Modeling studies of a composite tube floor in black liquor recovery boilers

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BLACK LIQUOR

ABSTRACT

Stress-strain analysis of a composite tube floor in black liquor recovery boilers used a commercially available finite element (FE) code. The analysis examined the stress state in an SS304L/SA210 composite tube floor at the normal operating cycle of a boiler and the stresses that develop from temperature excursions during operation. Measurement of residual stresses from tube manufacturing used neutron diffraction. With the residual stresses from assembly welding computed by finite elements, the residual stress measurements were incorporated into the FE models developed for analysis of in-service conditions. Results show high compressive stresses in the overlay material that exceed the yield stress at normal service conditions. They significantly exceed the yield stress during a temperature excursion and become tensile after returning to normal service conditions. A parametric study calculated stresses in the floor tubes as a function of the yield stress and the coefficient of thermal expansion of the overlay material. The analysis provided a generalized solution of stresses in the composite tubes for many overlay materials. Using these results, a recommendation for overlay materials with the most suitable mechanical properties is possible.

Application:

For mechanical behavior, SS304L is not a suitable overlay material, but alloy 625 is satisfactory.

A BLACK LIQUOR RECOVERY (BLRB) is an essential component in kraft pulp and paper mills. It recovers certain chemicals used in the papermaking process and generates process steam by burning the black liquor. Heat from this burning transfers to pressurized water running through tubes that form the floor and walls of the furnace. Chemicals known collectively as smelt are collected from the recovery boiler in a molten state. Smelt that deposits on the furnace floor can form a thick layer that significantly influences the heat transfer and tube temperature. The smelt layer next to the floor tubes is normally frozen. The frozen smelt is a good insulator and keeps the temperature at the fireside tube surface about 30°C above the temperature of the cooling water. The water temperature is normally about 285°C for a typical recovery boiler. Above the frozen smelt layer is a pool of molten smelt at temperatures higher than 800°C.

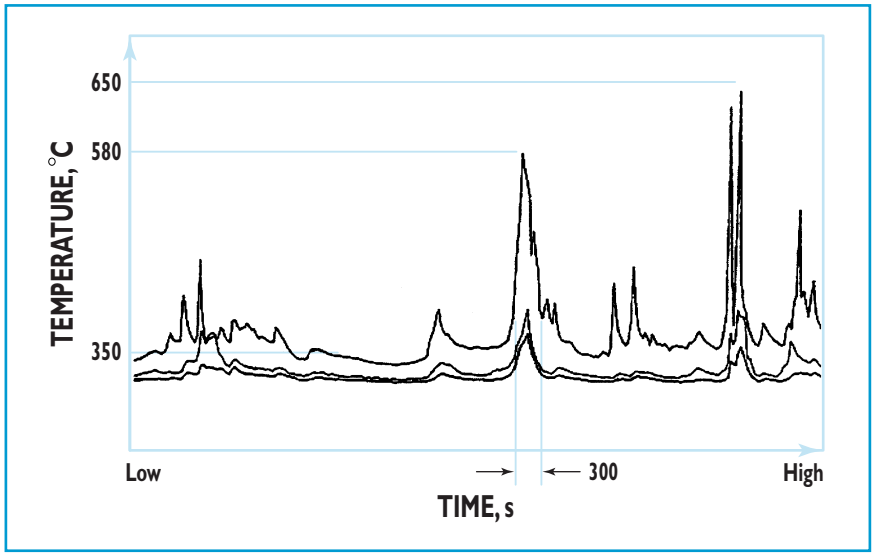
Molten smelt sometimes penetrates to the tube surface. This phenomenon is not well understood but may occur due to chemical reactions in the smelt or cracking of the frozen smelt. Some boiler manufacturers have measured the temperature of the floor tubes by thermocouples (TC). Temperature measurements confirm the expected temperatures for normal operation but sometimes show considerable temperature fluctuations. Such excursions typically have short duration. Their temperature is usually only 100°C higher than that of normal operation. Some reports show temperatures as high as 600°C are sufficiently high to melt the metal shield of a TC installed on the tube crown *(1)*. This suggests that the molten smelt had reached the TC shield positioned about 3 mm above the tube surface. Metallographic studies of several extensively cracked floor tubes do not show indications for the tube material being at that high temperature for a metallurgically significant duration. This means that some protective layer of frozen smelt still remains attached to the tube surface during such events *(2)*.

High operating pressure that causes higher floor and wall temperatures and a highly corrosive environment in the furnace contribute to rapid corrosion of carbon steel (SA210 Grade A1) tubes in the lower furnace—floor and lower walls. Type 304L stainless steel (SS304L) is highly resistant to the sulfidizing environment in the boiler. Composite tubes of conventionally coextruded SS304L overlay on SA210 base tube were selected to address this corrosion problem *(3)*. After various periods of operation, extensive cracking developed in the stainless steel layer of several boilers worldwide *(3)*.

