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NEW FLAWS FOR QUALIFICATION OF CAST STAINLESS STEEL INSPECTION

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ABSTRACT

For decades, cast austenitic stainless steels (CASS) have presented a challenge for inspection. However, recent advanced inspection technologies have shown promise in inspecting CASS materials with wall thicknesses that were once considered impossible.

Before being applied on larger scale, these new inspection methods must be proven to be effective at identifying discontinuities in CASS material. This presents a problem of its own. Several traditional flaw manufacturing methods cannot be applied to CASS due to the disruption of the parent material. Excavation and welding changes the cast material microstructure and thus significantly affects the inspection results. At the same time, due to the significant wall thickness and inspection limitations, the required qualification flaws can be quite large. Until recently, modern flaw manufacturing techniques, that do not require welding, have not been applied to flaws of this size.

In this paper, recent developments will be presented on the manufacturing of thermal fatigue cracks in centrifically CASS material. The presented developments make it possible to use real cracks for demonstrating the effectiveness of CASS inspection techniques.

The results also contain first published UT data on this kind of thermal fatigue cracks in CASS and reveal new insight on the inspectability of this difficult material.

INTRODUCTION

Cast austenitic stainless steel (CASS)materials are used extensively in reactor coolant pressure boundary components including pipes, fittings, valve bodies and pump castings in pressurized-water reactors (PWRs) throughout the world [1, 2]. The use of CASS materials for these components is motivated by the favorable corrosion resistance properties as well as the relatively low cost. The service record of CASS components has also been good thus far.

It has been shown that CASS material exposed to high temperatures for prolonged periods of time can be susceptible to thermal aging. The microstructure of cast stainless steels contains 5-25% of ferrite phase (with balance austenite phase). Over a period of time in normal reactor temperatures (290°C / 550°F), the ferrite phase goes through spinodal decomposition and a brittle α' -phase precipitates inside the former ferrite grains. The brittle precipitates decrease the fracture toughness of the material and the high toughness characteristic to austenitic stainless steels is eventually lost. The effect of aging depends, among other things, on the ferrite content of the material. Data suggests that increased ferrite content can be associated with more pronounced embrittlement. The initial Charpy impact energy for austenitic stainless steels is above 200 J/cm^2. For fully aged samples, the lower bound estimates are 20, 25 and 30 J/cm2 (for CF-8M, CF-8 and CF-8A, CF3 and CF-3A, respectively). [2, 3]

From inspection point of view, the most significant effect of thermal aging is that it decreases the size of the inspection target. The reduction in fracture toughness decreases the critical flaw size and thus the allowable flaw size for these components. E.g., Cicero et al. (2009) calculated critical flaw sizes in the range of 10 - 20 mm (0.4 - 0.8"; 40 - 80% through-wall) for aged valve component with remaining Charpy impact energy of 65 J/cm^2 [4].

While higher ferrite content has been found to increase the affects of thermal aging, it is also attributed to the beneficial effect of reducing sensitization. Sensitization is caused by precipitation of chromium-rich carbides and the resulting depletion of chromium at austenitic grain boundaries. In CASS the chromium carbides preferentially precipitate on the ferrite-austenite interfaces and not in the austenitic grain boundaries. The carbides form on the chromium-rich ferrite side of the boundary and do not cause the problematic chromium depleted zone [5].

Cast stainless steel components are used in safety-related systems and there is evidence that shows that CASS materials can be susceptible to thermal fatigue under certain conditions [6]. Consequently, there has been an increased interest in developing a reliable in-service inspection method for CASS material. The non-destructive evaluation of cast stainless steel components has proven quite challenging. The large and irregular grain size of some CASS materials greatly affects the propagation of ultrasonic waves causing attenuation, beam deflection and scattering.

During the PISC-III study, the then-current state of the art inspection methods were evaluated against cast stainless steel samples. In the PISC-III round robin summary Lemaintre et al. (1996) [7] conclude that "...the detection performance, in general, was satisfactory. The length sizing performance in general was poor, whereas the performance for depth sizing was very poor". For two fatigue cracks in centrifugally cast steel weld, the probability of detection was < 0.5.

