Weld repair practices without post weld heat treatment for ferritic alloys and their consequences on residual stresses: A review

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ABSTRACT

The use of the half-bead, temper bead welding (TBW), and cold repair techniques is proving to reduce the cost of repairs and extend the life of aged components in power plants, petrochemical and hydrocarbon processing industries. It has been a significant area of interest for more than twenty years. A critical factor in this context is residual stress. The presence of residual stresses can lead to cracking which ultimately results in structural failure. This paper reviews the half-bead, TBW, and cold repair technique practices and their consequences on residual stresses within the nuclear, power, refinery and petrochemical industries and some of the contributions made by our group of researchers in this area. This paper reviews recent work by the Monash University group. We report our work on TBW residual stresses when measured using neutron diffraction which shows very little reduction in residual stresses over normally completed welds. The use of automatic FCAW has been explored in our group and is reported.

1. Introduction

Components operating at high temperature or harsh working conditions are subjected to different failure regimes which require special consideration. In scheduled shutdowns, critical components are inspected and if necessary either replaced or repaired. Generally, the cost effective choice is to extend the life of aged components by repair rather than replacement. Repair can be the only alternative particularly if the required material for repair is not available within outage time constraints.

Repair welding maybe carried out using a range of welding techniques depending on the nature of the repair. Commonly, most weld repairs require post weld heat treatment (PWHT) to restore the deteriorated metallurgical and mechanical properties. However, critical issues in the course of PWHT such as time, component geometry and unsupported loading during the time the component is hot, mean that it is not always possible to carry out the full procedure. Duration of hold time during the PWHT cycle can be very long especially for thick walled components which result in the extension of the unit downtime. Complex geometry may cause difficulties in reaching the exact region of repair therefore a larger area has to be heated instead. This can lead to distortion particularly when mechanical loads are attached to the structure since deformation may occur at the elevated temperatures of the heat cycle. Due to the difficulties and limitations encountered with PWHT, alternative techniques have been developed.

The role of this paper is to review the development of alternative techniques to PWHT. Welding processes, parameters and techniques in the context of TBW and the key aspects of successful weld repair are also considered adding in recent work done by our group at Monash University, Melbourne.

2. A historical review

Researchers have shown great interest in studying and evaluating alternative techniques for PWHT. An important workshop is reported in the Welding Research Council Bulletin 412, 1996 [1]. This bulletin established comprehensive guidelines for repair welding pressure vessel and piping systems and associated equipment mainly for the manual metal arc welding process. For the alternative techniques to PWHT half-bead, TBW, and cold repair studies and limitations are given. A more recent survey is by Issler et al., 2004 [2].

2.1. Half-bead technique

The half-bead technique has been used widely by different industries for repairing different alloys such as 2.25Cr—1Mo steel. In this technique a cavity is made either by gouging or grinding in
the region required to be repaired. A pre-heat temperature of about 177 °C is followed. A stringer bead buttering layer is then deposited using a maximum 3 mm diameter electrodes [3]. The use of small electrodes with low heat input is aimed to reduce the hardness of the HAZ. An overlap of 50% between the adjacent weld beads is maintained to partially temper the previously deposited beads. Half of the first layer is then removed by grinding from whence the name “half bead” derives. A new stringer bead layer is placed over the previously machined layer using a larger electrode diameter such as 4.0 mm with higher heat input without weaving to refine the coarse grains of the HAZ [4,5]. Next is to overfill the cavity using 4 mm electrodes in order to temper each previous layer. The last layer crown is finally removed by grinding. Inter-pass temperature should always be controlled for a maximum temperature of 230 °C until the completion of the weld. A low temperature heat treatment of about 290 °C is followed to assist hydrogen diffusion [4,5]. The steps of the half-bead tempering technique are schematically illustrated in Fig. 1.