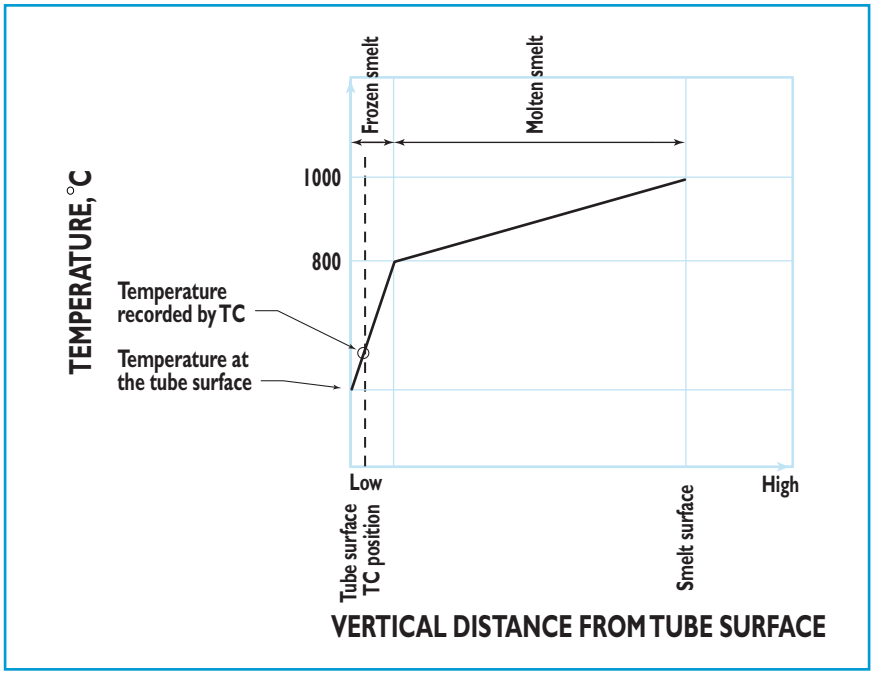
High temperatures in recovery boilers are the most significant cause of high stresses in composite tubes. This is especially true in those tubes with poorly matched coefficients of thermal expansion. A multi-disciplinary research program has studied the cause of the cracking phenomena in the stainless steel layer *(2–4)*.

Alternative materials and manufacturing processes are under consideration to improve the resistance to cracking and service life of composite tubes:

- Coextruded tubes with different overlay materials such as alloy 625 or alloy 825



1. Typical temperature excursion measured by a thermocouple



2. Temperature gradient through the smelt layer (Temperature measured by thermocouples may be higher than the actual temperature of the tube surface.)

- Carbon steel tube with a welded, corrosion-resistant overlay such as alloy 625 or type 309 stainless steel
- Chromized carbon steel tubes.

A modeling effort has studied the mechanical state of a boiler floor at normal operating conditions and at various events that can occur during operation. A commercially available finite element (FE) code *(5)* was used to perform the thermal and stress-strain analysis of a particular boiler floor configuration—SS304L/SA210 composite tubes—and perform the parametric response surface study for different overlay materials. The composite tube panel uses tubes with inside diameters of 49.0 mm and thicknesses of 7.1 mm (5.2 mm SA210 base and 1.9 mm SS304L overlay) with membranes of 12.7 mm widths between the tubes.

THERMAL ANALYSIS OF BLRB FLOOR

A two-dimensional FE model for thermal analysis of the smelt-tube-fluid system was developed to determine the temperature distribution in a tube 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 molten smelt at 800°C on top. The typical temperature excursion measured by TC presented in **Fig. 1** was simulated to determine the corresponding temperature distribution in the tube during the excursion. Cooling water at 285°C inside the tube provides cooling. The convection coefficient between the cooling water and the tube was assumed to be 56,780 W/m²K *(1)*. Ideal contact between the tube and the frozen smelt was assumed. Temperature dependent thermal properties used for SA210 and SS304L steels came from previous work *(6–10)*. A constant value of 5.0 W/mK was assumed for smelt thermal conductivity, and a constant value of 1.25 J/gK was assumed for the smelt specific heat *(11)*.

Temperature measured by a TC positioned at the crown of the tube verified the calculated temperature. Temperature measured by the TC was assumed to correspond to the smelt temperature at 3.2 mm above the tube surface. This is higher than the tube surface temperature. **Figure 2** shows the assumed temperature gradient through the frozen and the molten smelt layer.

The calculated temperature profile for normal operation was applied to a three-dimensional

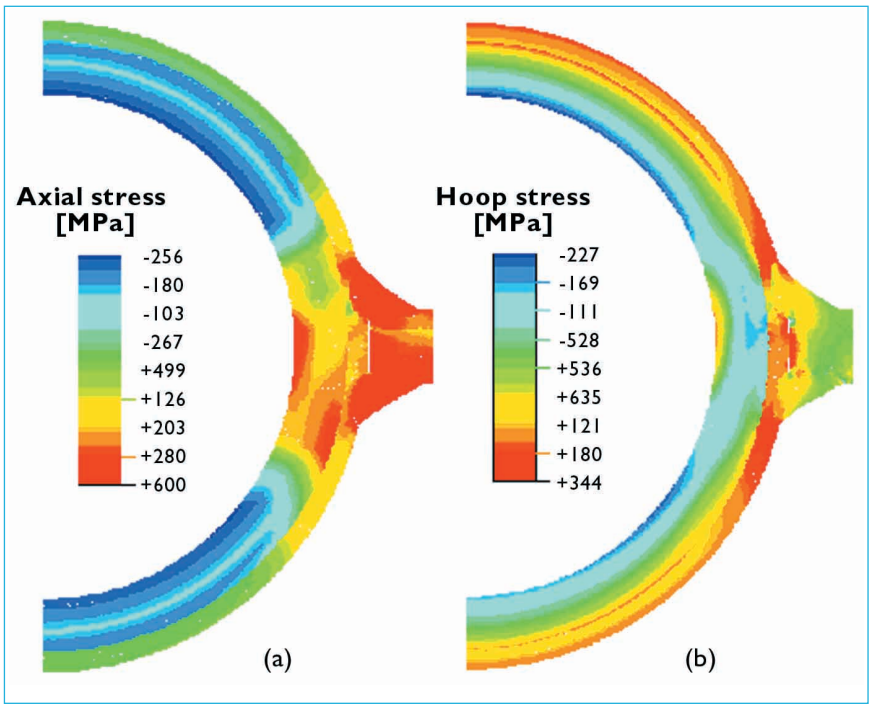
model of the boiler floor with the calculated residual stresses from manufacturing and the in-service pressurization to analyze the stress state at service conditions. To calculate the stresses during a temperature excursion, the calculated time-dependent temperature profile of a temperature excursion was superimposed on the temperature profile of normal operation.

