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Thermal expansion coefficient of steels used in LWR vessels

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ABSTRACT

Because of the impact that melt relocation and vessel failure have on subsequent progression and associated consequences of a light water reactor (LWR) accident, it is important to accurately predict the heat-up and relocation of materials within the reactor vessel and heat transfer to and from the reactor vessel. Accurate predictions of such heat transfer phenomena require high temperature thermal properties. However, a review of vessel and structural steel material properties in severe accident analysis codes reveals that the required high temperature material properties are extrapolated with little, if any, data above 700 °C. To reduce uncertainties in predictions relying upon this extrapolated high temperature data, new thermal expansion data were obtained using pushrod dilatometry techniques for two steels used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 stainless steel (SS304), which is used in LWR vessel piping, penetration tubes, and internal structures. This paper summarizes the new data and compares it to existing, lower temperature data in the literature.

1. Introduction

Melt relocation and vessel failure impact the subsequent progression and associated consequences of a light water reactor (LWR) accident. Hence, it is important to accurately predict the heat-up and relocation of materials within the reactor vessel and heat transfer to and from the reactor vessel. However, a review of vessel and structural steel material properties used to predict such phenomena in severe accident analysis codes, such as SCDAP/RELAP5 [1], MELCOR [2], and MAAP [3], reveals that the required high temperature material properties are extrapolated with little, if any, data above 700 °C. In some cases, published values were found to differ by more than 20%. To reduce uncertainties in predictions relying upon extrapolated high temperature data, the Idaho National Laboratory (INL) sponsored an effort to obtain high temperature data for two steels used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 stainless steel SS304, which is used in LWR vessel piping, penetration tubes, and internal structures. This paper summarizes high temperature thermal expansion data obtained for these materials. High temperature thermal conductivity and thermal diffusivity data for these two steels were also recently obtained by INL using laser-flash techniques. This new data may be found in Ref. [4].

Prior to obtaining new high temperature thermal expansion data, existing thermal property data for these materials were reviewed, so that new data could be compared with data available in the literature. Results from this review are found in Section 2 of this paper. New high temperature data obtained in this effort and comparisons of the new data with available data in the literature are reported in Section 3. Section 4 summarizes insights from this effort.

1.1. Method

The primary components of a pushrod dilatometer are the furnace, sample holder, pushrod, and displacement sensor (see Fig. 1). The sample is secured in the sample holder, with one side held in place against the pushrod. The sample holder assembly is inserted into the furnace. As heat is applied to the sample, elongation due to thermal expansion is transmitted via the pushrod to the sensor, in this case a linear variable differential transformer (LVDT). Typically, the displacement and temperature data are recorded by a software package provided by the manufacturer of the pushrod dilatometer system. It is necessary to perform two tests for each set of experimental data. The first test is a system correction using a standard sample (typically, alumina, sapphire, or quartz) provided by the manufacturer. The standard has been tested by the manufacturer, and has well defined thermal expansion characteristics. The correction test allows the software to measure the difference in elongation of the sample holder and the pushrod. This provides a baseline measurement that may be subtracted from

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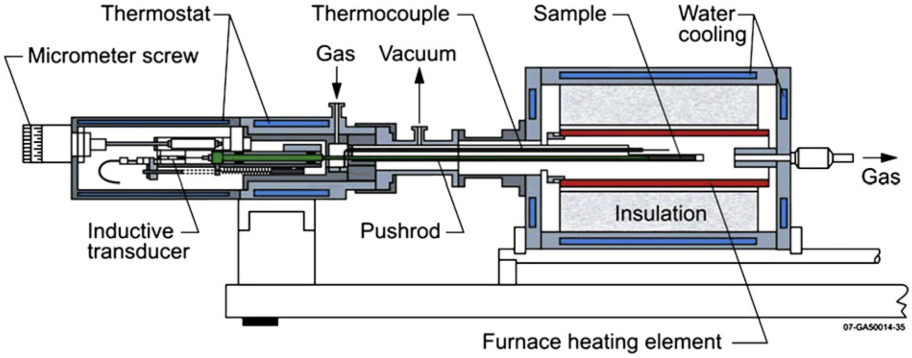

Fig. 1. Pushrod dilatometer schematic.

the data collected during the second test, isolating elongation of the test sample. The data for the elongation of the test sample is collected during the second test.