Different studies have been carried out using the half-bead technique. Several studies were conducted to allow the use of half bead welding in the US nuclear industry in the 1970s and 1980s. These studies include: Whitman [6] who reported one of the early practices of using the half-bead tempering technique for intermediate test vessels. Holz [7] discussed the standards and procedures used with half-bead repairs. Wismer and Holz [8] performed successful half-bead welding on cavities placed in three thick-walled pressure vessels. All three reported repairs were in accordance to Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code guidelines. Bryan et al. [9] pressurized to failure a vessel of SA533, grade B, class 1 steel, contained a fatigue-sharpened notch adjacent to a half-bead weld repair that had not been stress relieved. Feldstein [10] discussed a supporting EPRI program. Alberry [11] developed a predictive methodology for the calculation of heat-affected zone hardness distributions in thick-section multi-pass welds in SA 508 Class 2. This methodology was incorporated into a computer model that has been used to develop an alternative repair technique to the ASME XI half-bead technique. Lundin [12] considered programs of PVRC aiming to optimize welding for the fabrication and repair of Cr–Mo and low-alloy steels. These programs led to additional work on improving the utility of low carbon 1.25Cr–0.5Mo weld metal by introduction of elements designed to improve elevated temperature properties without impairing weldability potential. Lant et al. [4] appraised the practical weld repair procedures for low alloy ferritic steels and some of the precautions needed.

Although the half-bead technique has proven to be successful as an alternative for PWHT, some problems associated with it need to be taken into consideration. Firstly, precision grinding is needed for the first layer. The grinding stage is very critical for the repair: the main drawback of the technique being over or under grinding of the first layer. Over-grinding will result in shallow remaining of the first layer and thus deposition of the subsequent layer will result in a HAZ with a deeper penetration than intended causing new hard microstructure. On the other hand, under-grinding will result in insufficient penetration and inadequate tempering. The time needed for precision grinding in the half bead technique results in a noticeable delay.

2.2. Temper bead

The key difference of TBW from the half-bead technique is that the interlayer grinding is excluded in the TBW technique. Also, the heat input of the subsequent layer in the TBW technique is increased in order to be able to refine the coarse grain or temper the martensitic/bainitic microstructure of the HAZ. Fig. 2 shows a schematic illustration of the TBW technique.

There is a long history of investigation of TBW. At the same time as the early US work on half bead repairs, the Central Electricity Generating Board (CEGB) in the United Kingdom, established a two-layer refinement technique specifically to improve the sensitivity of the coarse grain heat affected zone (CGHAZ) in CrMoV steels to stress relief cracking [5,13]. A joint is prepared by making a suitable cavity and a single layer of stringer beads is deposited at low heat input using either 2.5 mm or 3.25 diameter electrodes, which results in a narrow HAZ. A minimum 50% overlap with controlled parameter was used to refine the adjacent layer for the stringer bead up to 80% [4,13]. Then, with a higher heat input using 4.0 mm diameter electrode the second layer is deposited then fill-up is completed with the same electrode. Tempering of the HAZ is achieved by controlling the heat input ratios between the first and second layers using different sizes of electrodes. Pre-heat is maintained at approximately 250 °C and PWHT is performed at 700 °C [5].

An early study by Feldstein [10] also reported a controlled heat input, multi-pass welding procedure without the necessity for grinding the first layer. Then, Felix et al. [14] described the development of welding procedures using gas tungsten arc welding (GTAW). Zeemann and Ferreira [15] presented a practical example of an incorrect use of TBW for a welded AISI 4130 oil extraction pipeline, where the last weld bead was not positioned on weld metal but on the HAZ creating a new hard HAZ. Ikeuchi et al. [16] examined the HAZ toughness and microstructure of SQV-2A steel welded by the temper bead technique. In their study, an intercritically reheated coarse-grained HAZ (ICCGHAZ) was simulated. Serious embrittlement was found in the ICCGHAZ.