STRESS ANALYSIS OF BLRB FLOOR

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 loadings are the high and often fluctuating operating temperature and internal tube pressurization. Tube material experiences different manufacturing processes such as extrusion, straightening, and rolling before the tubes undergo welding to a panel. After necessary adjustments, this panel becomes part of the boiler structure. The boiler structure therefore has built-in stresses even before it sees service. These stresses result from the sequence of manufacturing processes and have the collective term of residual stresses from manufacturing. High tensile residual stresses in the region near the weld can promote brittle fracture and change or aid the fatigue strength and stress corrosion cracking *(12–14)*. A thorough analysis of residual stresses is therefore essential for accurate study of boiler structure at service conditions.

Determination of residual stresses from manufacture of tube-web assemblies

SS304L/SA210 composite tubes in recovery boilers are made by coextrusion. The tubes are straightened and then welded to panels used to assemble the recovery boiler. The tube manufacturing processes and the assembly welding induce significant residual stresses into the boiler structure.

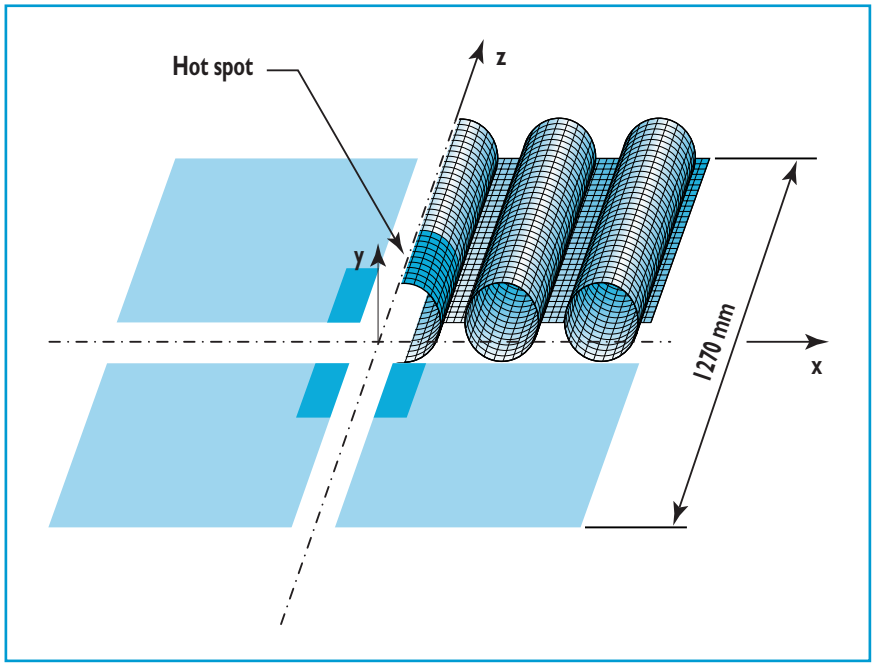


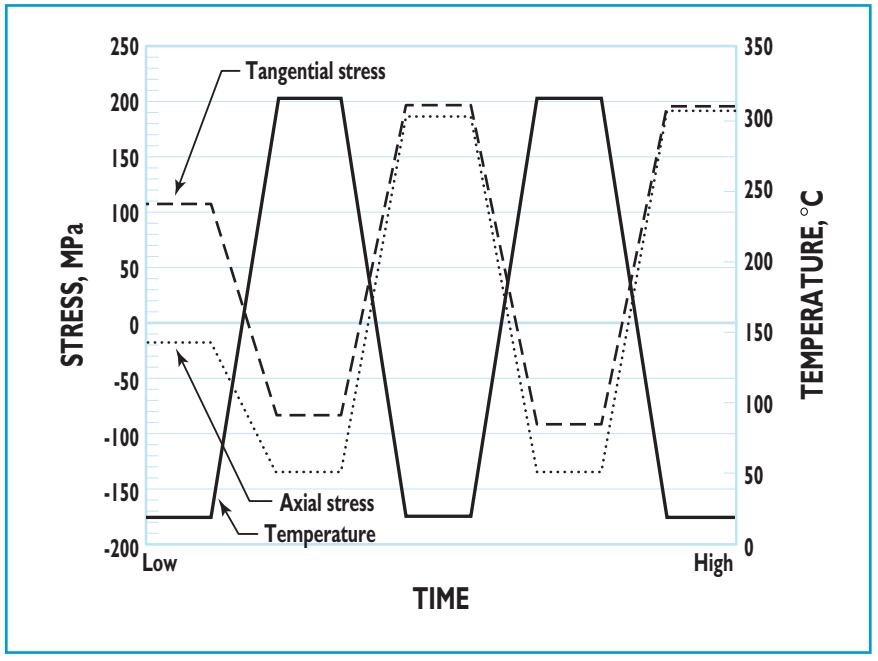
3. Calculated residual stresses from manufacturing include residual stresses measured by ND and stresses from assembly welding with (a) axial stress distribution and (b) tangential stress distribution

The residual stresses from panel manufacturing were analyzed by experimental and computational methods. A neutron diffraction (ND) technique measured the residual stresses from the tube manufacturing. Details of the experiment are available elsewhere *(13)*. The FE analysis of the assembly welding used the FE model of the tube-weld-membrane radial cross section of **Fig. 3**. The residual stresses in the tube measured by ND were the initial conditions. Linear, four-node finite elements with a generalized plane strain formulation were used. Uncoupled thermo-mechanical FE formulation and temperature dependent thermophysical and mechanical properties were considered. The thermal analysis used a heat conduction formulation with Gaussian heat input from the arc to calculate the transient temperature distributions during welding. The mechanical analysis relied on the thermal analysis results and calculated the stress and strain distribution. The simulation was performed such that the weld was first made on one side, the tube was cooled to room temperature, and the weld was then made on the other side. Properties of type 312 stainless steel were used for the weld filler metal. Figure 3a shows the axial stresses and Fig. 3b shows the tangential stresses in the tube-membrane assembly that result from the tube manufacturing processes and the assembly welding. Particularly high axial tensile stresses develop in the weld joint region. The stresses in the remainder of the tube are compressive. Tangential stresses are tensile in the overlay material and in the outer part of the carbon steel base but are compressive at the inner tube surface.