1.2. Approach

Fig. 2 shows the Netzsch DIL 402 ES dilatometer measurement system installed at INL's high temperature test laboratory (HTTL). The system consists of the dilatometer (which contains the LVDT, the sample holder, and the furnace), the thermal analysis system controller (TASC) 414/4 (which links the dilatometer hardware to the measurement software), the furnace power source, the coolant system (which keeps the LVDT at a constant temperature of 25 °C), the vacuum pump (for evacuating oxidizing gases), and the CPU (for recording and processing data). The Netzsch DIL 402 system is supplied with two separate software packages. First is the DIL 402E measurement package. This program allows data logging of sample elongation as well as temperature control programming. Second is the Proteus analysis package which allows data correction, analysis, and comparison.

To minimize oxidation of samples at high temperatures, the system was purged with a constant flow of ultra high purity argon for selected tests. Even with argon flow and vacuum purging there may be oxygen present. Possible sources include impurities in the argon and incomplete vacuum purging. The iron oxide produced may have a tendency to diffuse into the dilatometer components that are in contact with the sample (i.e., the pushrod and retaining plate). To stem diffusion of iron oxide into the dilatometer components, alumina rings and end pieces were included. These end pieces are disposable circular wafers placed between the sample and the dilatometer components. The rings separate the sample from the sample holder and allow the pushrod to be aligned parallel to the sample. The disposable alumina pieces were changed between tests to minimize oxidation contamination, and several samples of each material were tested to demonstrate consistency of results.

2. Existing data

Prior to obtaining new high temperature data, existing thermal expansion data for the SA533B1 and SS304 materials were reviewed, so that new data could be compared with data available in the literature. As documented in this section, a review of vessel and structural steel material properties used to predict phenomena in severe accident analysis codes, such as SCDAP/RELAP5-3D [1], MELCOR [2], and MAAP [3], and in other material property Refs. [5,6] reveals that the required high temperature material properties are extrapolated with little, if any, data above 700 °C.

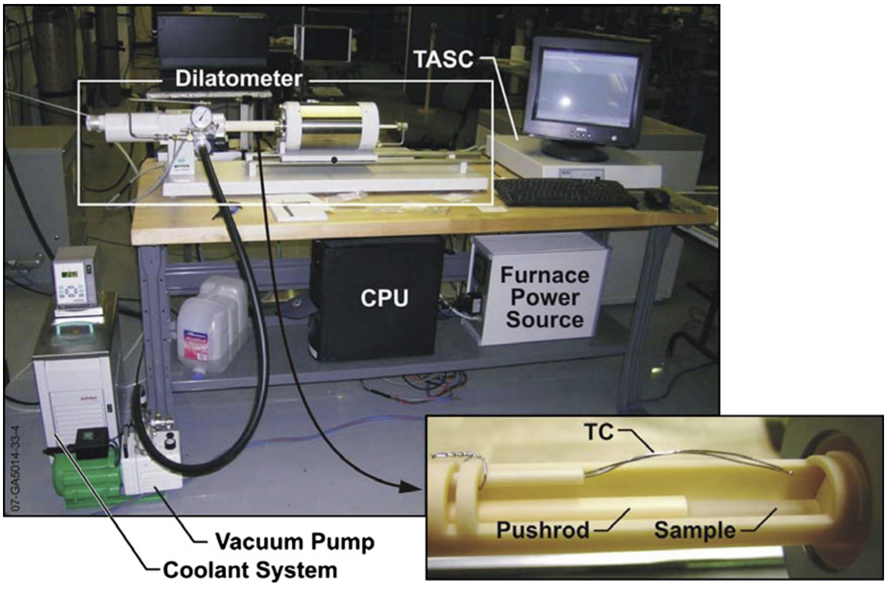

Fig. 2. Dilatometer measurement system installed at INL HTTL.