The TBW technique was developed by Ontario Hydro in Canada [17]. In their work, a low heat input of stringer beads are deposited

![Fig. 1. Schematic illustration of the half bead tempering technique (a) gouging and grinding, (b) applying the buttering layer, (c) machining half of the buttering layer, (d) applying the tempering layer, (e) filling the rest of the cavity and (f) ground flush the cupping.](image)

![Fig. 2. Schematic illustration of the TBW technique.](image)
with a minimum 50% bead overlap. Then, with the same overlap percentage, a second layer of stringer beads is deposited. The heat input of the second layer is approximately twice that of the first layer. Extensive grain refinement and tempering of the CGHAZ are aimed out of this procedure. In order to induce the tempering of the HAZ, larger diameter electrode is used with high heat input or weaved beads rather than stringer beads. A pre-heat of 177 °C is maintained till the completion of welding. Lastly, to diffuse hydrogen out of the weldment a temperature of 230 °C is maintained for 2 h.

EPRI studies found that TBW offered an alternative solution to PWHT from a creep, tensile, and toughness standpoint [18]. Gandy et al. [19] discussed industry case studies using conventional PWHT and the TBW technique. Viswanathan et al [20] discussed the results of evaluation performed on service-aged piping using both PWHT and TBW. TBW improved the toughness of the service-aged weldment, while the PWHT lowered the HAZ toughness. More recent work by Viswanathan and Gandy [21] documented the results of an industry survey of weld repair practices and described the results of experimental evaluations performed on service-aged 2.25Cr–1Mo steel piping. The overall results of this program provide substantial evidence that service-aged piping systems can be successfully weld repaired with TBW and that life extension by several decades is achievable under the right design and repair conditions. However the review also found that gas tungsten arc weld repairs with PWHT resulted in the best combination of tensile strength, uniform micro-hardness distribution across the weld, Charpy toughness, and creep rupture life. Another technique which involves a six layer refinement where a higher degree of heat input control is used to allow both refining and tempering of the structure employing GTA and SAW processes [22] was developed by EPRI in the 1990s. TBW has been expanding to be used in other materials such as chromium-molybdenum steels. TBW has been demonstrated for C–Mn steels so that the value of peak hardness was less than 350 HV which is critical for hydrogen cracking [5,13]. The work was also reviewed by Lundin [12] and input from the National Board of Pressure Vessel Inspectors was discussed. Moore [23] investigated weld repair of C–1%Mo coke drums without PWHT using the SAW process. The authors extended the work to include as-welded repairs with automatic gas metal–arc welding (GMAW). Automatic GMAW increased productivity and allowed repairs to larger areas of fatigue damage during short-duration turnarounds. Lau et al. [17] summarizes the work conducted by Ontario Hydro in non-PWHT weld repair technology with special emphasis on recent developments for Cr–Mo materials. Nawrocki et al. [24] evaluated and compared the stress relief cracking susceptibility of a temper bead weld in HCM2S (a new ferritic steel) and standard 2.25Cr–1Mo steel to single pass weld results using Gleeble machine Peddle and Pickles [25] developed TBW and PWHT of 2.25Cr–1Mo steel. Both procedures aimed to refine and temper the heat-affected zone (HAZ). The PWHT resulted in the greatest decrease in hardness and also reduced hardness variability throughout the HAZ. Bhaduri et al. [26] investigated repair welding methods for Cr–Mo steels, using 2.25Cr–1Mo and 9Cr–1Mo materials.

Our Monash University research group [27] has produced an analytical solution which was used to support the use of TBW in repair of damaged structures. A relationship was presented between the depth of penetration as an output and both the traverse speed and the arc length as inputs. We have also shown that while the metallurgical characteristics of TBW may be as good as PWHT welds, the residual stresses are virtually the same for TBW welds as for welds that are NOT heat treated. This is discussed below.

The TBW technique has been adopted by different codes and standards such as ASME Boiler and pressure vessel code, Section XI. However, with the enormous number of studies, some issues need to be taken into account when applying these techniques. A special attention should be given to the toe area in both the half-bead and the TBW techniques. The toe region of a temper bead weldment can have higher hardness because this region does not receive as many thermal cycles as the other regions of the heat affected zones. Therefore, one of the major limitations that needs to be taken into account when performing TBW is toe cracking.