Analysis of stresses at service conditions

A three-dimensional FE model was developed using shell finite elements with the composite material formulation. **Figure 4** shows the model. Three-dimensional solid elements were used to model the welds joining the tubes and membranes. The





model is sufficiently large relative to the hot spot dimensions so stress concentration in the hot spot region diminishes within the model and an infinity assumption is possible. The FE model eas built with the assumption of dual geometrical symmetry. This allows the actual FE mesh to be only one-quarter of the actual analyzed geometry. The analysis used a model 1270 mm long, a width of five tubes, and a 423 mm long hot spot at the crown of the middle tube.

The model analyzed the stress state in the tubes at normal operating conditions by simulating two cycles of heating to the operating temperature and cooling back to room temperature. Besides the thermal loading, the calculated residual stresses from manufacturing and internal pressurization were applied. **Figure 5** shows the imposed temperature cycle and the corresponding stresses for a point at the fireside surface of the tube crown. The results show that the compressive stresses in the SS304L overlay exceed the yield stress at operating conditions. Stresses at room temperature after service are tensile and much higher than the residual stresses from manufacturing. The performed analysis is a sequence of steady state thermal analyses. This means that transient stresses during cooling were not calculated. A question therefore arises about what temperature during the cooling transient do the stresses at the overlay tube surface become tensile. This is important in considering failure mechanisms during shutdown of a boiler. To answer this question, a thermo-mechanical transient analysis of the boiler cooling transient was performed assuming linear variations of temperature from 315°C to 20°C and internal pressurization from 8.62 MPa to 0 MPa in 300 min. **Figure 6** shows the axial and tangential stresses at the fireside surface of the tube crown during the transient and the yield stress of SS304L that corresponds to the actual material temperature. The stresses in the SS304L overlay become tensile at approximately 270°C and reach the yield stress at approximately 220°C.

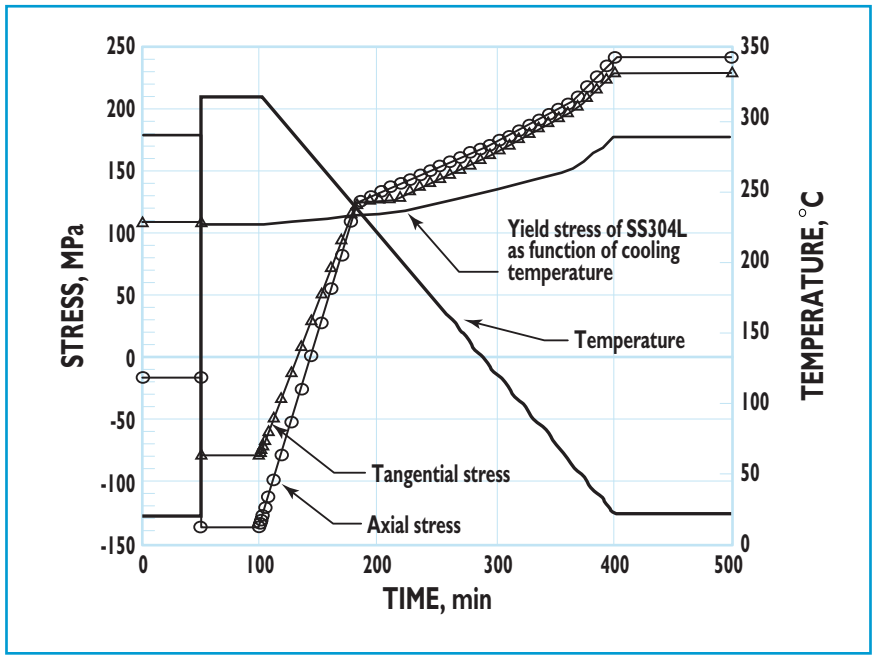
Analysis of stresses caused by temperature excursions

Two temperature loading scenarios analyzed stresses in the tubes at temperature excursions:

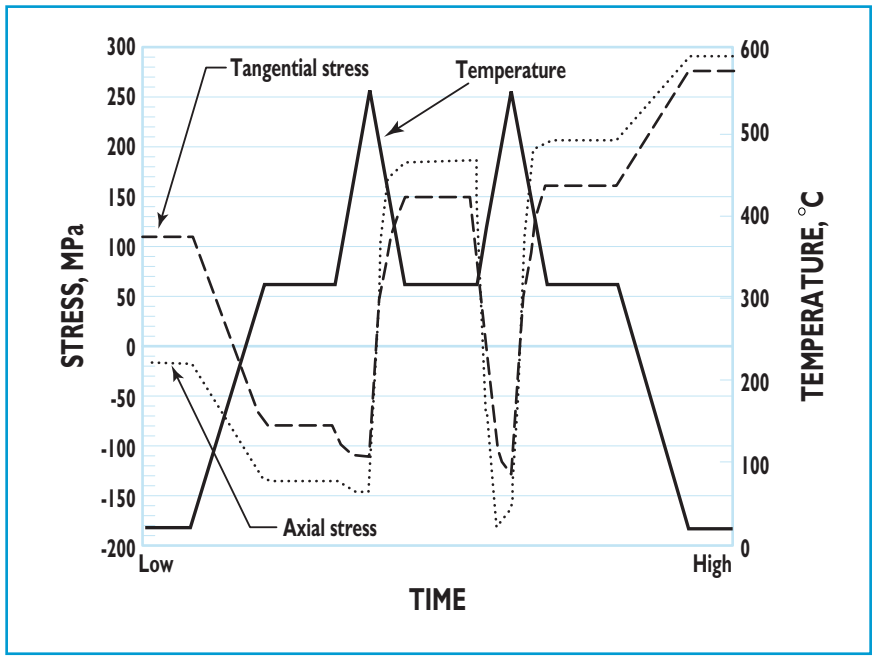
- Two temperature excursions of 235°C (550°C absolute temperature) one after another
- A temperature excursion of the same magnitude with a simultaneous occurrence of steam blanketing.

