Recent Progress in Cast Austenitic Stainless Steel Weld Inspection

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Abstract

The ultrasonic examination of cast austenitic stainless steel (CASS) components and welds has been a challenging issue for the nuclear NDE industry for more than three decades. Considerations about life-time extension of ageing plants have renewed the interest for this topic. Over the last 10 years, the introduction of low-frequency phased array probes and high-performance data acquisition systems have led to considerable improvements of the UT inspection capability for CASS components. In parallel, critical flaw sizes have been established and documented in ASME Code Case N-838, providing valuable input for realistic flaw acceptance criteria. This paper will give a summary of the results of research programs in the USA and the on-going regulatory efforts. In addition, results will be presented from inspection trials on practice mock-ups, in the framework of a recent technique validation program (round-robin trial) conducted by EPRI.

1. Introduction

Cast austenitic stainless steel (CASS) components are located in safety significant locations in the reactor coolant system of pressurized water reactor (PWR) nuclear plants: pipes and elbows, pump casings, pressurizer (PZR) safe-ends. Figure 1 shows the CASS components in a typical PWR design, and the austenitic grain structure of two typical weld configurations: on top a weld connecting a centrifugally cast (CCSS) pipe to a statically cast (SCSS) elbow, and below a weld connecting a wrought stainless steel (WSS) safe-end to a CCSS pipe. It can be observed that different macrostructures can exist depending on the chemical content and the cooling process: columnar (dendritic), equiaxed, mixed and layered. The ultrasonic examination of CASS components and welds is extremely challenging, exactly because of this anisotropic coarse-grain structure, with individual grains sometimes extending to more than 10 mm. The coarse-grain structure results in major issues for the ultrasonic beam when propagating through the material:

- high and variable attenuation of the sound beam,
- high ultrasound noise, caused by reflections from individual grains
- a low-pass filtering effect
- skewing and distortion of the acoustic beam by the large grains
- local variations of the material structure along the weld circumference
Therefore, ultrasonic inspection techniques need to be drastically adapted compared to common carbon steel weld examinations. Specifically, the wavelength-to-grain size ratio must be carefully considered.

![Figure 1: CASS components in a typical PWR design (left) and austenitic stainless steel grain structures (right); courtesy of PNNL](image)

2. Results from research programs and validation exercises

The challenges of UT examination on CASS welds and components was extensively investigated and documented through research and various round-robin trials (RRT) conducted in the 1980’s and 1990’s. The most widely known RRT was organized in the framework of PISC III, see (1) and (2), but other well documented RRT’s were conducted in the USA, Europe and Asia.

These trials strongly contributed to identifying the key elements for improving the inspection capability. The most successful examination procedures for CASS steel welds consistently involved low-frequency TRL (Transmit-Receive L-wave) probes. Indeed:

- low frequencies, between 0.5 and 1.5 MHz, aid in the reduction of attenuation in the coarse-grain structure
- compression or L-waves are less affected by the anisotropic structure than the vertically polarized shear waves (SV), commonly used for inspection of carbon and wrought stainless steel material
- the use of a Transmit-Receive configuration results in a better sensitivity and reduced noise level (SNR), due to the convolution of the beams; in addition, it eliminates a near-surface “dead-zone”, and “ghost echoes” caused by internal reflections in the wedge

The conclusions of the PISC III RRT also emphasized the importance of well-adapted procedures for detection and sizing, and encoded scanning sequences.
Conventional TRL probes from several probe manufacturers, were used for in-service inspection of CASS components and welds in nuclear plants. As an example, the inspection capability of such probes was validated and formally qualified in 1997 by SQC (Swedish Qualification Center), for the automated inspection of reactor coolant pump casing welds, conducted from the inner surface (3). The qualified scope included detection, length sizing and trough-wall sizing. Afterwards, three actual pumps were inspected using this procedure in the Ringhals NPP.

Phased array UT technology became commercially available at the end of the 1990’s. Very soon after, phased array type low-frequency TRL probes were manufactured and their additional benefits validated and documented (4). Indeed, dual 2D matrix array (DMA) probes allow for optimized focusing and optimized steering of the acoustic beam, thus simplifying on-site logistics by eliminating the need for multiple probes. In addition, these probes allow for simultaneous variation of refracted angle and skew angle, to improve detection capability in anisotropic materials, on mis-oriented flaws, and for increasing inspection coverage. Dual 2D matrix array probes were formally qualified through Appendix VIII for the examination of austenitic and dissimilar metal welds, by EPRI/Zetec, late 2005 (5).

