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A52M/SA52 DISSIMILAR METAL RPV REPAIR WELD: EXPERIMENTAL EVALUATION AND POST-WELD CHARACTERIZATIONS

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ABSTRACT

Aging management of the existing fleet of nuclear power plants is becoming an increasingly important topic, especially as many units are approaching their design lifetimes or are entering long-term operation. As these plants continue to age, there is an increased probability for the need of repairs due to extended exposure to a harsh environment. It is paramount that qualified and validated solutions are readily available.

A repair method for a postulated through cladding crack into the low alloy steel of a nuclear power plant's reactor pressure vessel has been investigated in this study. This paper is part of larger study that evaluates the current possibilities of such repair welds. The present paper documents the weld-trials and method selection. A parallel paper describes numerical simulations and optimization of weld parameters. The presented weld-trial represents a case where a postulated crack has been excavated and repaired using a nickel base Alloy 52M filler metal by gas metal arc welding-cold metal transfer with a robotic arm. A SA235 structural steel has been used as a base material in this weld-trial. No pre-heating or post-weld heat treatment will be applied, as it would be nearly impossible to apply these treatments in a reactor pressure vessel repair situation.

While Alloy 52M presents good material properties, in terms of resistance to environmentally assisted degradation mechanisms, such as primary water stress corrosion cracking, it is notoriously difficult to weld. Some difficulties and challenges during welding include a sluggish weld puddle, formation of titanium and/or aluminium oxides and its susceptibility to lack of fusion defects and weld metal cracking, such as ductility dip cracking and solidification cracking. Moreover, gas metal arc welding-cold metal transfer is not traditionally used in the nuclear industry. Nonetheless, it presents some interesting advantages, specifically concerning heat input requirements and automation possibilities, as compared to traditional welding methods.

The mechanical properties, in terms of indentation hardness, and microstructure of a weld-trial sample have been evaluated in this study. The fusion boundary and heat affected zone were the main areas of focus when evaluating the mechanical and microstructural properties. Detailed microstructural characterization using electron backscatter diffraction and nanoindentation were performed across the weld interface. Based on these results, the gas metal arc welding cold metal transfer is seen as a potential high-quality weld method for reactor pressure vessel repair cases.

NOMENCLATURE

Abbreviations

CMT	Cold metal transfer (GMAW welding)
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
EBSD	Electron backscatter diffraction
HAZ	Heat affected zone
NPP	Nuclear power plant
O&P	Oliver and Pharr
OES	Optical emission spectroscopy
PWSCC	Primary water stress corrosion cracking
RPV	Reactor pressure vessel
SEM	Scanning electron microscopy
TBW	Temper bead welding

XRD X-ray diffraction

INTRODUCTION

With the increasing lifetimes of the current nuclear fleet, there is a small, but increasing probability for the need of repairs to safety critical structures and components, due to extended exposure to a harsh environment (neutron flux, high temperature, high pressure, water chemistry). Indeed, some repairs, such as mitigative overlay welds of welds affected by primary water stress corrosion cracking (PWSCC), have been performed for a long time [1]. Over time, it can be expected that the need for and variety of further repairs will increase. Thus, it is of interest to study potential repair methods of safety critical components, even in absence of current acute needs.

One possible repair to be considered is a through cladding crack into the low alloy steel of a nuclear power plant's (NPP) reactor pressure vessel (RPV). Research on different repair welding techniques for nuclear power plant reactor pressure vessels in openly published literature appears to be sparse. While only few of the studies [2, 3] can be considered relevant in terms of clearly established links to actual repair cases of under-cladding defects in RPVs, others [4–6] were mainly intended for modelling and simulation purposes, such as the optimisation of weld thermal cycles, but without cladding, groove excavation or the use of irradiation-embrittled material. Most of the reviewed repair welding procedures are based on the use of the gas tungsten arc welding (GTAW) process, often with nickel-base alloy filler metal in combination with temper-bead welding techniques (TBW) with the aim of omitting both preheating and post weld heat treatments (PWHT), because of the difficulties associated with their practical execution on site. Many of the studies have recognised that the omission of preheating or PWHT is not realistic or safe, if carbon steel filler metals were used. Instead, the use of Ni-base alloy fillers resulting in the austenitic weld microstructure effectively dissolving and interlocking hydrogen, coupled with TBW techniques providing local tempering and hence a reduction in hardness of the RPV steel heat affected zone (HAZ) microstructure, are thought to provide safeguards against HAZ hydrogen cracking.