The poor performance observed lead to significant development efforts to facilitate the inspection of these important CASS components. In particular, synthetic aperture focusing (SAFT) techniques were utilized to decrease the noise level in the material by several authors [1,8, 9]. In parallel, the use of eddy current (EC) techniques were studied [6], although the ID access required by the EC inspection would clearly impose problems for several locations. More recently, phased array ultrasonic techniques have been studied for inspection of cast stainless steel components [8, 10].

In summary, it's generally believed that current phased-array ultrasonic systems hold the best potential for the reliable inspection of cast stainless steel components. However, before the systems are applied on a larger scale, these new inspection methods must be proven to be effective at identifying and characterizing discontinuities in CASS material. This presents a problem of its own. To be able to demonstrate NDE reliability, the test blocks must be representative of what is currently installed in the nuclear fleet. Since the main feature making the inspection so challenging is the material microstructure, it's important that the samples contain representative microstructures. Also, the flaws to be used should be representative of postulated in-service induced flaws. The complex grain structure and postulated fatigue damage mechanism eliminates several traditional flaw manufacturing methods in cast stainless steels base material. Because fatigue flaw faces are rough and tortuous, the EDM notches used in the PISC studies are not considered ideal for evaluating NDE techniques in CASS material. Also, the weld implanted flaws traditionally applied are problematic in components without joints due to the excavation required to introduce the simulated flaw. It is typically possible to detect the cavity and weld metal in the middle of the base material more easily than the actual flaw. Cracks have also been manufactured by mechanical loads. However, this is limited to simple shapes and, due to the heavy wall thickness, requires rather heavy loading equipment.

More recently, flaw manufacturing techniques based on controlled thermal fatigue have become available. These overcome many of the deficiencies in the more traditional flaw manufacturing techniques. The material microstructure is not disturbed, since there's no welding involved in the process. Also, the thermal loads can be applied to heavy sections or complex shapes like elbows or pump casings. However, due to the significant wall thickness and inspection limitations, the required flaws for CASS can be quite large. Until recently, modern flaw manufacturing techniques have not been applied to flaws of this size. In this paper, recent developments will be presented on the manufacturing of thermal fatigue cracks in CASS material. The work was performed by EPRI and Trueflaw and is still on-going.

MATERIALS AND METHODS

To develop test blocks for cast austenitic stainless steels, three samples were provided by EPRI. The samples were centrifically cast CF-8M grade stainless steel with a varied equiaxed grain structure. Figure 1 shows a section of the material, used for this study, which has been polished and etched to show the grain structure. Two of the samples were used for actual test blocks whereas the third was reserved for development. Figures 2 and 3 show the sample geometry of the components as well as the flaw locations.