![Figure 2: Benefits of dual 2D matrix array probes: beam steering (left), and beam skewing (right)](image)

Between 2002 and 2010, research has been conducted for the U.S. Nuclear Regulatory Commission (NRC) at the Pacific Northwest National Laboratory (PNNL) in Richland (WA). The studies have focused on developing and evaluating the reliability of nondestructive examination techniques, and phased array UT techniques in particular, for inspecting CASS primary system components in PWR’s. The performance of low-frequency DMA probes was evaluated on relatively thin ($T < 40$ mm) PZR surge line welds, as well as on thicker ($T \approx 70$ mm) main coolant piping welds. Multiple low-frequency DMA probes, with frequencies between 0.5 and 1.5 MHz were designed for these studies, in collaboration between PNNL and Zetec, and manufactured by Imasonic. Zetec’s DYNARAY phased array system provides the appropriate bandwidth and excitation parameters to efficiently drive low-frequency arrays, and was used for all recent CASS work at PNNL.

In three PZR surge line weld mock-ups, all flaws (ID thermal fatigue cracks) were reliably detected (SNR > 20 dB) using DMA probes operating at 0.8 MHz and 1.5 MHz (6). An informal blind trial on the same thin-wall mock-ups, by a qualified ISI supplier,
provided corroborating detection findings and resulted in length and depth sizing performance satisfying the Appendix VIII qualification criteria for dissimilar metal welds.

The thick section welds were fabricated by the industry’s Pressurized Water Reactor Owners Group (PWROG) and contain surface-breaking thermal fatigue cracks located on either side of a weld. The austenitic grain structures shown in Figure 1 belong to two of these specimens. For cracks larger than 30% in through-wall, 100% detection was achieved with 0.5 MHz DMA probes, clearly surpassing the detection rate of a 1.0 MHz DMA probe with comparable aperture (7). Length sizing with 0.5 MHz DMA probes showed results in the range of the typical ASME XI tolerance: RMSE = 19 mm. No crack tip signals could be reliably distinguished from the material noise, so accurate depth sizing is not considered feasible in most thick-wall welds.

3. Regulatory evolution

In 1997, a “Task Group on CSS Inspection” was installed to meet regularly during the ASME Code weeks, with the charter to resolve the issues concerning CASS inspection, and propose actions to complete ASME Section XI, Appendix VIII, Supplement 9. In 2009, a draft Code Case was prepared proposing inspection techniques for thin-wall piping, based on the research described in (6) and further validation. In 2011, a Supplemental Requirement for Appendix III was presented, calling for encoded scanning, and “best practice” probes and examination parameters. This requirement was approved by the NRC as Code Case N-824, subject to the following conditions: a) encoding the data; b) using phased array technology; c) using 0.5 MHz for thick-walled piping, and d) using a phased array search unit producing angles including, but not limited to, 30 to 55 degrees with a maximum increment of 5 degrees. As such, Code Case N-824 can serve as interim best practice while Supplement 9 of Appendix VIII is in course of preparation.

The Task Group also drove a project funded by EPRI and conducted by Structural Integrity, to determine the critical flaw size for CASS material and support the development of realistic qualification requirements for Supplement 9, which resulted in ASME Code Case N-838.

4. Recent PA UT inspection technique development

Given the considerable technological progress since the PISC III trials, and the regulatory evolution mentioned above, the EPRI NDE Center decided to organize a new round-robin study (RRS) on CASS components, to assess the capability of currently available inspection techniques for detection and sizing of service induced flaws. The goal is to quantify the performance of techniques and personnel in terms of probability of detection (POD) and false call probability (FCP), to serve as a basis for developing the qualification requirements in Supplement 9. An international invitation was issued in the spring of 2015, to a mixture of inspection vendors, equipment manufacturers and
research laboratories. Even if this exercise was not a formal qualification, it was organized as a blind trial with rules, reporting and data evaluation processes very similar to the actual PDI qualification (8).

The EPRI CASS-RRS includes 6 pressurizer surge line weld specimens (12” diameter) and 14 main coolant loop weld specimens (28” and 36” diameter). The specimens have the weld cap in place and contain thermal fatigue and simulated cracks, both circumferential and axial. The scope of the examination is detection, length sizing and through-wall sizing of the ID cracks. An important additional challenge for the data analysts is the discrimination between cracks and non-relevant ID features such as root and counterbore, especially since analysis on single-side data was requested.