Again, the analysis used the three-dimensional model. The residual stresses from manufacturing, the temperature distributions calculated with the two-dimensional model, and the internal pressurization were applied to the model. Steam blanketing was modeled by specifying an order of magnitude lower heat convection coefficient between the cooling water and the tube (567.8 W/m2K) for the 90° circumference at the tube crown.

Figure 7 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 compressive stresses in the SS304L overlay exceed the yield stress at operating conditions. The temperature excursion causes higher compressive stresses compared with those at normal operating conditions and considerable yielding. Returning to the operating temperature causes a stress reversal in the SS304L overlay—high tensile stresses that exceed the yield stress. The second temperature excursion causes an additional yield and even higher tensile stresses after the excursion. Stresses at the hot spot location remain tensile at normal operation after the temperature excursion. Cooling to room temperature introduces additional yielding and increases the tensile stresses. Results of some additional analyses show that stresses at the hot spot location remain tensile throughout the current service period but become compressive again after the shutdown and restarting of the boiler.

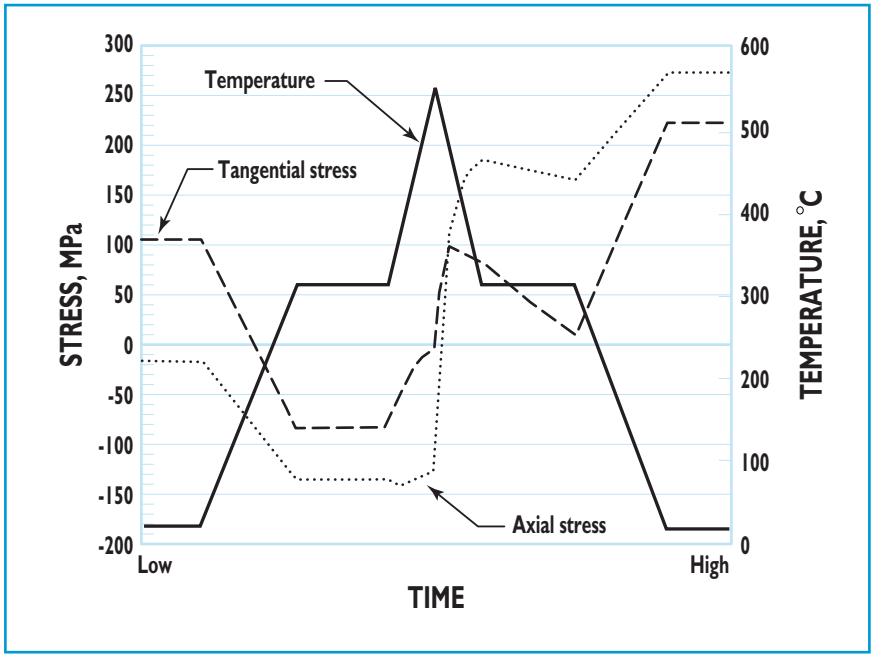


6. Axial and tangential stresses during cooling to room temperature

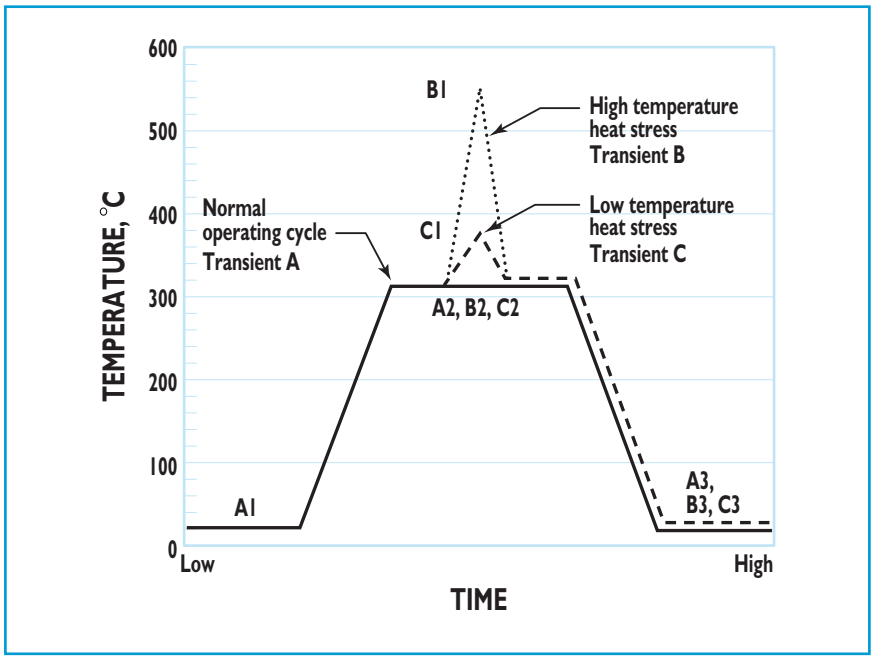


7. Axial and tangential stresses for a temperature excursion scenario

Figure 8 shows the assumed temperature variation for a temperature excursion scenario with steam blanketing and the corresponding axial and tangential stresses for a point within the hot spot region at the fireside crown of the tube. Simultaneous occurrence of temperature, excursion and steam blanketing causes higher tube temperature and larger deformation and yielding of the carbon steel base with more pronounced constraints from the adjacent tubes. The presence of steam blanketing causes higher temperatures at the inside tube surface. This means a lower temperature gradient through the tube thickness. In this case, the constraints from the adjacent tubes relieve the high compressive tangential stresses that develop at the fireside crown during temperature excursion without steam blanketing. No additional yielding therefore occurs during the temperature excursion. This agrees with predic-