FIG. 1 EXAMPLE OF THE SAMPLES GRAIN STRUCTURE

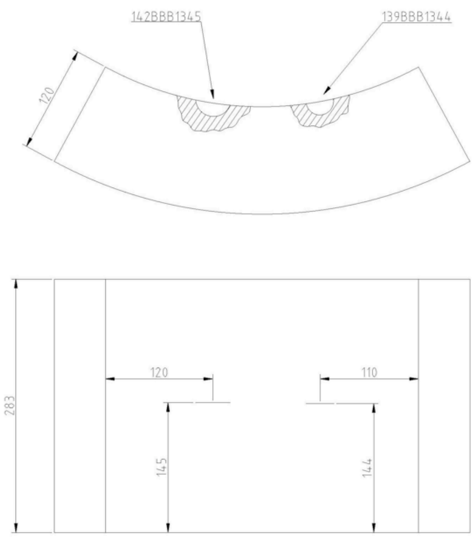

FIG. 2 SAMPLE GEOMETRY AND FLAW LOCATIONS FOR 15 mm TARGET DEPTH CRACKS

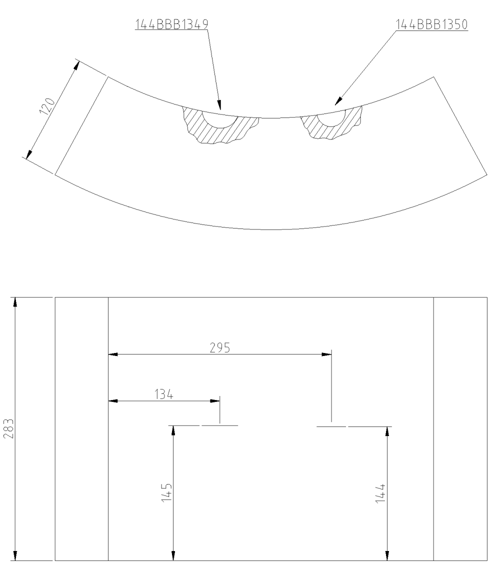

FIG. 3 SAMPLE GEOMETRY AND FLAW LOCATIONS FOR 30 mm TARGET DEPTH CRACKS.

In each test block, two flaws were produced by in-situ controlled thermal fatigue. Controlled thermal fatigue flaws have been available since early 2000's from Trueflaw. In recent years the technology has matured, tried and tested. Capability of the technique to produce realistic, representative flaws has been analyzed by comparing the crack characteristics to the characteristics measured from service-induced flaws. This comparison has been made against measured values from service-induced flaws reported by Wåle [11]. The comparison indicated the flaws produced by the new technique are representative of several types of service-induced flaws.

To ensure reliable crack production and to know the depth of the produced cracks, each different crack produced is first validated destructively. That is, a crack is grown with a predetermined set of parameters and destructively examined to reveal the depth. Then, the same process can be repeated any number of times to produce number of similar cracks with known depth. This process is followed specifically for each material and flaw size.

Thermal fatigue loading is characteristically greatest at the surface and decays with distance from the surface. Consequently, crack production is fastest near the surface and gets slower with increasing crack depth. Thus, the significant challenge for this project was that the cracks needed to be much deeper than previously manufactured.

The first sample contained two cracks with target depth of 15 mm (0.59"). One of these cracks will remain intact while the other will be used as a validation crack, and will be destructively examined at later time. Sample 2 was designed to have two cracks, with one serving as validation crack for the other after destructive examination. The target depth for the second set cracks was 30 mm (1.18"). A significant amount of development was necessary, because flaws of this depth had previously never been produced with Trueflaws techniques. During the development, numerous production tests were done and destructively examined. This included a number of partial validations, where crack growth rates from several depths were tested in samples with EDM-notch starter of known depth.

After the four cracks were grown in the two samples, the cracks were documented, photographed and surface features measured. Both samples were sent to EPRI for non-destructive evaluation. After thorough evaluation, the validation cracks will be destructively examined to confirm the true crack depths.

RESULTS

Figures 4 through 7 show penetrant images from the cracks produced for this study. It is suspected that the large grain structure caused significant tortuosity to all cracks. Additionally, some level of secondary cracking was present in all cases but was most significant in conjunction with the deeper cracks. Figures 8 through 9 show selected crack characteristics measured from the sample surface.

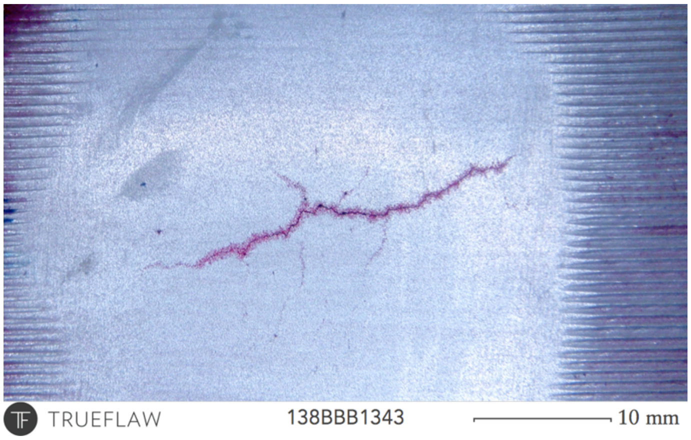

FIG. 4 PENETRANT IMAGES OF PRODUCED CRACKS (15 mm TARGET DEPTH).

