ELSEVIER

International Journal of Pressure Vessels and Piping 78 (2001) 813–818

INTERNATIONAL JOURNAL OF
Pressure Vessels
and Piping

www.elsevier.com/locate/ijpvp

Review of weld repair procedures for low alloy steels designed to minimise the risk of future cracking

T. Lant[a], D.L. Robinson[a,*], B. Spafford[b], J. Storesund[c]

[a]*ERA Technology Limited, Cleeve Road, Leatherhead, Surrey KT22 7SA, UK*
[b]*CONOCO Humber Refinery, South Killingholme, South Humberside DN40 3DW, UK*
[c]*DNV AB Tecnical Consulting, Stockholm, Sweden*

Abstract

Weld repairs to aged and degenerated materials are prone to early failure on return to service unless strict preparation and controlled welding procedures are followed. This paper reviews and appraises the practical weld repair procedures, which have been developed or are currently being considered, for low alloy ferritic steels used within the Power, Petrochemical and Refinery Industries. The half-bead and temper-bead approaches both manual and automatic are considered in detail. The alternative use of high nickel weld fills for repair welding of low alloy ferritic base materials are also considered. Some conclusions about the expected life of repair welds are drawn from recently sponsored projects.

Keywords: Weld repair; Temper bead; Half bead; Ferritic; Power; Petrochemical; Refinery

1. Introduction

Systems operating at high temperature and high pressure in Power, Petrochemical and Refinery plant are subject to innumerable degradation mechanisms. As these systems age and degenerate, components may fail in service or be declared unfit for further service on the basis of inspection and remaining life assessments. Decisions on whether to repair or replace these components inevitably involve weld repair of aged and degenerated materials or the welding of virgin components to aged and degenerated materials. These weld repairs and closure welds have to be made in-situ, with all the site work complications of access, pre-heat and post-weld treatment and inspection. Furthermore, the subsequent service life of these repair and closure welds has an important bearing on the decision processes to repair or replace any aged component.

This paper reviews and appraises weld repair procedures for low alloy ferritic steels, which have been developed, or are currently being considered, within the Power, Petrochemical and Refinery industries. This work, which reviews key developments published in the literature and includes a brief survey of current industrial applications, was undertaken as part of the EC sponsored High Temperature Industry Forum (EC BRRT-CT99-5086).

2. Repair weld considerations

2.1. Material condition

When an aged or degenerated component fails in service, or is replaced through the development of a life-limiting defect, it is important to establish the cause of the failure or defect development before a weld repair is undertaken [1]. The material preparation, prior to welding, must remove weld heat affected, creep damaged or otherwise cracked and 'defective' material. Residual cracks and defects in the repair weld region may propagate readily during the welding process or immediately following the welding process [2,3]. When faced with embrittled material the choice of weld preparation and repair is even more difficult. The critical defect size in embrittled parent material, or a heat affected zone subject to high residual weld stresses, may well be smaller than the minimum size defect detectable by standard non-destructive testing methods. To secure a sound weld repair, it may be necessary to heat treat the repair location in an attempt to restore original material properties. The restoration of ductility is of particular importance in any repair procedure.

* Corresponding author. Tel.: +44-1372-367-000; fax: +44-1372-367-070.

E-mail address: david.robinson@era.co.uk (D.L. Robinson).

0308-0161/02/$ - see front matter
PII: S0308-0161(01)00094-1

2.2. Weld material

Choice of filler metal must take account of the composition and condition of the parent material to be welded. Clearly electrode compositions that match the original parent will usually give the highest success rate. Nevertheless the original parent material properties may have changed so drastically that there could well be mismatches in strength and ductility. Low carbon electrodes ($C < 0.03\%$) for the controlled deposition weld repair of low alloy ferritic steels offer improved weld toughness and crack resistance. The chance of success in the repair of complicated joints is enhanced. Moreover, repaired and post-weld heat-treated welds using these electrodes afford useful creep rupture properties, despite their low carbon content [4].