8. Axial and tangential stresses for a temperature excursion scenario with steam blanketing



9. Temperature scenarios considered in response surface analysis

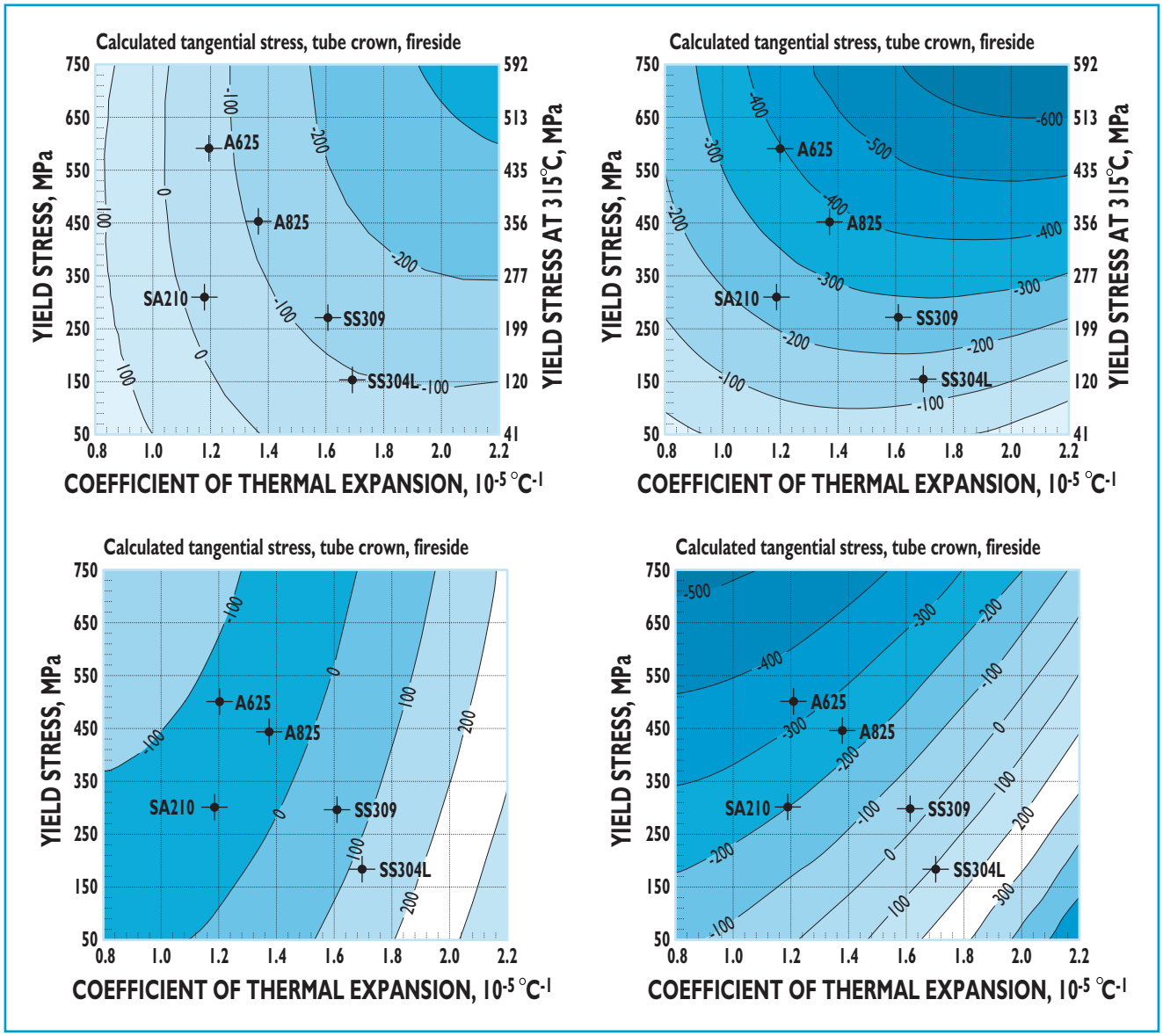
tions of previous models *(3)*. Stresses at the SS304L overlay are tensile after the temperature excursion despite different stress developing mechanisms caused by steam blanketing and remain tensile during operation. The stresses in the steam blanketing case are lower due to a smaller temperature gradient through the tube thickness.

PARAMETRIC STUDY OF OVERLAY MATERIALS

To obtain a generalized solution of stress state in the boiler floor made of SA210 carbon steel tubes with various overlay materials, a study combining the FE analyses and response surface technique was performed. The results of this study offer a recommendation for overlay materials with the most suitable mechanical properties.

Analysis setup

A response surface study provides a generalized solution of dependent variables over a selected array of independent variables by performing FE computations according to an appropriate response surface design *(15)*. Initially, two independent variables and two dependent variables were selected. The independent variables were the yield stress of the overlay material, σ_y, and its coefficient of thermal expansion, CTE. The dependent variables are the axial stress and the tangential stress. The selected range for σ_y was 100–700 MPa. The range for CTE was 0.9 x 10^{-5}–2.1 x 10^{-5}°C^{-1}. The selected range covers most applicable materials and the materials presently used in recovery boilers. The stresses or dependent parameters in the response surface analysis were evaluated at two locations—the fireside surface of the tube crown and the fireside surface of the membrane. **Figure 9** is a schematic of the three temperature scenarios analyzed. It shows temperatures of the fireside surface at the tube crown. Transient A is the transient from the unloaded state at room temperature to normal operating conditions and back to room temperature. The other two scenarios study the effects of temperature excursions on stresses in the tubes. In transient B, a temperature excursion with the peak temperature of 550°C is superimposed to the operating temperature of transient A. Transient C is similar but its peak temperature is 380°C. As measured by TC installed on some recovery boilers, temperature fluctuations with peak temperature of 380°C occur often. One of the highest



10. Tangential and axial stresses at service conditions, (a) and (b), respectively, and at room temperature after service, (c) and (d), respectively, at the tube crown as a function of CTE and y of the overlay material (The points inserted in plots show the yield stress and CTE of the particular material at the current overlay temperature.)