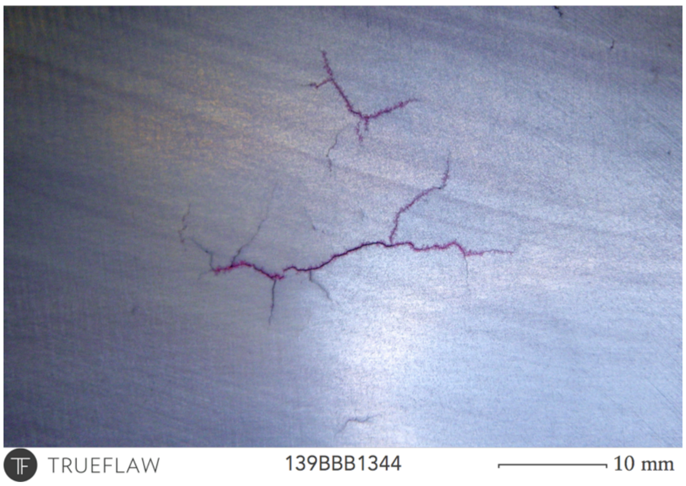

FIG. 5 PENETRANT IMAGES OF PRODUCED CRACKS (15 mm TARGET DEPTH).

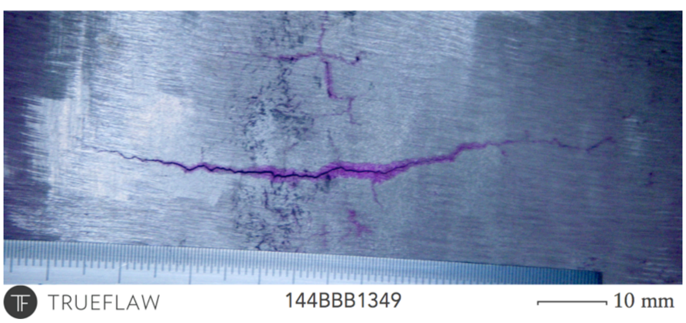

FIG. 6 PENETRANT IMAGES OF PRODUCED CRACKS (30 mm TARGET DEPTH).

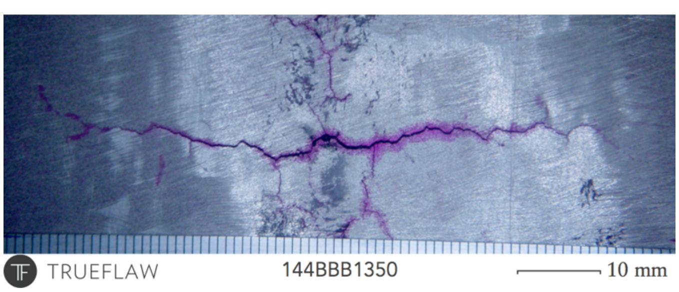

FIG. 7 PENETRANT IMAGES OF PRODUCED CRACKS (30 mm TARGET DEPTH).

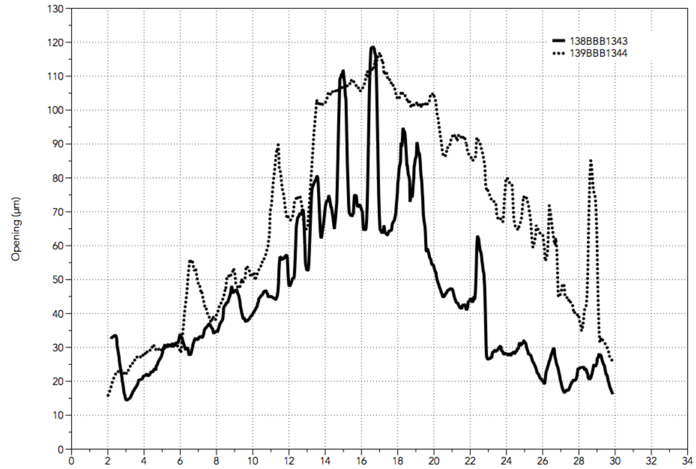

FIG. 8 CRACK OPENING MEASURED FROM THE SURFACE (15 mm TARGET DEPTH).

