

# Implications of Thermal Ageing of Cast Austenitic Stainless Steel and Weldments

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## INTRODUCTION

This paper is a result of work to develop a program plan for monitoring thermal embrittlement of primary coolant cast stainless steel components in nuclear power plants. The work included a review of available literature and industry experts to enhance the understanding of the thermal embrittlement phenomena. Additionally, candidate test methods to monitor thermal embrittlement of cast stainless steels were considered for evaluation.

Cast austenitic stainless steel (CSS) is a duplex structure alloy consisting of two metal phases, austenite and ferrite. The alloy is predominately austenitic, but the ferrite (10% to 25% by volume) significantly improves strength, resistance to corrosion, and weldability. CSS is used to varying extent in all nuclear power plants, usually in the form of statically cast reactor coolant pump casings or statically or centrifugally cast primary loop piping. The only grades used for nuclear applications are CF8, CF8M, and CF8A (1). CF8 and CF8M are chemically equivalent to (wrought) Types 304 and 316, respectively. CF8A, a strengthened CF8, is the most common CSS grade used.

## BACKGROUND

Until the mid-1980's thermal ageing was poorly understood because the precise mechanisms of embrittlement were unknown. Recent research (2,3,4) has identified five complex metallurgical processes within the ferrite or at its grain boundaries that are associated with ageing:

1. Spinodal decomposition of the ferrite (fcc) forming chromium-rich alpha prime (bcc) phase;
2. Nucleation and growth of the alpha-prime phase (Cr-rich);
3. Precipitation of G-phase (an fcc nickel silicide);
4. Precipitation of gamma-2 austenite; and,
5. Precipitation of spherical  $M_{23}C_6$  carbides at the austenite-ferrite boundaries.

Because carbon accelerates several of these processes CF8 grades are significantly more susceptible to ageing than low-carbon grades such as CF3.

## Changes in Fracture Toughness- Cast Material

Many of the published studies report the embrittlement of CSS in terms of Charpy impact energy changes, and most reports show dramatic drops in impact energy for the types of CSS grades in use in the nuclear industry (CF8M and

CF8A). Room-temperature impact strength can be reduced by 80% after ageing for 8 years at temperatures as low as 300°C (572°F) (5). However, Charpy impact data do not sufficiently characterize the toughness behavior. J-R toughness properties are also required (6).

Using J-R toughness data from their own ANL study and data published by Westinghouse (7), Framatome (8), and EPRI (9), Chopra and Chung demonstrate in Reference 8 that the  $J_{IC}$  and tearing modulus (T) of aged CSS decrease, that the decrease is seen at 290°C(550°F) (upper shelf) as well as at room temperature, and that the drop in  $J_{IC}$  is similar to the dramatic drop in Charpy impact energy. Even so, there is some opinion that the room temperature lower bound  $J_{IC}$  may be as high as 100 kJ/m<sup>2</sup> (600 in-lb/in<sup>2</sup>) (10). If this true, then perhaps CSS toughness levels do not drop to an aged level less than that of weldments, which would tend to alleviate the integrity issue. Weldments have long been known to possess much lower toughness than base metal without being thought to pose a significant compromise in integrity or safety.

#### Changes in Fracture Toughness- Weldments

There are few published data concerning the effect of thermal aging on weldments. It is known that the effect of thermal ageing in welds is much less significant as a percentage change in toughness than the effect in cast steels. A 1983 study by Slama et al (8) using Charpy impact data concluded that the effect of ageing is not important for welds. A 1987 English study by Hale et al (6) performed  $J_R$  testing on CF3 and manual metal arc (MMA) weld metals and found that aged weld metal experiences a considerable reduction in resistance to stable crack growth, although the reduction is not as great as for the parent CF3 material. Unaged weld metal  $J_{IC}$  at 300°C (572°F) was estimated to be approximately 100 kJ/m<sup>2</sup> (571 in-lb/in<sup>2</sup>); after ageing at 400°C for 10,000 hours,  $J_{IC}$  was reduced to 75 kJ/m<sup>2</sup> (428 in-lb/in<sup>2</sup>). The significance of 75 kJ/m<sup>2</sup> (428 in-lb/in<sup>2</sup>) is that it is well below the lower-bound  $J_{IC}$  value of 114 kJ/m<sup>2</sup> (650 in-lb/in<sup>2</sup>) assumed for flux welds in the ASME Code (IWB 3640) evaluation of flaws in austenitic piping. It raises the possibility that some aged welds in LWR plants do not in fact meet the assumed toughness characteristics of the Code.

#### CANDIDATE TESTING TECHNIQUES

Material property testing of in-service components should not damage the CSS component. Two potential testing methods are:

1. miniaturized/subsized specimen testing: the physical removal of a very small sample of the component to perform subsized tests which yield fracture toughness properties or properties which can be correlated to fracture toughness;
2. surface replication testing: microstructural analysis of a surface replica taken from the CSS component of interest, enabling approximation of the fracture toughness by comparing the microstructure of the replica to the microstructure of a body of aged samples whose fracture toughnesses are known. The process requires two types of replicas be taken: a microstructural replica and an extraction replica (11).