In the absence of preheating and PWHT, safe repair welding of under-cladding defects in RPV materials requires careful optimisation of numerous parameters including (i) total number of layers, (ii) number of beads per layer, (iii) bead placement & welding sequence, (iv) bead overlap in terms of bead side-shift, (v) heat input, (vi) interpass-temperature and (vii) cumulative thermal efficiency of temper-beads. The literature survey [2-6] revealed, for instance, that limiting the RPV steel HAZ hardness to between 350 – 380 HV was in most cases very difficult even when TBW was applied. It appeared that at least four, but preferably 5 to 6, weld layers, were necessary in order to control the hardness increase in the HAZ via the local tempering effect. Nonetheless, occasional HAZ hardness values in excess of 380 HV were often recorded.

In addition to the protection offered to the RPV steel HAZ to hydrogen cracking, the use of Ni-base alloys, such as Alloy 52/52M provides many advantages. Alloy 52 weld metal exhibits high fracture resistance, good high-temperature static strength, adequate resistance to fatigue crack propagation and virtually no PWSCC at 300 °C. Compared to austenitic stainless steel weld, the thermal expansion coefficient of Ni-base alloy weld is also closer to that of RPV carbon steel, which should be a benefit in terms of welding residual stress build-up, especially in the absence of PWHT. Furthermore, carbon migration from the RPV steel towards the Ni-base weld metal remains less than with an austenitic stainless steel weld. This minimises the formation of martensitic constituents at the weld interface, hence improving the fusion boundary integrity and toughness. The disadvantages and challenges in using Ni-base alloys for repair-welding, in turn, manifest themselves as a lack of detailed data on optimal welding parameters, difficulties in achieving smooth weld bead appearance due to highly viscous and sluggish molten weld metal, difficulties in RPV steel HAZ hardness control when trying to optimise the applied TBW technique, as well as susceptibility to hot-cracking and ductility-dip cracking.

As an alternative to conventional GTAW process, the use of automated gas metal arc welding (GMAW) utilizing cold metal transfer (CMT) mode is expected [7] to offer many advantages, such as good weld quality, exceptionally stable arc, easy automation and very low heat input along with narrow HAZ. In GMAW/CMT, digital process control detects a short circuit and helps to detach the droplet by retracting the wire: during welding, the wire moves forward and is pulled back again as soon as the short circuit occurs. As a result, the arc only introduces heat for a very brief period during the arc-burning phase. A short circuit sending a signal that retracts the welding filler material, thereby gives the weld time to cool before each drop is placed (sc. drop-by-drop molten metal transfer). In GMAW/CMT, the computer adjusts parameters such as wire feed, welding speed, and welding current (amps) going through the wire, which allows precise welding with very little slag and spatter, resulting in a cleaner finish weld. The short circuit is controlled and the welding current is kept low, resulting in a spatter-free material transfer. The arc length is detected and adjusted mechanically. The arc remains stable, no matter what the surface of the work piece is like or how fast the user welds. Moreover, a small bead size owing to very low heat input is expected to favour tempering & normalising effects due to successive passes. See Ref. [8] for an up-to-date review and CMT weld quality comparison with different methods.

The essential challenge in the present study is to optimise all relevant welding parameters of the GMAW/CMT process, including the thermal efficiency of temper-beads, in order to obtain a sound, defect-free repair-weld with controlled RPV steel HAZ maximum hardness 380 HV [2-6] (equivalent to nanoindentation of 3.7 – 4.0 GPa). This requires interaction between (i) numerical modelling & simulation and (ii) experimental tests & microstructural characterisation.

In the present paper, a repair method for a postulated through cladding crack into the low alloy steel of a nuclear power plant's (NPP) reactor pressure vessel (RPV) has been investigated. A small-scale weld-test has been made for this case using by joining two plates of SA235 structural steel using a Ni-base Alloy 52M filler metal by GMAW/CMT with a robotic arm, without any preheating or PWHT. Weld quality is of the utmost importance when considering this repair situation. In addition to the weld quality, one specific interest is to study and optimize the residual stresses caused by the repair welding. If unmanaged, these residual stresses can make the complete repair susceptible to further degradation during subsequent use and exposure to NPP environment. A parallel paper, Ref. [9], discusses the investigation of the residual stresses by simulation. A full experimental residual stress measurement, with the contour method, is planned for the full-scale mock-ups, to be performed later.

