Thermal Aging in Cast Stainless Steels of LWR Systems: A Statistical Approach to Modeling Mechanical Properties

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1. Introduction

Austenitic stainless steels are extensively used in the nuclear industry for core internal structures and primary piping due to their excellent mechanical properties [1]. Although austenitic stainless steels are fully austenitic when fabricated, the weld zones often contain a ferrite content of 5-12% due to the welding process. The ferrite phase can become embrittled due to phase transformation during long-term aging at the operating temperatures of pressurized water reactors, which range from 290 to 325°C. While thermal aging embrittlement and its kinetics have been extensively studied in cast austenitic and duplex stainless steels [2,3], research on thermal embrittlement phenomena in austenitic welds is still actively ongoing [4]. Since acquiring thermal embrittlement data is time-consuming, it is necessary to collect diverse data from literature and to develop a model for long-term thermal aging. This study has digitized various data on mechanical properties related to thermal embrittlement characteristics and proposes a predictive model for thermal embrittlement that can be robustly used for PWR applications.

2. Methods

2.1 Dataset

Chopra et al. reported various characteristics of thermal embrittlement impacting tensile properties through the NUREG report [2]. The reported tensile properties provide detailed information of measurement for a total of 373 specimens tested. In particular, they offer data on fracture strength and reduction in cross-sectional area, which can serve as a basis for predicting fracture toughness. The data encompasses tensile test results at room temperature and 290°C after aging experiments conducted between 290-450°C for 2,570-30,000 hours across 10 different heats. These data was utilized to present a model depicting the degree of thermal embrittlement according to CASS grade.

2.2 Modeling

Chopra et al. reported various characteristics of thermal embrittlement impacting tensile properties in the NUREG report [2]. The reported tensile properties provide comprehensive measurement details for a total of 373 tested specimens. Specifically, the data includes information on fracture strength and reduction in cross-sectional area, which can be fundamental in predicting fracture toughness. The data covers tensile test results at room temperature and 290°C, following aging experiments performed at temperatures ranging from 290 to 450°C over periods of 2,570 to 30,000 hours across 10 different heats. This data was employed to develop a model that illustrates the level of thermal embrittlement in relation to CASS grade.

The model proposed by Chopra et al. includes the following aging parameters:

$$P = \log_{10}[t] - \frac{1000Q}{19.143}\left(\frac{1}{T+273} - \frac{1}{673}\right)$$

The activation energy Q for each heat, which is sensitive to the heat's composition, was calculated from other experiments that considered compositional changes [5]. In our study, we incorporated heat variation into the model, employing multilevel modeling to capture the global trend. Accordingly, data points were classified and modeled based on their respective heat. Time was transformed using a log10 scale, and temperature was modeled as inversely proportional to the absolute temperature to maintain a linear relationship. We utilized the open-source statistical software R for modeling, installing the 'brms' package to facilitate the multilevel modeling process.

3. Results

3.1 Unaged results

Fig. 1 shows the results of room-temperature and high-temperature measurements for unaged specimens across various heats before thermal embrittlement experiments. The values represented in black indicate the average behavior for each grade. As can be seen in the figure, CF-8M exhibits a distinct increase in tensile strength, while CF-3 and CF-8 show almost similar behaviors. However, it is important to note that the variation in strength within the same grade due to different heats is significantly larger than the variations between grades. It is observed that CF-3 and CF-8 exhibit a similar decrease in strength with an increase in measurement temperature, yet CF-

8M demonstrates a different response to the measurement temperature compared to the other grades.

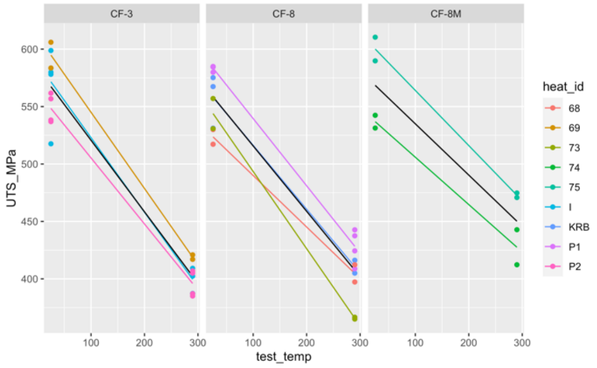

Fig. 1. UTS variation with measurement temperature for unaged specimens.

3.2 Aged results

Fig. 2 illustrates the change in UTS over log10(time) for specimens aged at 320°C. There is considerable variation among different heats, and the overall trend by grade also varies significantly. Given the nature of thermal embrittlement experiments, the results are particularly sensitive to compositional changes. Even within the same grade, the quantity of ferrite can significantly alter thermal embrittlement behavior, making predictions difficult, though the macro behavior of the material can be inferred.

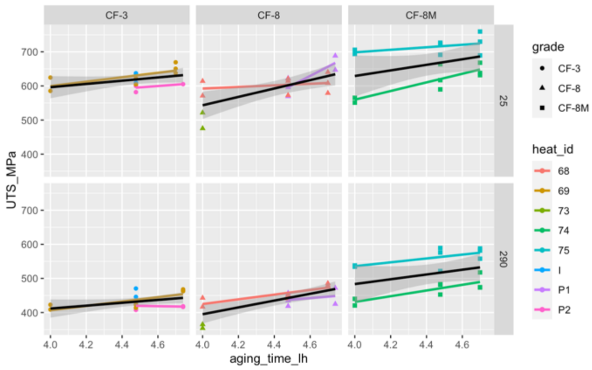

Fig. 2. UTS variation of specimens aged at 320°C for various times. Aging times have been converted to log10.

3.3 Multilevel model

Multilevel modeling can be effectively applied to simulate heat-dependent behavior by incorporating additional parameters that account for the varied thermal degradation behaviors among different heats. The model's performance is bolstered by the integration of these appropriate parameters. When employing such a multilevel model, the aged data typically exhibits performance similar to what is depicted in Fig. 3. The performance of the multilevel model is commendable. Although this modeling technique still requires further research, it proves to be particularly useful in material fields where there is significant variance due to heat.

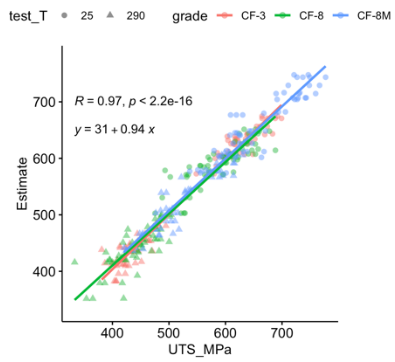

Fig. 3. Predictive performance of the developed multilevel model on the properties of aged specimens.

4. Conclusions

We have analyzed data on the thermal embrittlement characteristics of cast austenitic stainless steel and stainless steel welds. The developed multilevel model can predict the mechanical properties of aged specimens by considering aging temperature, aging time, and test temperature from tensile tests. This new model proves to be effective as it readily accounts for heat-induced variations and is expected to be useful in calculating activation energy shifts due to compositional differences.

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