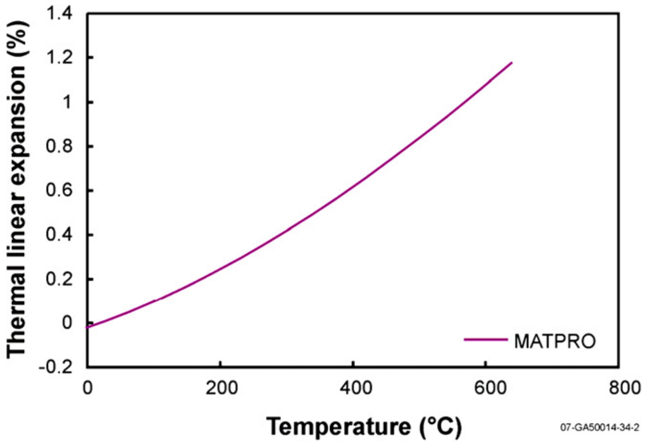

Fig. 3. Thermal elongation of SA 533B1 steel published in MATPRO.

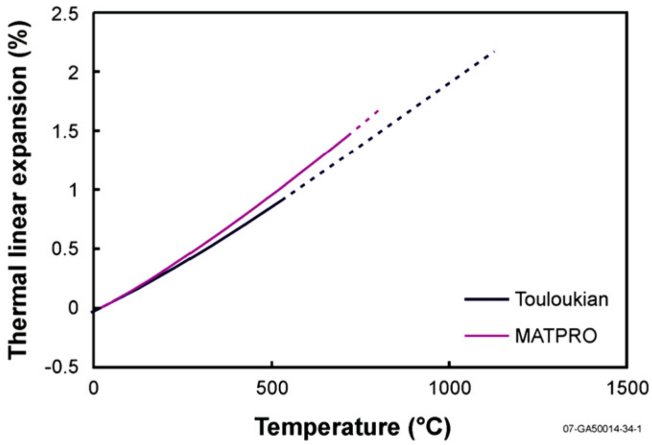

Fig. 4. Thermal expansion of SS304 stainless steel published in Touloukian and MATPRO.

2.1. SA533B1

Fig. 3 shows a curve based on material property data found in the SCDAP/RELAP5-3D© material properties package, MATPRO, for vessel steel. As seen in Fig. 3, data were only available below 700 °C, which is below the temperature where SA533B1 starts to experience a transformation from ferritic (body centered cubic) to austenitic (face centered cubic) steel [7].

2.2. SS304

Fig. 4 compares data from Touloukian [6] and MATPRO for 304 stainless steel elongation. As seen in this figure, values differ as temperatures exceed 230 °C. Also, data are extrapolated at higher temperatures, above about 540 °C for Touloukian and 670 °C for MATPRO.

3. Results

3.1. SA533B1

Fig. 5 shows test results for a sample of SA533B1 steel, designated SA-A. This sample was tested in two cycles, one up to 700 °C and one up to 1200 °C to detect the impact of heating on expansion data. Before each test cycle, the dilatometer was calibrated using the Netzsch alumina standard. The data closely match for the overlapping range. However, a significant drop in expansion data occurs when the material is heated above its transition temperature, between about 730 °C and 830 °C.

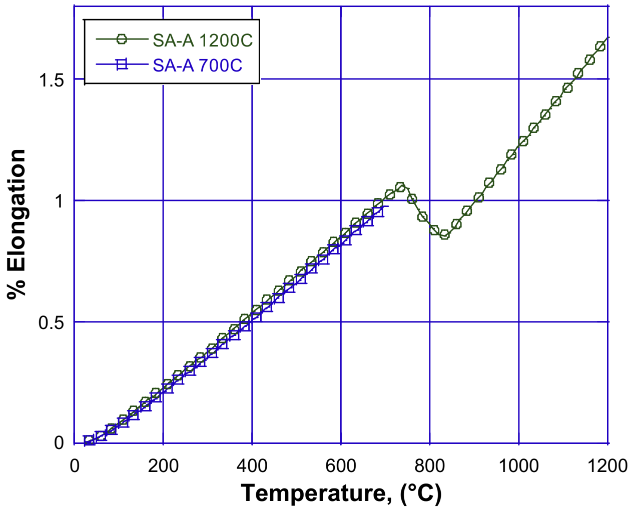

Fig. 5. Thermal expansion data for SA 533B1 low alloy steel sample heated to 700 °C and 1200 °C.