Toe cracking is caused by the high-strength weld metal having a higher yield point and tensile strength than the parent materials. When the weld area shrinks on cooling from the welding temperature cracking occurs in the heat-affected zone (HAZ) of the steel because the yield and strength levels of the HAZ are lower than those of the weld metal. The toe region is highly susceptible to fatigue cracking due to the presence of weld defects, stress concentration due to toe geometry and adverse metallurgical conditions such as tensile residual stresses and coarse HAZ microstructure. Moreover, the toe region experiences high dilution and thermal stresses depending upon the type of welding process and procedures adopted during the repair [28].

One method of avoiding toe cracking is to apply a final temper bead weld to a level above the surface being repaired without contacting the base material but close enough to the edge of the underlying weld bead to ensure tempering of the base material HAZ [3]. Ibarra [29] also proposed this solution by ensuring that the toe of the weld to the base metal is not the last pass and the final temper bead pass should be ground off. An alternative solution to the ones presented by the previous studies [3,29] is the use of run-off plates which is suggested by [30]. Run-off plates may be tack welded in place at the inside surface of the repair cavity as shown in Fig. 3. Another solution to this problem is to use a low strength weld metal and increase the fillet size to meet the weld joint strength requirements.

### 2.3. Cold repair

Cold repair is the repair process which eliminates the need of preheat or PWHT hence time saving in a shutdown repair can be significant. Cold repair was used early in Russia [22,31–33] then it was developed by the CEGB in the UK to be used with CrMoV steels by employing the SAW process through the use of nickel-based electrodes which does not require a specialized welding procedure due to its resistance to hydrogen [5]. Typically, in this technique a stringer bead is deposited with 50% overlap on the preceding weld bead using 2.5 mm SAW electrode. The second layer is deposited with 4 mm electrodes using stringer beads and 50% overlap. Then, the excavation is filled with 4 mm electrodes normally by maximum weave width of 3 times the core wire diameter [34].

This procedure is designed to improve the as-welded HAZ toughness satisfactorily, so that reheat cracking does not occur during start-up, when residual stresses at maximum. The small

**Fig. 3.** Schematic illustration of run-off plates.
electrode size and low heat input when using manual metal arc welding produce fine grained heat affected zone structures in ferritic base materials, eliminating the need for controlled deposition techniques or subsequent tempering or refinement [35].

Recently, Mitchell [36] reported the use of nickel-based wire using FCAW for cold repair. It was used for CrMoV and 2.25Cr–1M components and predicted that the repair applications for cored wires in the power industry will grow significantly and the use of cored wires will provide clear benefits in terms of cost and time [34].

The anisotropic nature of the structure of the nickel-based weld metal complicates the detection of ultrasonic devices of subsurface defects. Also, the difference in the thermal expansion between weld and base metals may lead to cracking and failures. Therefore, this technique is recommended only for repairs of hardenable ferritic components in tightly scheduled plant shutdowns [35]. TBW technique is preferred than cold repairs using nickel-based wires when welding dissimilar materials welds because the later are prone to fatigue cracking during plant cycling [31,32].

3. TBW and residual stresses

In recent research from our group, the neutron diffraction technique was used to investigate the residual stress distributions in carbon steel components with weld repairs [37,38]. Two full penetration weld repairs were made using (a) the stringer bead and (b) the TBW techniques in 25 mm thick plate as shown on Fig. 4.

![Fig. 4. Schematics illustration of (a) preparation for full penetration repairs using (b) Sample I (SW: Stringer Bead Weld) and (c) Sample II (Temper Bead Welded) techniques. The red-dotted line represents the line scans for neutron diffraction (ND) measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).](image)

The welds were not post weld heat treated. The focus of the measurements is on the values of the sub-surface and through-thickness residual stress near the middle and the toe of the weld.

Comparison of the experimental results with the estimates in BS 7910 [39] and R6 [40] (Figs. 5 and 6) show that these codes underestimate the longitudinal surface stress within the weld and HAZ. The transverse surface stresses are by contrast overestimated by both codes. High longitudinal residual stress values have been found in all our work in the longitudinal direction. These stresses normally exceed the uniaxial yield value of the parent and weld metal because of the tensile tri-axiality of the residual stress in the weldment.