Moreover, the current paper documents the rationale and the pre-tests conducted using structural steel base metal plates welded using Alloy 52. This pre-test is in preparation for a full-scale repair mock-up to evaluate welding techniques and compare residual stresses between different weld bead arrangements. Finally, the results from these studies will be used for making an RPV repair weld mock-up on a representative, cladded VVER-440 pressure vessel steel.

MATERIALS AND METHODS

In the weld-trial performed in this study, a SA235 structural steel was welded using Ni-base Alloy 52. Chemical analysis via optical emission spectroscopy (OES) was performed to verify the chemical composition and carbon content of the steel, which reported as 0.14 wt.%.

The welding test was completed using a robotized set-up with a Fronius CMT TransPuls Synergic 5000 welding power source and VR 7000 CMT wire feed control unit. The welding torch was attached to KUKA KR5-2arc Hollow Arm with KRC4 programmable control. The welding was performed at a working temperature of 20 °C. No preheating or PWHT was applied. The weld geometry and bead order are shown in Fig. 1. The weld groove was first lined with Inconel Alloy 52 starting from the bottom, and then the remaining weld volume filled in sequence.

The welding was then completed using the CMT-process with Inconel Alloy 52 and the equivalent Sanicro68HP filler materials. The applied weld parameters are shown in Table 1. Argon was used as a shielding gas, which provided good weldability with the CMT process. The first passes were completed with 0.9 mm filler wire (heat input of 0.18 - 0.27 kJ/mm). Some instability in the arc was observed for this weld configuration. The latter beads were welded with 1.2 mm wire (0.21 – 0.25 kJ/mm heat input). This configuration showed good arc stability and weld quality. During the test, the root was supported by a metallic backing plate. In the final repair tests, the root will not need support, since the repair shape will have an intact bottom (excavated from a thick carbon steel plate).

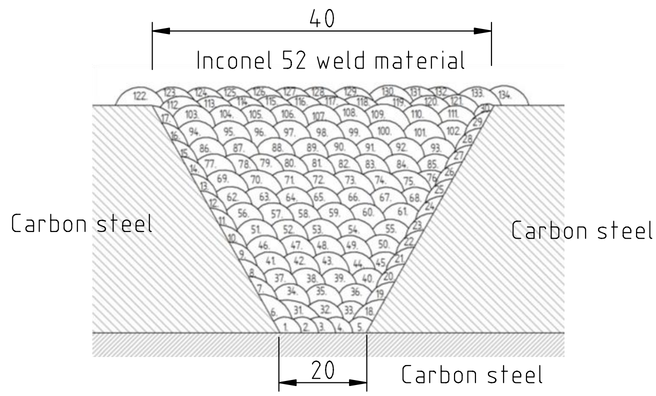


FIG. 1. WELD PASS CONFIGURATION IN THE WELDING TRIALS. THE ORDER OF THE WELD BEADS IS INDICATED. (MEASUREMENT UNITS ARE IN MM).

TABLE. 1. FINAL WELDING PARAMETERS USED IN THE TRIALS.

Working temperature	**20 °C**
Preheat temperature	**not used**
Interpass temperature	**not controlled**
Polarity	**DC+**
Gas	**Ar, 20 l/min**
Current	**195-210 A**
Voltage	**17.9 – 20.7 V**
Travel speed	**80 cm/min**
Stick out	**12-15 mm**
Wire feed rate	**9.0 m/min**
Wire diameter	**1.2 mm**
Heat input	**0.21-0.25 kJ/mm**

After completion of the welding, the test-weld was sectioned and a metallographic cross-section was prepared to study the weld quality. The cross-section was mechanically ground, using sequential grinding with SiC grit papers, and then polished to a mirror finish, with the finishing step using a 0.25 µm colloidal silica suspension. The microstructure was then investigated using scanning electron microscopy (SEM) coupled with electron backscatter diffraction (EBSD). In addition, light optical microscopy was performed, after chemical etching using an aqua regia (HNO_3 + 3HCl) solution to reveal the microstructure.