For many of the hardenable ferritic steels there is a choice between employing a matching ferritic electrode or dissimilar nickel based electrode. The choice of the matching ferritic electrode will inevitably involve the use of weld region pre-heat to reduce potential hydrogen damage and may also involve the use of post-weld heat treatment to reduce residual weld stresses to operationally acceptable levels. The 'half-bead' and 'temper-bead' weld procedures described in subsequent sections of this paper can avoid the requirement for post-weld heat treatment. The techniques require careful planning consideration, welder training and certification prior to use. The choice of ferritic filler material, and the weld procedures involved, will often give a satisfactory weld with a long potential service life. It is perhaps unfortunate that the procedures involved are time consuming, costly and not best suited to emergency or unforeseen weld repairs to critical items in tightly scheduled plant shutdowns.

An example of a boiler steam drum repair illustrates the complexities encountered and the time necessary to effect a site weld repair [5]. The Ducol W30 steam drum in question had a lamellar tear defect in the steam drum shell adjacent to a set-on downcomer nozzle. Formed during the original welding process this tear had gradually grown in service to an unacceptable size. Various defect excavation and weld repair possibilities were rejected in favour of replacing the set-on nozzle with a set-through nozzle. The use of a larger diameter nozzle ensured complete removal of the tear defect. A post-weld heat treatment was included in the repair procedure for two reasons. The first of these was to avoid the development of bending stresses in the aged and potentially embrittled Ducol W30 alloy. The second was that the critical defect size in aged Ducol W30 could be so small that propagation in a residual weld stress field might be expected. To achieve a cylindrical heat treatment band around the drum circumference it was necessary to introduce a temporary support and remove a permanent support sling from within the heat treatment zone. These pre-repair procedures added considerably to the repair time and cost.

For emergency or unforeseen weld repairs to hardenable ferritic components (hardenable ferritic steel being defined as one which will give high strength low ductility heat affected zones in weldments without PWHT and/or age harden in high temperature service) in tightly scheduled plant shutdowns it is often preferable to use a nickel based filler material. The nickel based filler welds have low residual stresses, inherent resistance to hydrogen cracking, superior fracture toughness and the weld metal deposition techniques required are not specialised. No pre- or post-weld heat treatment is required. The timesaving for an emergency repair usually outweighs the disadvantages of unreliable weld inspection and the propensity dissimilar junctions have to failure by thermal fatigue. If a nickel based weld repair is adopted in an emergency situation it creates the time to plan a replacement ferritic weld for execution in a subsequent shutdown.

2.3. Weld pre-heat

Pre-heating of a ferritic weld repair region in the range 150–200°C is employed to ensure that the weld deposit cools at a sufficiently slow rate to avoid hydrogen induced cold cracking. In thin section repairs the heat input from the welding process and inter-pass temperature may be high enough for pre-heating to be omitted. As the repair section increases and heat conduction from the weld deposit increases, the application of weld pre-heat assumes greater importance. With the application of pre-heat, the control of the inter-pass temperature to a maximum of 300°C is important to restrict grain growth and precipitate coarsening which may reduce the creep strength of the repair region [6].

2.4. Post-weld heat treatment

The coarse grained, high hardness region of a weld heat affected zone in a ferritic steel is susceptible to hydrogen induced cold cracking as a weld cools and subsequently to reheat or stress relief cracking when the weld is placed in high temperature service. Post-weld heat treatment is used immediately after welding to temper high hardness regions in the weld heat affected zone, therefore reducing residual weld stresses and also to remove hydrogen from the weld metal and heat affected zone of the weld.

The considerations whether or not to apply post-weld heat treatment to a repair weld may be precluded by poor access or time constraints. Defects in high temperature and pressure systems may be revealed during inspection work late in a scheduled shutdown. If such late discovered defects are unacceptable for further operation there is no choice but to repair. If a time consuming post-weld heat treatment procedure has to be included in this weld repair a shutdown overrun and consequential penalties of business interruption may be incurred. Clearly any weld procedure, which can avoid the requirement to post-weld heat treat, has significant cost and time advantages for the plant maintenance engineer.