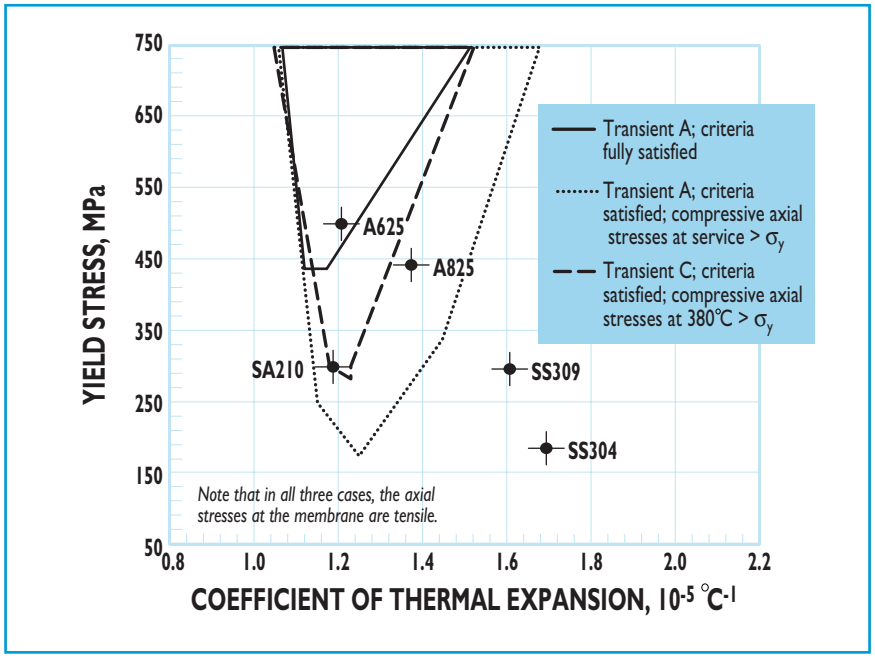
excursions recorded was 550°C *(16)*.

The response surface study is subject to the following assumptions:

- SA210 carbon steel material was the base tube material in all calculations.
- Thermal properties of SA210 carbon steel were considered for the base material and the overlay material in all thermal analyses—assembly welding and in-service heating.
- All cases used the same residual stresses from tube manufacturing.
- The yield stress of overlay materials was assumed to decrease linearly to 10 MPa at 1200°C.
- A single linear work hardening rate was considered for all overlay materials. This was determined by averaging the work hardening rates of alloy 625, alloy 825, SA210, SS304L, SS312, and SS309 materials.
- Similarly, the temperature dependency of CTE used in the analysis was determined by averaging the CTE temperature dependency of the same materials.

FE computations were performed at nine CTE-σ_y points distributed inside the selected CTE-σ_y region according to a particular response surface computational design. Each computation consists of the following:

- Analysis of residual stresses from assembly welding using the measured residual stresses from man-



11. Regions of recommended overlay materials in terms of CTE and y

ufacturing of tubes as a basis
- Thermal analysis of temperature transients
- Mechanical analysis using results of thermal analysis with superimposed residual stresses from manufacturing and superimposed in-service loading.

RESULTS

Figure 10 shows the calculated tangential and axial stresses at the fireside surface of the tube crown at different times of transient A. The calculated stresses are functions of the two independent variables, CTE and σ_y. Figures 10a and 10b show the tangential and axial stresses at service conditions, respectively. Figures 10c and 10d show the same stresses at room temperature after service. Positive numbers in the plots of Fig. 10 represent tensile stresses, and negative numbers denote compressive stresses. Note that the axis at the right side of plots showing σ_y of the overlay 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. Similar plots were made for transients B and C and evaluated at three different conditions of temperature excursion, service conditions after the excursion, and room temperature after service.

To prevent stress corrosion cracking in tubes, tensile stresses should be avoided and the stresses should not exceed the elastic limit throughout the service. An evaluation of the results provided by the response surface analysis was therefore made according to the following criteria. Stresses should not be tensile and stresses should be smaller than the yield stress. Using these results, some regions were defined in the σ_y-CTE plots that fully or partially satisfy the criteria.

The evaluation used 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. 9. In particular, the positions A1–A3, B1–B3, and C1–C3 in Fig. 9 were evaluated. **Figure 11** shows the results and the three regions that satisfy the established criteria with an exception for the axial stresses at the membrane that are tensile. Region 1 is determined based on the transient A and the overlay materials defined with CTE and σ_y falling inside the region satisfying the criteria. The region becomes considerably larger—Region 2—if we allow the compressive axial stresses at the tube crown to exceed the yield stress during service. Region 3 includes the materials that comply with the criteria throughout transient C with an exception of the compressive axial stresses at the tube crown that exceed the yield stress during temperature excursion. After returning to operating conditions, the criteria are again satisfied. 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. Using the analysis of transient B, one can conclude that the tangential and axial stresses are tensile at service after the excursion and at room temperature after service. For much of the analyzed region, they exceed the yield stress. While most of the analyzed CTE-σ_y region satisfies the criteria for tangential stresses at the membrane, the axial stresses are also tensile and often exceed the yield stress. The criteria therefore cannot be met for a high temperature excursion. Stresses in any overlay material would likely exceed the yield stress during such severe temperature conditions and develop tensile stresses at service conditions. Note that the assumed temperature for the high temperature excursion at the tube crown was very high at 550°C, defining a high gradient through the tube thickness.