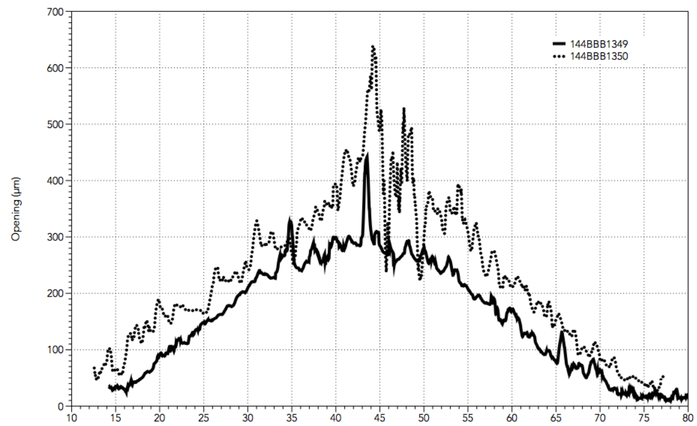

FIG. 9 CRACK OPENING MEASURED FROM THE SURFACE (30 mm TARGET DEPTH).

Preliminary results from the NDE evaluation indicate that the 15 mm cracks in Sample 1 are readily detectable with techniques utilizing low frequency ultrasonic transducers. Currently, data has been collected using phased array search units ranging in frequencies between 500 kHz and 1.5 MHz. It has been noted that the data collected with lower refracted angles and lower frequencies experience less affects from the varying grain structure. Figures 10 through 13 show the signal characteristics of the flaws using search units with different frequencies. In some cases, the beam redirection has been noticeably different when scanning with the same search unit in opposite directions. The extraneous cracking around the intentional flaws has also been identifiable using the UT techniques and in some cases it is believed to partially mask the response from the primary target. Work is currently underway to subject Sample 2 to the same UT evaluation used on Sample 1.

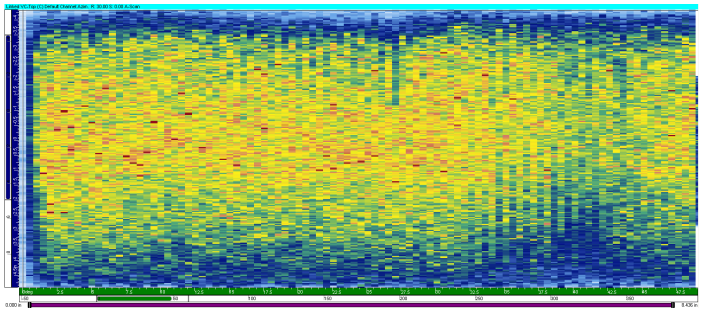

FIG. 10 SAMPLE 1 USING 1.50MHZ SEARCH UNIT (C-Scan)

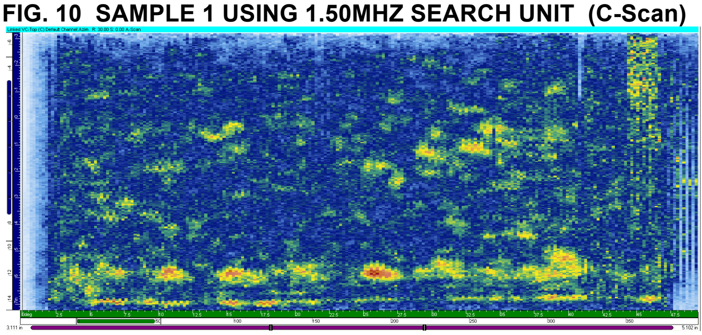

FIG. 11 SAMPLE 1 USING 1.00MHZ SEARCH UNIT (C-Scan)