The hardness across the fusion boundary into the HAZ was investigated using Vickers microhardness and both traditional and in-situ nanoindentation techniques. The results presented in the paper will focus on the nanoindentation results, and Vickers microhardness results will not be presented, nor further discussed here.

Nanoindentations, across the HAZ and weld interface, were performed using both an in-situ SEM nanoindenter (Alemnis AG, Switzerland) [11] inside a Zeiss Leo 1450 SEM and a CSM Ultra-Nano Indentation Tester, located in a controlled environment – the temperature was regulated at 20 ± 0.01 °C and relative humidity fixed a 48 %. A Berkovich pyramidal tip shape was used for indentation. A coarse grid, comprising 610 indents with 50 µm spacing, across the weld, fusion boundary, HAZ and into the structural steel, was performed with a peak load of 45 mN and maximum indentation depth of approximately 900 µm. A finer grid, separated by 5 µm and peak load of 2.5 mN was subsequently applied to investigate the local hardening of the interface with respect to surrounding regions. The load-displacement data was analysed using O&P analysis for extracting indentation modulus and hardness values from each of those indents [10]. A Poisson's ratio of 0.3 was assumed in this analysis. Nanoindentation parameters can be found in Table 2.

Following in-situ nanoindentation, EBSD mapping of the indented area was performed using a Zeiss UltraPlus FE-SEM equipped with an Oxford CMOS Symmetry detector to investigate the microstructural evolution close to the interface due to the welding process and to correlated the mechanical properties obtained from nanoindentation with the underlying microstructure.

Preliminary residual stress measurements were completed using X-ray diffraction (XRD). The X-ray measurements provide limited information and only from the surface. The purpose of these measurements was to acquire an initial estimate of the surface stresses to compare with the numerical simulations and provide baseline values for the next phase. Furthermore, using a small sample sectioned from a larger mock-up is expected to relieve some of the residual stresses, due to insufficient constraint. Therefore, the measured values may underestimate the true residual stresses that would arise in a full-scale mock-up. Unfortunately, the weld microstructure and large grain size made the XRD measurements unreliable and no meaningful residual stress measurements could be extracted at this time. This further emphasizes the importance of using the contour method to study weld residual stresses. The preliminary residual stress measurements will not be presented nor discussed further in this paper.

RESULTS

A cross-section of the completed weld-test is shown in Fig. 2. Despite the relatively small size of the mock-up (approx. 50 mm plate thickness), the sample did not experience any marked deformation during welding, see cross-section in Fig. 2. This can be attributed to the very low heat input used in CMT welding. Most notably, the weld features a very small heat affected zone and the weld fusion line is straight indicating small penetration into the base material. Despite the small

TABLE. 2. TRADITIONAL AND IN-SITU NANOINDENTATION EQUIPMENT AND MEASUREMENT PARAMETERS.

Parameter	Traditional nanoindentation	In-situ nanoindentation
Indention equipment	CSM Ultra-Nano Indentation Tester	In-situ SEM nanoindenter [9]
Indenter tip shape	Berkovich pyramidal	Berkovich pyramidal
Indentation force	2.5 mN	45 mN
Poisson's ratio	0.3	0.3
Indentation spacing	5 µm	50-100 µm

FIG. 2. CROSS-SECTION OF THE MOCK-UP WELD AFTER POLISHING. SEE FIG 1 FOR THE WELD PASS LAYOUT, DIMENSIONS AND MATERIALS.

penetration, no lack-of-fusion was noted in the sample and the fusion boundary is intact. The overall weld quality was good and no susceptibility to hot cracking or other weld defects were noted in the investigated weld-test piece.

The cross-section was investigated using SEM and EBSD techniques, see Fig. 2. The EBSD grain orientation map revealed the columnar grains of the Alloy 52M weld. The HAZ measures approximately 500 µm in thickness and displays a narrow coarse grained zone followed by fine grained zone. Additional microstructural investigations and chemical analyses are required to assess the presence and composition of any precipitates/oxides (e.g. titanium and/or aluminium oxides) that may have formed during the welding along with the migration of chemical species.