The highest residual stresses in the transverse direction were found within the weld at approximately 40% for Sample I (Fig. 5b) and 60% for Sample II (Fig. 6b). At the surface, a stress distribution value below the yield was achieved in the longitudinal direction at the toe and the HAZ (Figs. 5a and 6a).

Fig. 6 shows comparisons of the through-thickness residual stress distributions at the weld centre line, x = 0 mm for TBW and stringer weld. The key issue from the perspective of this paper is that from the point of view of residual stress the temper bead weld appears not to better than the stringer bead weld. Thus we reach the conclusion that while TBW may improve the metallurgical structure compared to stringer bead, the residual stresses are not improved.

Note the error bars on the measurements themselves are shown in Fig. 5. The error that may be involved in relation to the exact nature of the welds being tested in this paper is a separate issue. However powerful commonalities are emerging from many measurements being accumulated by many researchers. Examples of these principles are:

- The residual stresses in the last bead to solidify are close to the yield condition (unless relieved by distortion of the sample). This means that this location demonstrates high values of tensile tri-axial residual stress and the measured uniaxial longitudinal stress tends to exceed the uniaxial yield stress.
- Transverse stresses are lower but the toe of the weld near the HAZ exhibits small scale stress variations due to effects of re-crystallisation and rotation of the stress tensor.
- Residual stresses drop dramatically on the application of post weld heat treatment.

The work in the Monash group has also sought to consider the errors in neutron diffraction and its comparison with theoretical procedures. These issues are considered in detail in Price et al. [41].

4. The use of automatic FCAW for TBW

Welding process can be considered as an important parameter when carrying an alternative technique for PWHT. It has consequences on the speed, quality, preciseness and the cost of repairs and therefore should be considered in this context. SMAW is one of the oldest and still most commonly employed process, which was first used between 1905 and 1910 [42]. Most of the reported practices and researches of half-bead and TBW techniques used SMAW process. However, there are some disadvantages such as the low deposition rate. Furthermore, since the SMAW is a manual process and a great variation in weldment properties may occur. The gas tungsten arc welding (GTAW) process was used also in carrying some of the repairs that employs half-bead or temper bead techniques. Viswanathan and Gandy [18] reported that GTAW weld repairs to the base metal were generally to outperform SMAW welds. This might be as a result of the lower and better control heat input in GTAW process.
Recently other processes such as gas metal arc welding (GMAW), and flux cored arc welding (FCAW) have been used and are showing promising results. The use of both processes has become well established recently in fabrication and repairs due to cost and time effectiveness and reliability [34,36,43,44]. One of the main advantages of GMAW and FCAW processes is the high deposition rate which result in a higher welding speed hence saving time and lowering the cost of repair. Another advantage of the GMAW and FCAW is the possibility of automation of these processes that reduce the need for skilled welder and resulting in better control of bead parameters which is vital in carrying the TBW technique [45].

Among the investigations carried out by our group was manipulating the traveling speed, studying overlap between welding beads and changing the shielding gas.

With respect to changing traveling speeds different heat inputs were studied, i.e. slow traveling speed results in high heat input and vice versa. Aloraier et al. [46] have varied the traveling speed of a FCAW process in order to obtain different heat inputs between the layers. The fast traveling speed was used to attain small HAZ and the slow traveling speed was then used to temper and refine the HAZ of the previous layer. In automated welding processes, the controlling of the traveling speed is easy; however in manual welding processes the control of the traveling speed becomes very critical since human error may be introduced.

In any tempering technique, the overlap between the adjacent beads in each layer must be controlled and is considered a vital parameter for TBW. Most researchers have used 50% bead overlap between the beads because of its practicality. This was consistent that the optimum percentage of bead overlap between the beads in the TBW technique should be within a range between 50% and 70% as reported by Aloraier et al. [47]. Aloraier [48] have measured the residual stresses using the RS-200 hole drilling method to study the effect of the percentage of bead overlap on residual stresses. It was shown that the 50% bead overlap gave the best results in terms of compressive residual stresses.