Fig. 6 shows data collected to 1200 °C for three SA533B1 steel samples (SA-A, SA-B, and SA-C). There is a slight divergence between 600 °C and 800 °C, but the data obtained from each sample at high temperatures (e.g., greater than 800 °C) agree well. Although all of the tests were conducted in argon, it is suspected that these differences may be due to different levels of oxidation or decarburization that may have occurred in the samples during these initial tests. The sensitivity of the dilatometer to sources of vibration may have also caused some error. Nevertheless, the data were found to agree with in 10% for the transition region and 3% for higher temperature data.

Fig. 7 compares the newly obtained SA533B1 steel data, based on the average values plotted in Fig. 6, with values published in MATPRO. As shown in this figure, the new data differ significantly from values in the MATPRO curve. As noted in Section 2, prior data had only been obtained below the transition temperature of this

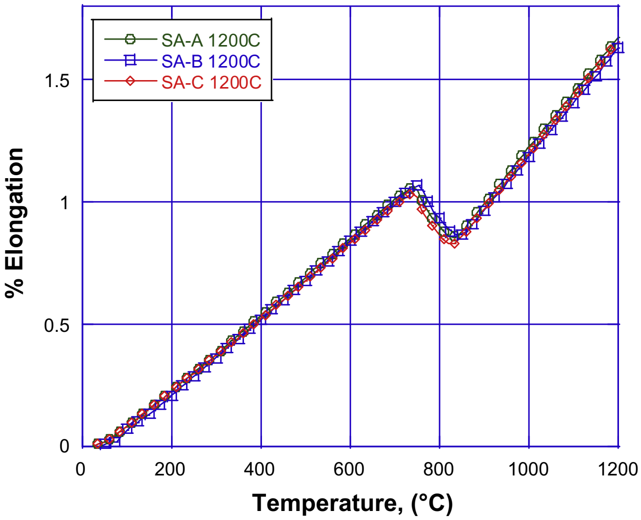

Fig. 6. Thermal expansion data for three samples of SA 533B1 low alloy steel heated to 1200 °C.

material. Hence, the MATPRO curve did not reflect the dip that was measured at temperatures above the transition temperature.

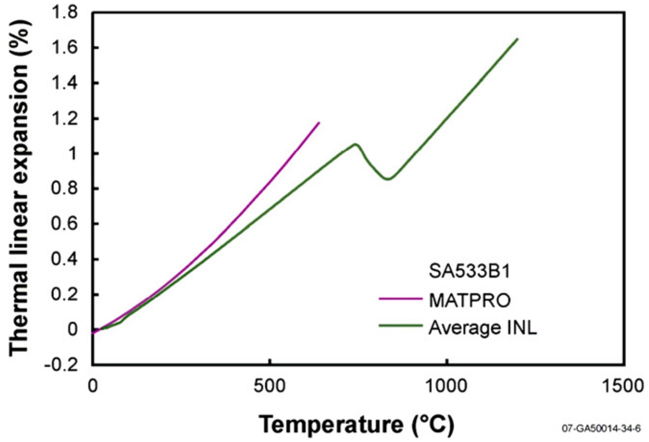

Fig. 7. Comparison of SA533B1 curves based on MATPRO and INL tests.

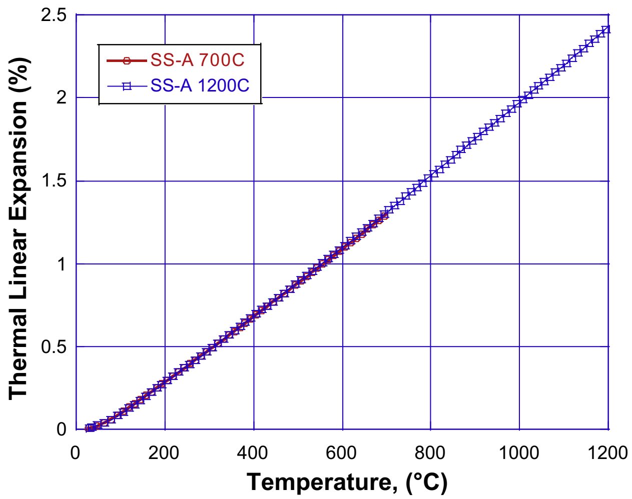

Fig. 8. Thermal expansion data for SS304 sample heated to 700 °C and 1200 °C.