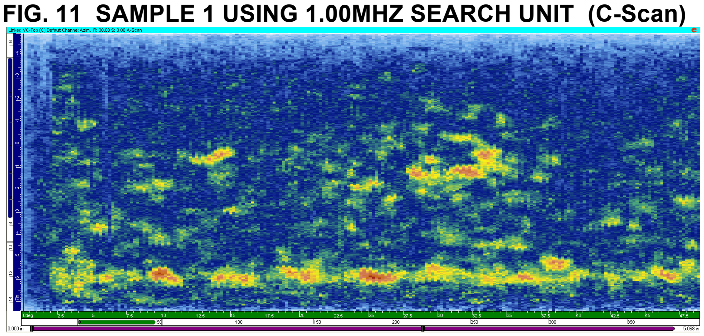

FIG. 12 SAMPLE 1 USING 0.75MHZ SEARCH UNIT (C-Scan)

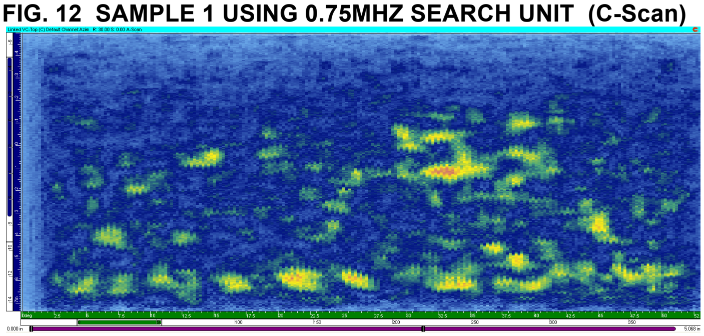

FIG. 13 SAMPLE 1 USING 0.50MHZ SEARCH UNIT (C-Scan)

DISCUSSION

In view of the production tests and partial validations, the development of crack growth into cast stainless steel was a success. The final depth will be revealed, after the destructive examination is complete. Further development is needed to eliminate the secondary cracking experienced with the deeper flaws. Secondary cracks could be avoided in the production tests and partial validations, and thus can be overcome with some additional development.

The ultrasonic data images above show the C-scan images for a 30° angle with four different search unit frequencies. It can be seen that the noise level increases as the search unit frequency is increased up to 1.5MHz. The noise levels decrease because increased wavelengths of the pulsed energy from a low frequency search units interact less with the individual grain boundaries of course grained material. In this case the 30° 0.75MHz search unit images the two flaws in Sample 1. The higher frequency search units have too much noise and the lower frequency search unit does not seem to have enough resolution to image the first flaw.

Additional NDE work is scheduled for this study throughout 2012. Once all of the data is collected on the two specimens, at full thickness, the samples OD will be machined to reduce the thickness by 25%. Ultrasonic data, matching that which has already been collected, will be acquired and compared before taking additional material off of the OD surface. By reducing the wall thickness of the mockup the crack height percentage will increase. After several iterations of taking data and removing additional material it is hoped that conclusions can be made on the effects of CASS material thickness and the inspectability. Once the sample thickness has been reduced enough that the cracks represent 80 to 90% through wall the validation cracks will be destructively analyzed to determine the true depth.

CONCLUSIONS

In view of the production tests and partial validations, the development of crack growth into cast stainless steel was a success. The final depth will be revealed, after the destructive examination is complete and final judgment will then be available. With the increased NDE technology now available it seems that meaningful inspections of CASS components has increased, but additional work is needed to quantify its true capability. It is important to have realistic mockups to evaluate new NDE techniques and controlled thermal fatigue flaws have shown promise for this purpose. Additional work is required to develop methods of creating deeper flaws and determine if the individual grain structure of the base material has any effect on the crack growth.

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