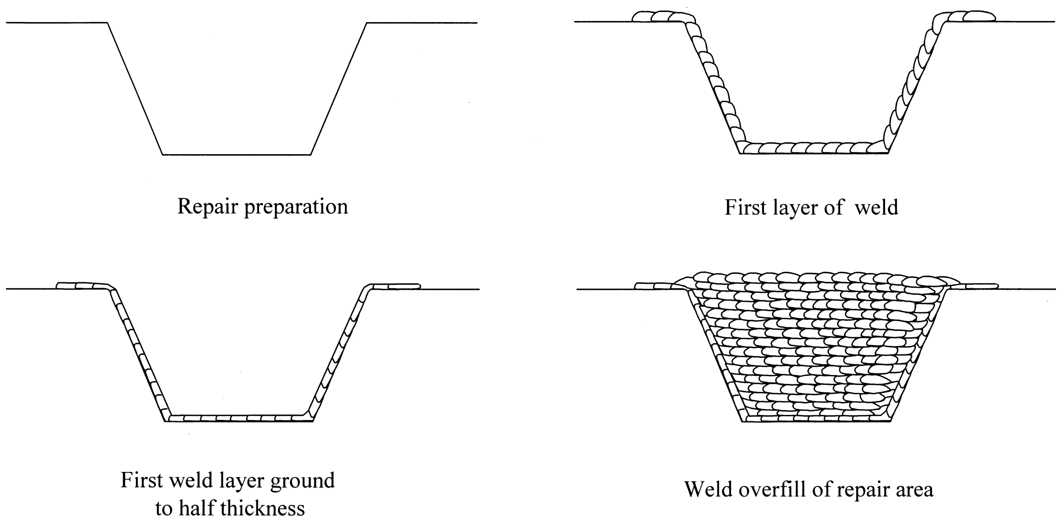

Fig. 1. Half bead welding.

2.5. Weld technique

Weld repair techniques are usually geared to meet the harsh time constraints of plant shutdowns. Any technique, which avoids time consuming procedures such as post-weld heat treatment, has significant time and cost saving advantages. Post-weld heat treatment of ferritic steel welds is employed to temper high hardness regions of the weld heat affected zone and reduce high residual weld stresses. Without post-weld heat treatment the residual weld stresses decay with time at operating temperature. Weld heat affected zones with coarse grain structures have low creep ductility and are highly susceptible to cracking during this period of stress relaxation. The principal role of weld repair techniques employed is to avoid the requirement of post-weld heat treatment by generating weld heat affected zones with fine grain structures. This objective can be achieved by minimising the as formed grain size in the heat affected zone, by minimising the heat input during the welding process, or by refining an initially coarse grained heat affected zone using the heat input of overlaid weld beads. Accepted weld repair procedures, designed to avoid post-weld heat treatment, incorporate both of these approaches.

2.6. Half-bead technique

The weld repair procedure referred to as the 'half-bead' technique employs a controlled deposition of the first layer of weld material as overlapped beads (Fig. 1). The first layer is deposited with a maximum electrode diameter of 3 mm, a minimum pre-heat temperature of 177°C and a maximum inter-pass temperature of 232°C. The top half of this initial layer is removed by careful grinding. The ground surface is overlaid with a subsequent pass of weld material using the same bead overlap welding technique, to ensure that tempering of the first layer heat affected zone is achieved. The second layer is deposited with a maximum electrode diameter of 4 mm again using overlapping beads. The procedure continues in this way until the required fill is achieved [7–10]. The final temper-bead layer should be proud of the surface repair region. There should be no contact between this layer and the base metal, but it should terminate as close as possible to the edge of the underlying first layer weld bead to temper the base material heat affected zone. The completed weld should be immediately heated from the pre-heat temperature to 260°C and held at this temperature for two hours to accelerate hydrogen diffusion from the weld. After cooling, the final temper-bead layer is ground flush with the repair area surface and the repair inspected using magnetic particle or liquid penetrant techniques. Radiography is advised if the weld repairs are deep, or in pressure vessels subject to this requirement in construction codes.

A major shortcoming of this technique for tempering the coarse grained heat affected zone is the difficulty in judging the half depth removal of the first deposited weld layer. The effectiveness of the tempering produced by the subsequent weld layer is reduced if too little or too much of the buttering layer is removed.

2.7. Temper-bead technique

The 'temper-bead' technique uses a similar approach to the half-bead method. The essential differences between the methods are the absence of interlayer grinding and the progressive increase in bead size and hence heat input in the temper-bead technique [10–15].