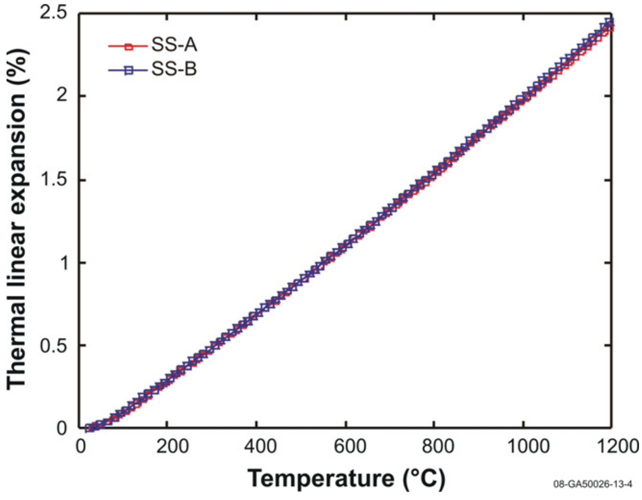

Fig. 9. Thermal expansion data for two SS 304 samples heated to 1200 °C.

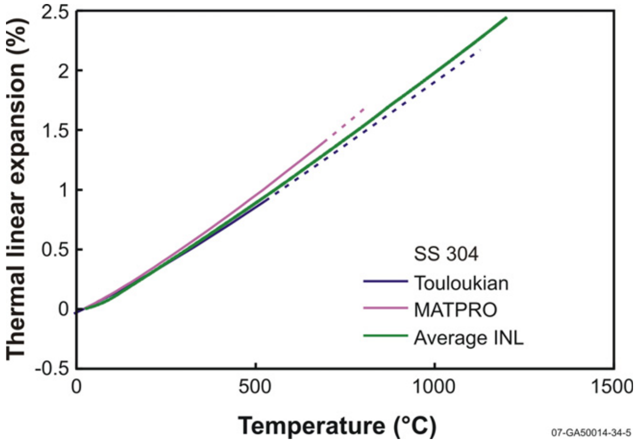

Fig. 10. Comparison of SS304 curves based on MATPRO, Touloukian and INL tests.

3.2. SS304

Fig. 8 compares results for a SS304 sample (SS-A) heated to 700 °C and then to 1200 °C. Again, tests results were found to be repeatable. Data obtained during the second cycle to 1200 °C were consistent with data obtained from the first heating to 700 °C. However, two features are notable about this data when compared to that of SA533B1 steel. First, as anticipated, there is no decrease in thermal expansion due to a transition phase. Second, the SS304 expands to a greater degree than the SA533B1.

Fig. 9 shows data collected to 1200 °C for two stainless steel samples (SS-A and SS-B.). The data for the two samples are very consistent, showing about 1% variation for temperatures above 300 °C.

Fig. 10 compares a curve based on average values from the newly obtained stainless steel data with values found in Touloukian and MATPRO. As shown in this figure, the new data are consistent with values published in these references, especially data from Touloukian.

4. Summary

Pushrod dilatometry techniques were applied to obtain thermal property data up to 1200 °C for two steels used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 Stainless Steel SS304, which is used in LWR vessel piping, penetration tubes, and internal structures. Prior to this effort, little, if any data were available for these steels, above 700 °C forcing analysts to rely on extrapolated data.

Thermal expansion data obtained for these steels were found to, in general, be consistent with published values for low temperatures (e.g., below 400 °C). For higher temperatures, new expansion data varied by over 20% from published extrapolated data. Note that in the case of SA 533B1, the error introduced by extrapolating existing data to values above its transition temperature may introduce even larger errors (exceeding factors of two) because prior data was only obtained below this material's transition temperature.

5. Product disclaimer

References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the US Government, any agency thereof, or any company affiliated with the Idaho National Laboratory.

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