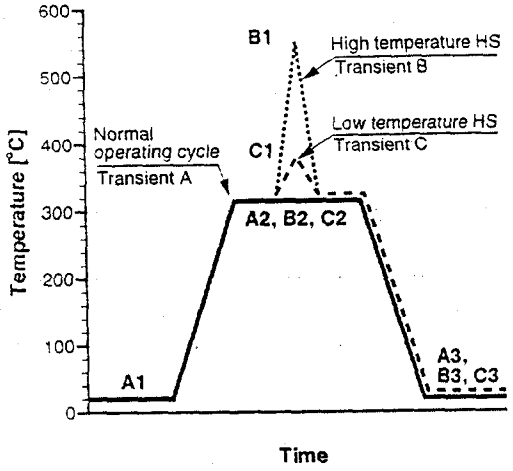


Figure 5. Temperature scenarios considered in response surface analysis.

To prevent stress corrosion cracking in the tubes, tensile stresses should be avoided throughout the service. Also, the stresses should not exceed the elastic limit. Therefore, an evaluation of the results provided by the response surface analysis was made according to the following criterion: *stresses should not be tensile and stresses should be smaller than the yield stress.* Based on these results some regions were defined in the σ_y - CTE plots that either fully or partially satisfy the above criterion. The evaluation was based on the tangential and axial stress components calculated, at the fireside surface of the tube crown and at the fireside surface of the membrane for the transients defined in Fig. 5. In particular, the positions A1-A3, B1-B3, and C1-C3, shown in Fig. 5, were evaluated. The results are presented in Fig. 8 and show three regions that satisfy the established criterion. The axial stresses at the membrane, which are tensile, however, are an exception. Region (1) is determined based on transient A, and the clad materials defined with CTE and σ_y falling inside the region satisfying the criterion. The region becomes considerably larger if one allows the compressive axial stresses at the tube crown to exceed the yield stress during service, region (2). Region (3) includes the materials that comply with the criterion throughout the transient C, with an exception of the compressive axial stresses at the tube crown that exceed the yield stress during temperature excursions. However, after returning to operating conditions, the criterion is again satisfied. The analysis of transient B shows that the compressive axial stresses at the crown exceed the yield stress during the temperature excursion for any CTE - σ_y combination. After returning to normal service conditions, the axial and tangential stresses become tensile and stay tensile during operation at the location where the hot spot occurred. This means that the criterion cannot be met in the case of a high temperature excursion.

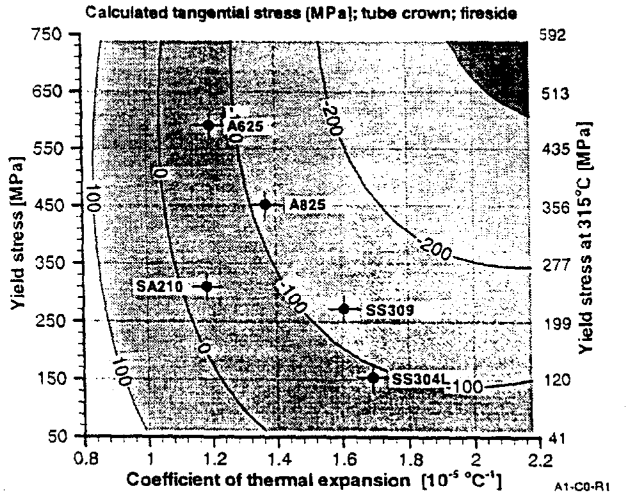


Figure 6. Tangential stresses at service conditions at the tube crown as a function of CTE and σ_y of the clad material. The inserted points show σ_y and CTE of several clad alloys under consideration.

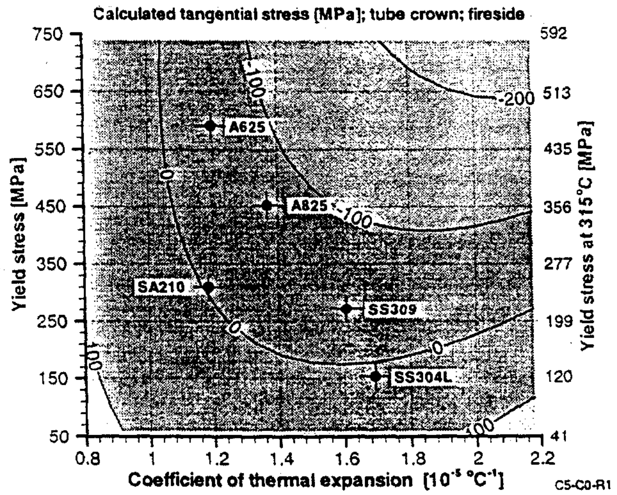


Figure 7. Tangential stresses at service after a temperature excursion at the tube crown as a function of CTE and σ_y of the clad material. The inserted points show σ_y and CTE of several clad alloys under consideration.

The results suggest that a clad material within the suggested CTE - σ_y region (see Fig. 8) may well survive the normal operating conditions, as well as low temperature fluctuations, whereas temperature fluctuations of higher magnitudes clearly cause severe stresses in the clad material. According to Fig. 8, a suitable material has a yield stress higher than, say 300 MPa, and a CTE around 1.2×10^{-5} $°C^{-1}$. Interestingly, the SS304L clad material falls outside the acceptable range, which is consistent with the extensive cracking observed in boilers made of composite tubing with SS304L clad. On the other hand, the alloy 625 clad material is almost always within the acceptable region.

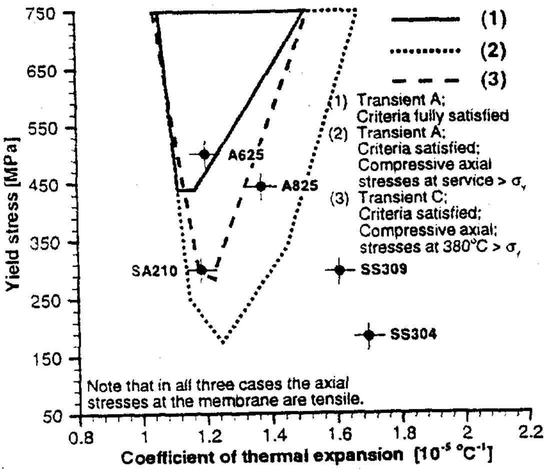


Figure 8. Regions of recommended clad materials in terms of CTE and σ_y.

CONCLUSIONS

The finite element analysis of the SS304L/SA210 composite tube floor reveals that SS304L cladding material is not recommended from the mechanical standpoint. The established facts supporting such a conclusion show that compressive stresses in the SS304L clad:

(1) exceed the yield stress at operating conditions,

(2) are reversed to tensile stress at operating conditions by a temperature excursion of 40°C or higher, and

(3) are reversed to tensile stress on cooling from the normal operating temperature at about 270°C and exceed the yield stress at about 220°C.

Regions of CTE and σ_y defining the recommended clad materials from the standpoint of mechanical behavior were determined based on a combined FE and response surface approach performed for both normal service conditions and for conditions where temperature excursions occur. A recommended clad has a CTE of approximately 1.2×10^{-5} °C^{-1} and a yield stress higher than 300 MPa, in the case where the SA210 carbon steel is used as the base material. A cladding material that well satisfies the criterion established in this work is alloy 625.

ACKNOWLEDGMENTS

The authors would like to thank Dr. B. Radhakrishnan and Dr. G. B. Sarma for reviewing the paper. The research was sponsored in part by an appointment to the ORNL Postdoctoral Research Associates Program administered jointly by the Oak Ridge Institute for Science and Education and ORNL. The research was also sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Materials Program, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

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