Using manual metal arc welding, the first weld layer is carefully deposited using 2.4 mm diameter electrodes. The objective is secure minimum heat input and to achieve even sized beads with between 40 and 60% overlaps. The deposit thickness should be uniform with smooth topside and underside profiles (Fig. 2). Typically in the first deposited layer a

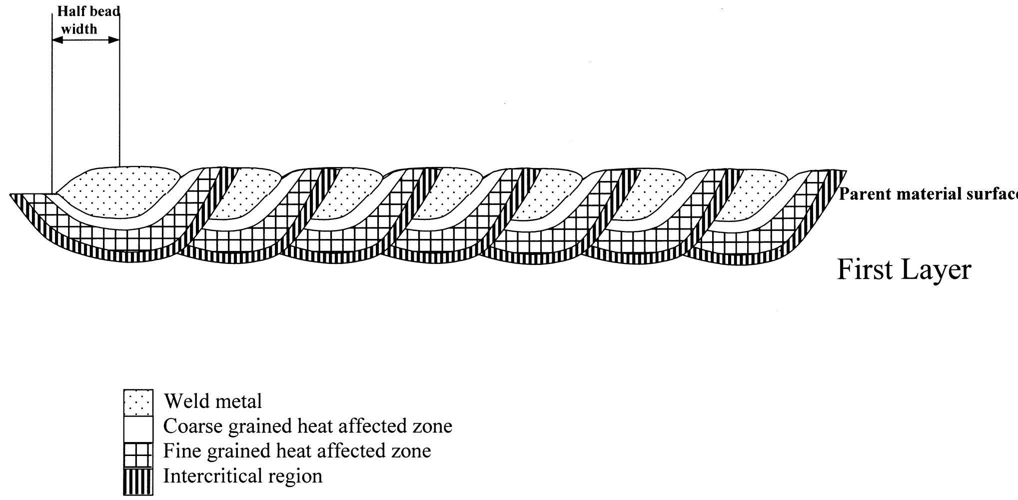

Fig. 2. Temper bead welding.

50% overlap in the weld beads results in 80% refinement of the coarse grained heat affected zone [6]. A second layer of weld material comprising even sized weld beads with between 40 and 60% overlap is deposited using a slightly larger, 3.2 mm diameter, electrode (Fig. 3). Again the deposit thickness should be uniform with smooth topside and underside profiles. The use of the larger electrode and higher arc energy ensures good penetration of the first layer to maximise the refinement of the coarse-grained heat affected zone in the underlying parent metal. Furthermore, the coarse-grained heat affected zone generated by the second weld layer will be contained essentially within the first layer of weld metal. Further weld layers temper the grain refined heat affected zones of the under-layers. The repair region should be overfilled one weld layer proud of the surrounding surface. There should be no contact between this layer and the base metal but it should terminate as close as possible to the edge of the underlying first layer weld bead to refine and temper the base material heat affected zone. This temper-bead layer is ultimately ground flush with the repair area surface. A further layer of weld metal should be deposited, again without overlapping the base metal at the weld edge, to temper the underlying weld heat affected zone. This additional layer of weld metal is also ground flush with the surrounding metal.

When the temper-bead technique is used to weld thick section, hardenable ferritic steels with ferritic consumables pre-heating and often post-heating is required to promote hydrogen diffusion from the weld to prevent hydrogen assisted cracking.

2.8. Automated welding

The degree of welder skill required for successful half- and temper-bead weld repairs is high. Consistent control of bead placement and heat input or electrode run out could