Hardness measurements were performed to investigate the HAZ using in-situ nanoindentation. These results can be seen in see Fig. 3. A clear hardness increase in the HAZ can be observed. The hardness increases by approximately 0.9 – 1.1 GPa (≈ 92 – 110 HV) from a base value of 2.3 GPa (≈ 235 HV) in the SA235 structural steel and by 0.4 GPa (≈ 40 HV) from base value of 2.5 GPa (≈ 255 HV) in the Alloy 52 weld metal. While this hardness increase is significant, it still remains within the acceptable range of hardness for an an RPV (< 380 HV) [2-6, 12]. The fusion boundary was further investigated using nanoindentation, see Fig. 5. The measured indentation hardness also indicates that there is a very narrow (less than ± 10 µm) band of high hardness at the interface. The average measured indentation hardness at the interface is 8.2 GPa, with a maximum indentation hardness approximately 12 GPa in one location.

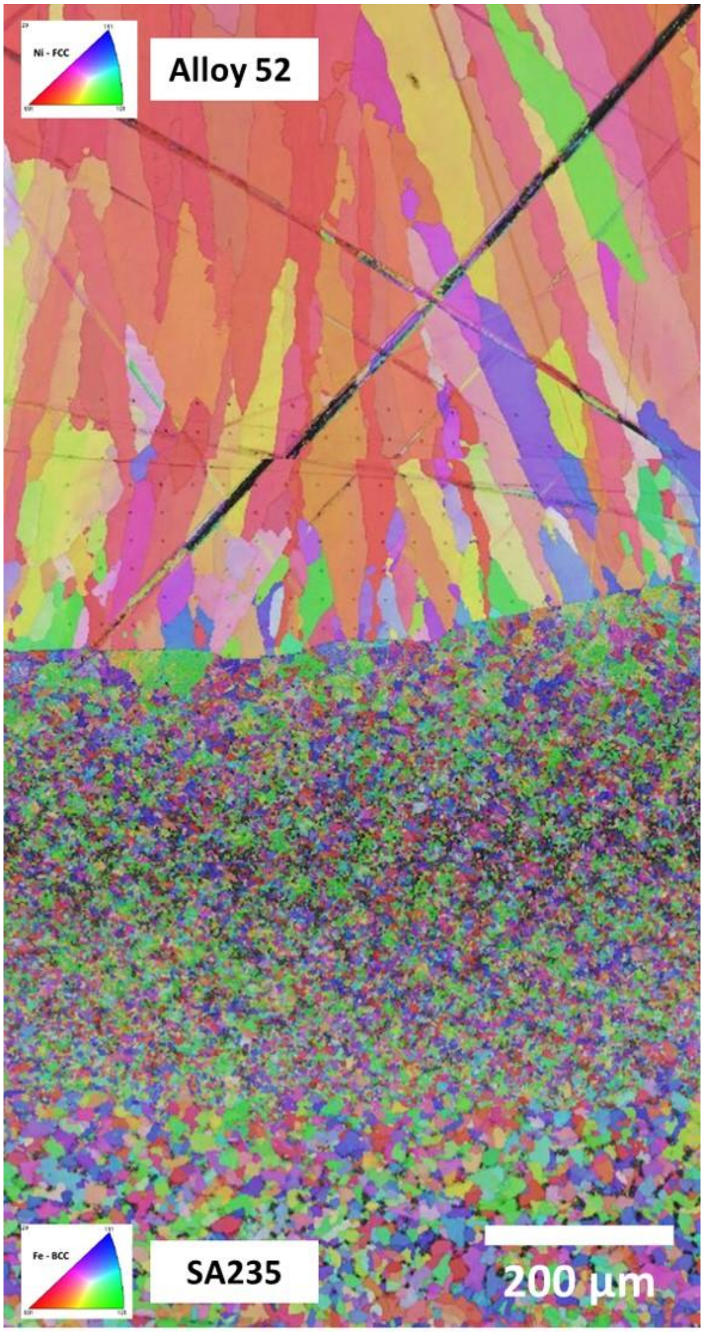


FIG. 2. A NORMAL DIRECTION INVERSE POLE FIGURE (IPF) ORIENTATION MAP SUPERIMPOSED ON THE BAND CONTRAST (BC) MAP COLLECTED BY EBSD FROM THE WELD FUSION LINE.