#### Preliminary Small Specimen Testing Results

In support of the feasibility assessment of small specimen testing techniques, the University of California, Santa Barbara (UCSB), laboratory has performed some small specimen testing of four aged and unaged CF8 samples obtained from Argonne National Laboratory. The four samples were broken Charpy halves from

the ANL program whose material properties (strength, toughness) had been determined by full-size sample tests. One sample was unaged; the other three were aged at 400°C for 1000, 3017, and 9998 hours.

The objective of the UCSB testing was to explore the ability of subsized specimen tests to evaluate mechanical property changes. Replication tests were not conducted. Tests employed were the dynamic and static shear punch and standard 50 gram microhardness tests. Results of the tests are provided in Table 1. Some test results from the ANL program are also included for comparison.

The microhardness test was successful in detecting a significant hardening of the ferrite in the aged CF8 as compared to the unaged CF8. Property changes measured by the shear punch and Rockwell B Hardness tests were not as detectable. This is largely because of the small volume of ferrite and the lack of hardening in the austenite phase. These tests results are only preliminary, however.

Fracture surfaces were examined and indicated ductile failure. While dynamic shear punch tests at room temperature also did not indicate a difference, it is believed that transitions in fracture mode could be determined by dynamic shear punch and/or bulge tests at lower temperatures.

#### PROPOSED PROGRAM PLAN

An effective and economical program to monitor thermal ageing would screen each CSS component in a plant on the basis of material chemistry and service temperature, establish a thermal embrittlement susceptibility hierarchy, and monitor those components which present a bounding or limiting condition. Such a program minimizes the number of plant components subjected to physical tests. The Program Plan for monitoring primary coolant cast stainless steel components at nuclear power plants consists of three phases whose final objective is the implementation of a surveillance method that is an industry standard with regulatory acceptance.

#### Phase One

- 1) Determine the feasibility of monitoring inservice aging effects by miniature specimen testing and surface replication methods, by showing that these test methods can detect material property changes in materials aged at LWR operating temperatures.
- 2) Develop preliminary correlations between microstructural and/or micromechanical results with measured fracture toughness changes.
- 3) Maintain a database of fracture toughness information on aged materials as it relates to structural integrity and long-term degradation.
- 4) Establish validity of laboratory-induced embrittlement data for predicting material toughness after long-term exposure at LWR operating temperatures.
- 5) Screen all CSS components at the nuclear plant on the basis of material composition (chemistry) and service temperature. Identify specific components (welds, pipe runs, and RCP casings) that will envelop the embrittlement issue.

#### Phase Two

- 1) Establish the technical basis for the program.
- 2) Develop procedures for field implementation.
- 3) Provide technical support documentation for ASME Code/NRC Licensing.

### Phase Three

- 1) Conduct a pilot plant study.
- 2) Prepare Pilot Study Report.

### SUMMARY

Thermal ageing occurs in both CSS and weldments, but the effect on CSS is more dramatic. Potentially more significant to the LWR integrity issue is the thermal ageing of weldments, where toughness may drop well below the toughness assumed for flux welds in the ASME Code (IWB 3640) evaluation of flaws in austenitic piping. Clearly, additional research is required.

A three phase program for monitoring the thermal embrittlement issue at nuclear power plants has been developed to screen CSS components and weldments on the basis of their susceptibility to ageing (a function of material composition and service temperature) and monitor a small but fully representative set using subsized specimen or surface replication tests.

### REFERENCES

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TABLE 1

SMALL SPECIMEN TEST RESULTS AND COMPARISON WITH FULL SIZE SPECIMEN ANL DATA

PROPERTY	VALUE FOR EACH MATERIAL SPECIMEN (Note 1)			
	P12A-02 (unaged)	P13A-03 (400°C/1000h)	P13A-03 (400°C/3017h)	P14A-18 (400°C/9980h)
1. $\Delta\sigma_y$ (ksi)	1mm punch	---	0	12 $\pm$ 6
	3mm punch	---	0	3 $\pm$ 3
	tensile test (Note 2)	---	---	---
2. $\Delta UTS$ (ksi)	1mm punch	---	0 $\pm$ 3	0 $\pm$ 3
	3mm punch	---	5 $\pm$ 5	6 $\pm$ 3
	tensile test (Note 2)	---	---	---
3. Rockwell B Hardness	83 $\pm$ 2	---	---	90 $\pm$ 2
4. Vickers hardness:				
Austenite (50g)	175 $\pm$ 10	---	---	170 $\pm$ 8
Ferrite (50g)	180 $\pm$ 20	---	---	290 $\pm$ 26
Combined (500g)	191 $\pm$ 7	---	---	205 $\pm$ 7
5. $J_{IC}$ (kJ/m <sup>2</sup> ) (Note 2)	2171 $\pm$ 1450	---	---	254 $\pm$ 44
6. CVN Impact Energy (J/cm <sup>2</sup> ) (Note 2)	236.6	67.7	60.7	47.6

Note 1: All test specimens are CF8 material from heat P1 of the Argonne National Laboratory CSS program.

Note 2: Full size specimen test performed by ANL CSS program.

Note 3: Yield and ultimate tensile strength changes are referenced to the unage material properties.