The results suggest that an overlay material within the suggested range (See Fig. 11) might survive the normal operating conditions and low

temperature fluctuations. Temperature fluctuations of higher magnitudes clearly cause severe stresses in the overlay material. According to Fig. 11, a suitable material would have yield stress higher than about 300 MPa and CTE approximately 1.2 x $10^{-5}°C^{-1}$. A higher yield stress is recommended when using a material with higher CTE, but not higher than 1.6 x $10^{-5}°C^{-1}$.

Curiously, the SS304L overlay material falls outside the acceptable range in both locations—tube crown and membrane—for both stress components and at almost any position of the three analyzed transients. Alloy 625 overlay material is within the acceptable region.

DISCUSSION

The residual stresses from manufacturing for the SS304L/SA210 composite tube panel were analyzed in the same sequence as the tube panel was manufactured. The assembly welding changes the residual stresses from the tube manufacturing in the 60° circumference around the weld and affects the stress state in the remainder of the tube. High mismatch in CTE between the SA210 and SS304L materials causes very high stresses in the overlay when the composite tube is heated to operating temperature. This condition prevails over most of the residual stress in the tube meaning that the manufacturing residual stresses in the SS304L /SA210 composite tube do not significantly contribute to the stresses at service conditions.

The mismatch in thermal expansion between the base and the overlay material and the low yield strength of SS304L is the primary reason for the very high stress and yielding in the SS304L overlay. As the analysis results show, simply heating to the operating temperature causes the SS304L overlay to yield. On cooling from the normal service temperature, the stresses become tensile and exceed the yield stress. The axial and tangential stresses become tensile during cooling at 270°C and exceed the yield stress at 220°C. This is an important factor in determining the cracking mechanisms of the overlay material. During a hot spot occurrence, additional yielding occurs in the SS304L overlay. The stresses reverse to tensile when returning to normal service conditions. The stresses remain tensile at the hot spot location throughout the service period. Small temperature fluctuations of 40°C or higher cause the reversal of compressive to tensile stresses. The stress development mechanism is different for steam blanketing where the constraints of the adjacent tubes play an important role during a temperature excursion. These effects become substantial especially because of higher tube temperatures and smaller temperature gradients through its thickness. Despite a different stress development in the temperature excursion scenario with the presence of steam blanketing, the final results are again high tensile stresses that remain at the hot spot location at normal service conditions.

The results of FE analyses of particular events during boiler operation such as the following may provide valuable information for future studies of active failure mechanisms:

- High tensile stresses in the overlay during operation at locations where temperature excursions occurred with the highly corrosive environment in the boiler
- High tensile stresses in the overlay at temperatures below 270°C during cooling with the water wash that usually starts when the boiler is cooled to about 160°C.

Some assumptions were necessary for the response surface analysis that require an appropriate interpretation in evaluation of the results:

- The same distribution of residual stresses from tube manufacturing was used throughout the response surface approach. As with the SS304L/SA210 composite tube, the residual stresses from manufacturing do not significantly affect the in-service stresses in composite tubes made of materials with high CTE mismatch. The influence may be important in composite tubes made of materials with no or small CTE mismatch.
- The SA210 thermo-physical properties were used for the overlay and the base tube materials in performing the thermal analyses of assembly welding and in- service heating. This assumption was necessary since fictitious materials with the specified range of the two mechanical properties, CTE and σ_y were used as an overlay material.
- Because the response surface is a functional representation of the calculated data, the method itself introduces an approximation error. This error depends on the compatibility between the fitting polynomial function selected and the nature of the actual response. The approximation error in our case averages about 10 MPa.

Using the results of the response surface study, some CTE and σ_y regions were determined that fully or partially satisfy the chosen stress criteria. The results show that the most suitable material for CTE and σ_y for use in recovery boilers has CTE at approximately 1.2 x $10^{-5}°C^{-1}$ and the yield stress higher than about 300 MPa. The CTE of the overlay material should match the CTE of the base tube material as close as possible to avoid high stresses. The yield stress of the overlay material should be higher than that of the base material. The overlay is thinner than the base tube. Higher yield stress would therefore

assure that the overlay material does not yield in case of a small CTE mismatch.

The results of this study provide a strong argument against the SS304L/SA210 material combination for composite tubes in recovery boilers. The alloy 625/SA210 material combination satisfies the established criteria.

Note that the response surface study considered stresses at the fireside surface of the tube crown and stresses at the fireside surface of the membrane. The area on the tube adjacent to the weld where the cracking also occurs was not part of the response surface study. The results of this work represent a particular geometry of the tubes and membranes, and different tube and membrane dimensions might result in different conclusions.

CONCLUSIONS

The FE analysis of the SS304L/SA210 composite tube floor reveals that SS304L is not a suitable cladding material from the mechanical standpoint. The established facts supporting this conclusion show that compressive stresses in the SS304L overlay do the following:

- Exceed the yield stress at operating conditions
- Reverse to tensile stress at operating conditions by a temperature excursion of 40°C or higher
- Reverse to tensile stress on cooling from the normal operating temperatures at 270°C and exceed the yield stress at 220°C.

Regions of CTE and σ_y defining the recommended overlay materials for mechanical behavior were defined using a combined finite element and response surface approach performed for the normal service conditions and the occurrence of temperature excursions. A recommended overlay has a CTE about 1.2 x $10^{-5}°C^{-1}$ and the yield stress higher than 300 MPa in case the SA210 carbon steel is the base material. The cladding material that satisfies the criteria established in this work is alloy 625. **TJ**

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