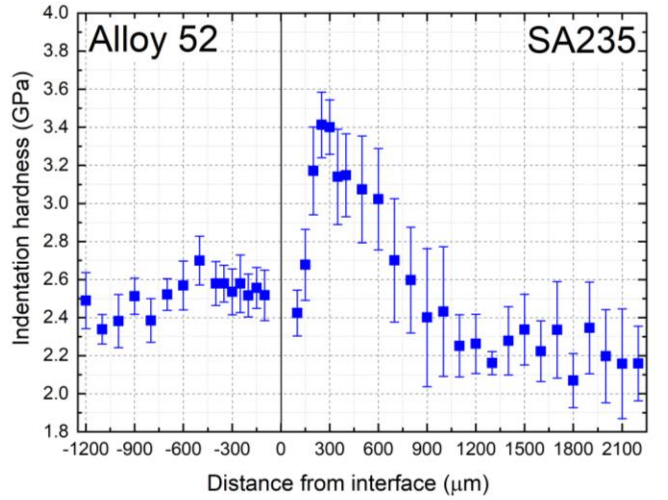
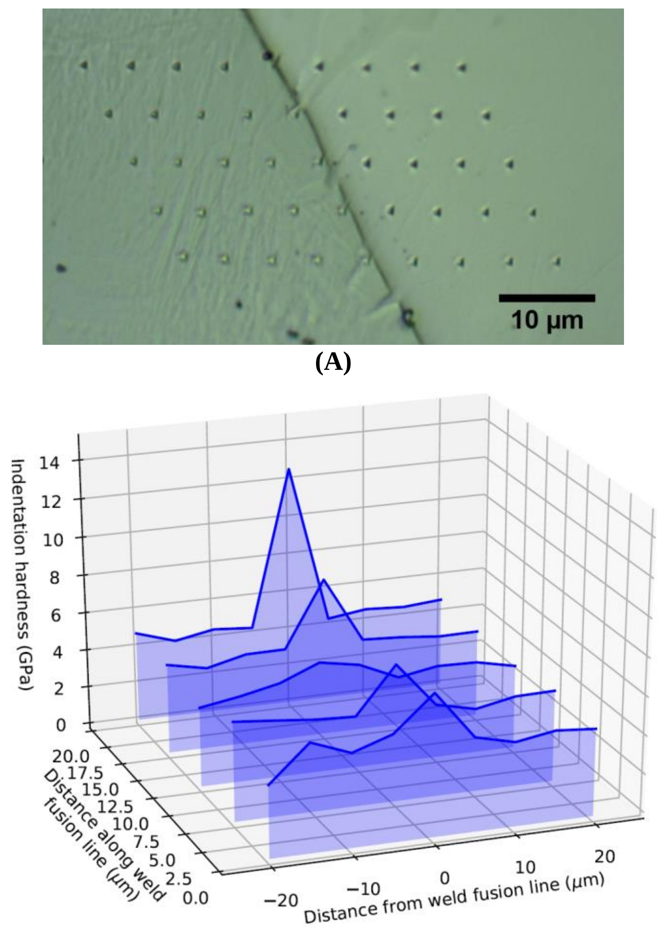


FIG. 3. MEASURED INDENTATION HARDNESS ACROSS THE FUSION LINE, USING IN-SITU NANOINDENTATION.



(A)

(B)

FIG. 5. (A) GRID OF TRADITIONAL NANOINDENTATION MEASUREMENTS ACROSS THE FUSION LINE AND (B) 3D PLOT OF INDENTATION HARDNESS VALUES ACROSS THE FUSION LINE.

The traditional nanoindentation results, performed applying a 2.5 mN force, indicate a higher hardness at the interface as compared to in-situ nanoindentations. This discrepancy is likely due to the difference in analysis parameters, specifically the indentation force, which was significantly lower for traditional nanoindentation (2.5 mN vs. 45 mN). When applying a smaller indentation force, the indentation depth and interaction volume with the material decreases. These shallow nanoindentation results are measuring the very near surface hardness of the material, and therefore may present some artefacts of sample preparation, e.g. the residual cold working from grinding and polishing. This likely explains the slightly higher base hardness values observed here in comparison to in-situ nanoindentation indents probing larger depths. Moreover, these results correspond to indentation hardness of 1-2 grains while nanoindentations performed at 45 mN (approximately 900 µm penetration depth) are providing an average hardness for possibly several grains with different orientations. Anisotropy and orientation effects have been shown to introduce higher scatter in measured indentation hardness values [14]. In addition, as nanoindentation is an extremely sensitive technique, the indentation locations should be examined in more detail to determine if there may be underlying microstructural features, such as precipitates/oxides, that have contributed to these measured values. Furthermore, as the fusion boundary extends through the material, any deviation from perpendicular to the surface may have direct implications on the measured hardness values. Nonetheless, while the indentation hardness magnitudes may be different between the two methods, both methods clearly highlight a clear increase in hardness at the interface. The significance of this hardened layer will be investigated in future studies.