Another parameter that needs to be considered is the shielding gas [49]. A study has been carried out by our group [50] on the effect of welding process parameters on the welding geometry on steel components. The primary function of the shielding gas is to protect the molten metal from atmospheric nitrogen and oxygen as the weld pool is being formed [51]. In addition, the shielding gas plays an important role in effecting the electrical characteristics of the arc. A sample of the results obtained is as follows.
The height of the weld bead reaches its maximum value at 25 volts for both gases tested (CO₂ and argon).

In the range of 23–25 volts, the size of the HAZ increased when CO₂ was used, but it decreased when argon was used.

5. Finite element modeling

Computer simulation using finite element (FE) modeling will enhance the understanding of TBW. Researchers have used different FE software to model different welding processes. Many authors have utilized the commercial finite elements code ABAQUS, enhanced with user subroutines, to model weld simulation with great success [52–59]. The finite element code ANSYS was used by several authors [60–64] while others [65–71], have utilized SYSWELD to perform these weld simulations. Although there are numbers of different commercial software shells, researchers did not model the microstructure resulting from the TBW technique. This might be due to the lack of software which are dedicated for welding and particularly which deals with microstructure modeling. However, a package similar to SYSWELD can be dedicated for welding and particularly which deals with microstructure simulation. Our recent work has focused on the theoretical limitations of both neutron measurement and finite element modeling in describing residual stress [41].

Recent focus on FE modeling was obvious by the special issue of this Journal which was devoted to round robin activities covering residual stress measurement and residual stress prediction. These activities were aimed to develop experimental and numerical techniques and standards for the reliable characterization of residual stresses in structural welds. However, important areas such as the microstructural modeling still in need to be explored.

In recently reported work from our group [41] the use of a neutron beam as a non-destructive method of measuring residual stress due to welding has been explored and compared to a model of the same situation, calculated using the software package SYSWELD.

The work demonstrates that the results are in general conformity. In detail, however, there are differences. Some of these differences are presumably due to familiar difficulties with theoretical models of complex non-linear material properties and welding parameters. These differences have been minimized by experimenting with varying some of the material properties a little until the results were in best agreement.

However, when the cases are compared in detail, new issues emerge. These other issues relate to fundamental difficulties in comparing FE results with the neutron beam (or any other) measurement method. Three issues, which were identified in the paper, were as follows:

- The difference in the shape and size of the gauge or estimation volumes between the experimental and theoretical techniques.
- The difference in the means of averaging or integrating results within these gauge volumes to produce a single output.
- Experimental diffraction technique normally measure only direct strain (no shear strains can be measured). When comparing with FEA, these direct strains have to be converted into elements of a six element tensor. To do this fully requires three to six measurements at each point. This is often physically difficult, time consuming and expensive which means that approximate assumptions are often made about the principal directions of the tensor.

6. Conclusions

A review of studies on alternative techniques to repair welding using post weld heat treated (PWHT) welding was carried out to assess the advantages, limitation and considerations. The summary of the review can be outlined in the following conclusions.

- The main alternative techniques to PWHT for large welds are termed half-bead, temper bead welding (TBW) and cold repairs. They are said in the literature to be effective in carrying out weld repairs but work continues to be developed which will refine that choice.
- Repairs without PWHT are not recommended to be used in highly stressed areas or in components which are susceptible to stress corrosion cracking.
- The temper bead welding technique is recommended in when compared to the other two techniques not requiring heat treatment.
- New work by our group at Monash University [37] shows that residual stresses are not significantly affected by the implementation of TBW when compared to stringer bead welding. The advantage in TBW is metallurgical resulting in higher ductility and not in reducing residual stress.
- We report our recent work on the use of automatic Gas Metal Arc Welding (GMAW) and flux cored arc welding (FCAW) [46–50].
- The understanding of TBW is being improved by computer simulation using finite element modeling. Our recent work has focused on the parameters determining the residual stress.

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