Nucleom, an emerging Canadian inspection service vendor specialized in advanced NDE techniques, teamed up with Zetec in a shared-cost collaboration to participate in the EPRI CASS-RRS. The preparation work included optimization of low-frequency DMA probe design and inspection technique design, based on experience gained from the above-mentioned PNNL studies and the formal PDI qualification on dissimilar metal welds. The probes and inspection techniques were implemented on the industry-proven DYNARAY phased array system controlled by Zetec’s UltraVision software. Technique validation and procedure development and training were performed on two “open” practice specimens made available by EPRI. Several motorized mechanical scanners were used to record the data. The objective was to prepare a “qualifiable” and “industrially deployable” commercial solution for PA UT examination on various types of CASS welds in nuclear power plants.

In April 2017, a team of Zetec and Nucleom PA UT specialists, inspected the 20 specimens, and completed the data analysis (including formal reporting for detection and sizing) in less than 10 days. Complete data sets were recorded for two separate procedures, using the same DMA probes, one procedure using classic raster scanning with discrete refracted angles, and the other using a dual-line scan approach combined with a typical sectorial sweep. Each procedure was assigned a dedicated data analyst.

### 4.1. Inspection techniques

The applied procedures were developed to benefit from previous experience with CASS weld inspection and the results from the PNNL research work. For circumferential flaws, in each thickness range, DMA probes at two different frequencies were used. The higher frequency is intended to offer the best lateral resolution for flaw characterization if the material allows for adequate propagation. The lower frequency becomes the preferred detection technique for highly attenuating material. The low refracted angles typically provide crack detection from the ID corner trap, while the higher refracted angles are used to pick up signals from various facets of the crack, and possibly tip diffraction signals in the thin-wall specimens. Skewed beams are intended to provide discrimination between cracks and non-relevant ID geometry. Figure 3 shows a schematic representation of the inspection techniques and pictures of the large aperture DMA probe assemblies for the 28” main loop piping welds. Nominal probe frequencies of 0.5 and 1.0 MHz are used, and both transmitter and receiver arrays
have 50 or 60 elements, to maximize beam focusing and steering capabilities. All wedge assemblies are contoured to closely match the OD surface of the component. For axial flaw detection with the weld ground flush, the same probes and inspection techniques for circumferential could be used, by simply changing the probe orientation and the wedge contouring. With the weld cap in place, an alternative inspection technique is required. Two single matrix array probes are each mounted on a single wedge with appropriate wedge and roof angle, and positioned on either side of the weld. A dedicated mechanical interface keeps the probes aligned along the weld. For each orientation of this assembly, clockwise and counterclockwise, three sets of focal laws are generated: pulse-echo skewed beams from each of the two arrays are intended to pick up non-specular signals from crack facets, and a pitch & catch configuration through the weld is intended to benefit from the specular reflection of an axial ID crack.

28” MCP Weld, T = 50 mm

Figure 3 : Inspection techniques and low-frequency DMA probes for 28” MCP weld (T = 50 mm), for circumferential and axial flaws

Figure 4 : Acoustic beam simulation for pitch & catch inspection technique for axial cracks in 28” MCP weld (T = 50 mm)
Figure 4 shows the acoustic beam simulation in UltraVision Classic, for the pitch & catch focal law at 45 degrees. With the available practice specimens, only the efficiency of the pitch & catch technique could be successfully verified, using the edge of the specimen as a “virtual” axial crack.

4.2. Preliminary results

Figure 6 and Figure 6 show examination data from the 28” practice specimen, with two ID cracks (through-wall extent 20% T and 30% T) located in the weld bevel, slightly tilted along the bevel orientation.

The ID geometry for this specimen is not considered very challenging. In this material, the optimized 1.0 MHz DMA probe provided the better results. Specular incidence on the cracks (Figure 5), through the weld, provided better SNR (around 14 dB) and length sizing results, using the full amplitude drop technique. On the other hand, non-specular incidence (Figure 6) allowed for more accurate estimation of the flaw height.

Figure 5 : Examination data (merged) from two-line scan with optimized 1.0 MHz DMA probe on 28” MCP practice specimen: two ID cracks are well detected from the far-side (specular)
5. Conclusions

Based on the information presented in this paper and the various references, the following conclusions can be drawn in relation with CASS weld inspection:
1. Since 2000, the introduction of phased array UT technology in combination with dedicated research programs have led to considerable progress in the inspection capability for CASS components.
2. A combination of optimized low-frequency DMA probes, generating L-waves between 0.5 and 1.5 MHz, can reliably detect flaws in thin-wall CASS components (T < 40 mm), and large flaws (> 30% T) in thick-wall components.
3. Commercially available high-performance phased array hardware and software allow for setting up and deploying all required inspection techniques with industrial efficiency.
4. Accurate through-wall sizing and reliable discrimination of cracks from varying ID geometry conditions remains a tough matter.

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