DISCUSSION

Traditionally, weld repairs in the nuclear industry have been completed using GTAW welding. GTAW has a reputation of providing high weld pool control and, consequently, high quality welds. In the present study, it was of interest to study alternative ways to complete similar weld repairs. As the expected repair weld volume is rather small, the limited productivity of GTAW is not considered problematic. However, since the weld may need to be completed in harsh conditions, highly and easily automated weld methods would be preferred. At the same time, weld quality is still paramount and excessive need for repairs during welding would be problematic, let alone hidden defects let into the weld seam. To facilitate easier automation, GMAW welding was evaluated for the repair. CMT was utilized to obtain an improved weld quality and energy input control, as compared to traditional GMAW.

Nickel base Alloy 52 is known to be susceptible to hot cracking and various other weldability issues [13]. However, in the present study, the weld-trial results using GMAW/CMT, resulted in good weld quality, with no indications of hot cracking or other weldability issues. This can be attributed to the very small and tightly controlled heat input allowed by the use of CMT. This produced very consistent weld pool conditions and reduced the risk of weld defects. At the same time, the small heat input caused only a small penetration and a narrow HAZ (< 1 mm). The narrow HAZ can be considered to have an overall beneficial effect on the repair quality. However, it could also indicate susceptibility to lack-of-fusion defects and local hardening on the carbon steel side. Despite the small penetration and associated susceptibilities, no lack-of-fusion defects were found in this investigation. Furthermore, hardness results, obtained via nanoindentation, indicate that there is a thin, locally hardened layer near the fusion line. The majority of these hardness measurements appear to fall within the acceptable hardness for an RPV (up to 380 HV) [2-6]. Moreover, it should be noted that for some materials (e.g. group 3 materials in SFS EN ISO 15614-1) a hardness of up to 480 HV10 is acceptable [12].

In addition, the simulations presented in Ref. [8] indicate that the tempering effect of subsequent layers reaches to about 3 mm, thus welding the fusion line layer with a somewhat smaller layer thickness or increasing the energy input for the subsequent layer would result in better tempering of the first layer and may alleviate the hardened layer. In addition, residual stress measurements using the contour method shall be performed, thus providing more insight to the mechanical state of the weld and the local properties of the HAZ and fusion line. These points will be investigated and addressed in more detail in future works.

CONCLUSIONS AND PERSPECTIVES

The following preliminary conclusions can be drawn from this work:

- GMAW and CMT provide a promising alternative to the more traditional GTAW for RPV repair welds.
- The very small and tightly controlled heat input of CMT resulted in a very narrow heat affected zone and an acceptable overall hardness increase in the HAZ.
- While only a small weld penetration into the base material was observed, this resulted in an intact fusion boundary and no lack of fusion defects were observed.
- Microstructural investigations revealed a the columnar microstructure of the weld, along with the narrow HAZ, comprised of a coarse followed by fine grained zone. Additional microstructural investigations are required to assess the formation of precipitates/oxides in the weld and HAZ during the welding, along with any significant migration of chemical species.
- A hardened layer was observed at and near the fusion boundary and extending into the HAZ. The effect and possible implications of this hardened layer will be investigated in ongoing works.
- Estimation of the residual stresses in very a narrow HAZ using XRD methods proves difficult,

and the results were inconclusive. The contour method would be more effective in evaluating residual stresses. This will be further investigated in ongoing works.

These preliminary conclusions and the results obtained in this study highlight some important points of further investigation, including (i) the effect of the hardened layer at the fusion boundary, (ii) the residual stresses present in the repair weld and (iii) any additional microstructural features or precipitates/oxides present in the weld and HAZ that may contribute to the overall performance of the weld in terms of mechanical performance and resistance to environmental degradation. These items are being investigated in ongoing works. Moreover, as the overall soundness and quality of the repair weld is promising, when using the GMAW/CMT technique and Alloy 52/52M weld material, this approach will be applied to a postulated repair weld case using a representative, cladded and thermally embrittled VVER-440 RPV material with a postulated through cladding crack.

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