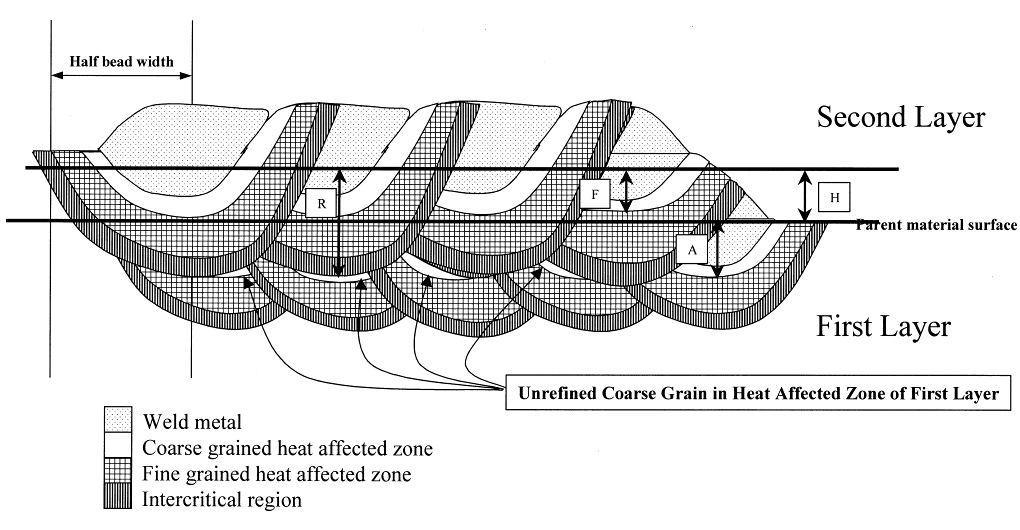

Fig. 3. Temper bead welding. Second layer boundary depth (F); first layer fusion boundary depth (A) + average layer height of first weld layer (H); second layer refining depth (R).

clearly be achieved at a higher rate with automated welding processes. Such automated systems have been developed for simple geometry weld repairs and where weld repairs had to be conducted remotely in the nuclear industry [16,17]. One of the techniques, known as the alternate temper-bead repair technique, used controlled deposition of six layers of buttering on the repair surface with heat input controlled within 10% of that used in the weld procedure qualification [16]. The technique provides heat affected zone refinement throughout the buttered layer and confers toughness characteristics, which match or exceed that of the base metal. Subsequent controlled weld fill of the repair area provides heat affected zone tempering.

2.9. Nickel based welding

Pre- and post-weld heat treatment of ferritic steel welds can be avoided by use of nickel based weld fill materials [18–20]. The high nickel alloy welds are essentially free from hydrogen assisted cracking. They have high fracture toughness and in the as welded condition the residual weld stresses are low. The small electrode size and low heat input involved in manual metal arc welding produce fine grained heat affected zone structures in ferritic base materials so there is no need for controlled deposition techniques or for subsequent tempering or refinement. Welder skill requirements are greatly reduced and time saving in a shutdown repair can be significant. Despite these comments it has been shown that the temper-bead technique can be applied with advantage for the formation of dissimilar metal welds [21].

It is unfortunate that the dissimilar metal junctions or transition joints between high nickel welds and ferritic base materials are prone to fatigue cracking in locations subject to cyclic thermal fatigue loading [22]. It is for this reason that such repairs can only be considered as temporary in nature. Nevertheless, in a time short shutdown they can solve immediate repair requirements and allow time for a ferritic weld fill repair to be planned and implemented during a following plant shutdown. Business interruption losses can be minimised.

One other disadvantage of the high nickel, weld repair technique is that post-weld inspection is more difficult than for ferritic welds. Ultrasonic techniques used for the detection of subsurface defects are rendered less reliable by the anisotropic structure of the nickel based weld metal.

2.10. Repair weld life

The efforts made to improve and define weld repair procedures for degraded and defective high-energy system components over the last two decades have been extensive. Work has been carried out evaluating the effect of creep strength mismatch of the various weldment components and its effect on weldment creep life [23,24]. This work indicates that the larger the creep strength mismatches between the different regions of the weldment the shorter the predicted life. Nevertheless, little is recorded concerning the subsequent service life of weld repairs effected by different techniques. When planning any weld repair it would be of considerable advantage to know whether the technique ultimately chosen would confer the ‘best’ subsequent service life. Indeed the whole concept of repair might be rejected in favour of component replacement if the latter option offered a most cost effective, long-term solution.

In recent years many sponsored projects have been established to provide guidance with respect to the expected life of weld repairs [14,25–28]. The effective conclusions from this work were that service degraded piping from high energy systems could be effectively repaired with or without post-weld heat treatment and that life extensions of several decades could be expected at original design conditions. In terms of life extension there was little to distinguish between repair welds made using shielded metal arc temper-bead welding without post-weld heat treatment, shielded metal arc welding with post-weld heat treatment and gas tungsten arc welding with post-weld heat treatment. The general provision was made that all creep cavitation must be excavated from the repair region to achieve these life extensions. These investigations did not study the effect of hydrogen service on the use or life of repair welds made without post-weld heat treatment.

The susceptibility of dissimilar metal junctions to thermal fatigue cracking has already been discussed.

2.11. Weld repair practices and outcome in Europe

Results of a two industrial surveys conducted during the EC sponsored HTI Forum indicated that few owners and operators of high energy systems applied the temper-bead and nickel based weld fill techniques and then only if time constraints prevented completion of fully code compliant weld repairs. In general terms the repaired welds had chequered success with many lasting less than 10 000 h until failure recurred [29].

3. Conclusions

This review focused on developments in weld repair procedures designed to produce high quality, long life weld repairs in aged and degenerated ferritic steels. The outcome of the review can be summarised in the following conclusions.

Service degraded piping from high energy systems can be effectively repaired with or without post-weld heat treatment. To be successful and to offer an economic return in terms of operational life, weld repairs to aged, degenerate ferritic materials require careful planning and control. A full appraisal of the metallurgical condition of the component or components to be welded is a prime consideration in planning any weld repair. The choice of weld filler material, welding technique and requirements for pre-heat and post-weld heat treatment are significantly influenced by the metallurgical condition, location and section thickness of the component to be repaired. Time constraints during plant shutdowns have a significant bearing on the choice of weld technique.

The half-bead and temper-bead weld repair techniques offer considerable time savings in the repair of aged components by avoiding sometimes difficult and prolonged post-weld heat treatment procedures. Nevertheless these repair techniques require careful application control. Welder skill and training in these techniques is vital for success. Automated procedures offer potential for greater consistency in bead overlap control and thus higher quality in temper-bead weld repairs.

Nickel based weld fill repairs offer a number of short term advantages but the life of the weld repairs may be restricted.

The review of weld repair techniques currently employed by plant owners and operators indicates that they are limited to coded repair applications. Codification of temper-bead weld repair techniques for application in Power, Petrochemical and Refinery environments would offer economic advantages to the industries.

Acknowledgements

The authors of this paper would like to thank Ing C. Aiello (AGIP Petroli), Dr R. Ainsworth (British Energy), Ing S. Concari (ENEL) Dr U. Gampe (Siempelkamp), Mr M. Richez (Elf Antar) and Mr P. Segle (DNV) for their useful contributions. These were given during the running of the CEC sponsored HTI Forum in which all parties were involved.

References

[1] Doty WD. Challenges and solutions in repair welding of ferritic materials. WRC Bull 1996;412:1–2.

[2] Viswanthan R, Gandy W. Performance of repair welds on aged Cr–Mo piping girth welds. Proceedings of International Conference on Integrity of High Temperature Welds, Nottingham, UK, Nov 3–4. PEP, 1998. 15–40, ISBN 1860581498.

[3] Viswanathan R. Weld repair of aged piping — a literature review. Proceedings of International Conference on Welding and Repair Technology for Power Plants EPRI TR-107719, 9004-02, 3887-01, 1997. p. 164–86.

[4] Lundin CD, Liu P, Zhou G, Khan KK. Efficacy of low carbon $1\frac{1}{4}$Cr–$\frac{1}{2}$Mo weld metal for repair welding of elevated temperature service exposed Cr–Mo components. WRC Bull 1999;439:3–10.

[5] Allen DJ. Weld repair of steam drum downcomer nozzle cracking in coal-fired power plant. Weld Metal Fabr 1995;63(6):225–8.

[6] Allen DJ, Kelly TW. Cold weld repair — development and application. Second International EPRI Conference and Vendor Exposition, Daytona Beach Florida, May 21–24, 1996.

[7] United States National Board Inspection Code. National Board of Boiler and Pressure Vessel Inspectors, Columbus, Ohio, 1989 and 1995.

[8] Ibarra SJ. Weld repairs without PWHT in the petroleum industry. WRC Bull 1996;412:12–5.

[9] ASME Boiler and pressure vessel code. Section XI Rules for service inspection of nuclear power plant component, Paragraph IWA-4513. Repair welding procedures A-SMA, New York: ASME, 1992.

[10] Gandy DS, Findlan SJ, Viswanathan R. Temper-bead welding of P-Nos 5 and 5. Proceedings of International Conference on Integrity of High Temperature Welds, Nottingham, UK, Nov 3–4. PEP, 1998. p. 111–24, ISBN 1860581498.

[11] Alberry PJ, Myers J, Chew B. An improved welding technique for HAZ refinement. Weld Metal Fabr 1976;45(9):549–53.

[12] ASME Boiler and pressure vessel code, Section XI Rules for service inspection of nuclear power plant components, Paragraph IWA-4633.1, Alternative repair welding methods — shielded metal arc welding, ASME, 1995.

[13] Friedman LM. EWI/TWI controlled deposition repair welding procedure for $1\frac{1}{4}$Cr–$\frac{1}{2}$Mo and $2\frac{1}{4}$Cr–1Mo steels. WRC Bull 1996; 412:27–34.

[14] Lundin CD. Overview of results from PVRC programs on half-bead/ temper-bead/controlled deposition techniques for improvement of fabrication and service performance of Cr–Mo steels. WRC Bull 1996;412:16–26.

[15] Kim YJ, Prince JW. Temper-bead weld heat affected zone properties in A517-70 steel. Trans ASME J Engng Mater Technol 1987;109:157–63.

[16] Repair welding of heavy section steel components in LWRs. EPRI Report NP-3614, Babcock and Wilcox, vols. 1 and 2, 1984.

[17] Gandy GW, Findlan SJ, Childs WJ. Repair welding of SA-508 class 2 steel using 3 layer temper-bead approach. Proceedings of Conference on Fatigue Fracture and Risk. San Diego: ASME, 1991. p. 117–22.

[18] Brett SJ. Methodology for the use of weld repairs without post-weld heat treatment on creep resisting steels. BALTICA III, June 6–8, Helsinki, Finland, ISBN 9513845427, vol. 2, 1995. p. 363–78.

[19] Zemzin VN, Bagramova TI, Boyeva AV, Titiner ZK, Dimetrieva GK, Biryukov VM. Using high nickel electrodes for repair welding of defects in cast casting componets for steam turbines. Leningrad: Leningrad Organisation of the Znanie Association, 1974. p. 24.

[20] Schron RZ, Zemzin VN, Ehrenburg BS, Bukin YaA, Titiner ZK. An analysis of the damage to cast turbine casing components and the effectiveness of repair welds to them. Teploenergetica 1987;7:16.

[21] Higuchi M, Umemoto T, Matsusita A, Shiraiwa T. Development of temper-bead technique applied to dissimilar welded joints of nuclear pressure vessels. WRC Bull 1996;412:77–86.

[22] Brett SJ. The long term creep rupture of nickel based cold welds in Cr–Mo–V components, Proceedings Conference on Refurbishment and Life Extension of Steam Plant, London, Oct 14–15. ImechE, 1987. p. 253–60, Paper C288/87, ISBN 0852986319.

[23] Storesund J. Repair welding of creep exposed welds in high temperature plant. Proceedings of the Third International Symposium on Risk, Economy and Safety, Failure Minimisation and Analysis, Planesberg, South Africa, July 6–10, 1998.

[24] Samuelsson P, Segle, Storesund J. Life assessment of repaired welds in high temperature applications. International Conference on Welding and Repair Technology for Fossil Power Plants, Williamsburg Virginia, March 23–25, 1994.

[25] Viswanathan R, Gandy DW. Performance of repair welds on aged Cr–Mo piping girth welds. Proceedings of International Conference on Integrity of High Temperature Welds. PEP Ltd, 1998. p. 15–40, ISBN 1860581498.

[26] Gandy DW, Viswanathan R, Findlan SJ. Performance of weld repairs on service-aged $2\frac{1}{4}$Cr–1Mo girth weldments utilizing conventional post-weld heat treatment and temper-bead repair techniques. WRC Bull 1996;412:43–59.

[27] State of the art weld repair technology for high temperature and pressure parts. Vol. 1 Life assessment, vol. 2 Repair guidelines, vol. 3 Utility survey, Vendor survey and bibliography, vol. 4 Weld repair of 2 1/4Cr − 1Mo pipe header girth welds, Report 103592-V1-V4, EPRI, Palo Alto, CA, 1997.

[28] Croker ABL, Findlay MR, Law M. Weld repair of creep damaged steels. IIW Asian Pacific welding congress (productivity beyond Proceedings 58th NZIW Annual Conference and WTIA 43rd National Welding Congress, Auckland, NZ, Feb 4–9, vol. 2 1996. p. 635–45, ISBN 0908694334.

[29] Lant T. High temperature industry forum final report, EC BRRT-CT99-5086, June 2000.