Some Characteristics of Weld Repair for Creep Applications

A Klenk [+], S Issler **, I A Shibli *** and J A Williams *

+ MPA Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany.

* Consultant to European Technology Development., Ltd., Pine Bank, West Leake Road, East Leake, Loughborough, Leics. LE12 6LJ, UK.

** Previously MPA Stuttgart, Pfaffenwaldring 32, 70569 Stuttgart, Germany. Now at Daimler Chrysler AG, Mercedes Benz Technology Centre, D-71059 Sindelfingen, Germany.

*** European Technology Development Ltd., Ashtead, Surrey, KT21 2HR, UK.

Dr Ahmed Shibli is the Director of the UK based engineering and service company European Technology Development. He has over twenty five years of experience of working in the area of power plant R&D and life assessment/extension issues, with particular expertise in materials development and defect assessment under creep and fatigue conditions. His previous experience includes working for Mitsui Babcock Energy, ERA Technology and British Steel. Other experience includes working as a consultant/expert for the European Commission and UK and European power utilities. ashibli@etd1.co.uk

Eur Ing Dr Adrian Williams has been an independent consultant since 1992, acting for ETD and other companies. In addition, he is an Industrial Fellow at the School of Mechanical, Materials, Manufacturing Engineering and Management at the University of Nottingham, UK. He has 27 years experience in the UK power industry, up to 1992, in the fields of high temperature materials, including similar and dissimilar weld performance, component testing, life assessment and weld repair.
jaw@globalnet.co.uk

Abstract.

With the increasing demand for electricity, there is a continuing need for the operation of existing plant and the design/construction of new plant. For existing plant, the actual life of homogeneous components will be in excess of the design life and there are advantages if the plant life can be safely extended beyond the original design life. However, plant operation can lead to damage and cracking in homogeneous materials and, especially, in welds due to time-dependent processes such as creep, fatigue and oxidation. Thus, there is a need for weld repair on plant components.
The objectives and requirements for weld repair, and typical procedures for both "conventional" repair and for the more advanced "cold weld" repairs, are outlined. Finally, the performance of repair welds is considered from the viewpoint of operating plant results, and, where available, multiaxial vessel testing and uniaxial cross weld testing.

Key Words: Weld repair, Creep, Materials data, failure, power plant, life extension.

1. Introduction

An increasing demand for power, and for fluid and gaseous fuels and bi-products, has led to a requirement for increased generating capacity and other high temperature plant. This can be met by the extension of existing plant life combined with new construction. Thus, there is an increasing need for the appraisal and continued maintenance of high temperature plant as it ages, [1]. This paper is focussed on power industry applications, see [2, 3] for examples, but similar considerations will apply to other industries.

High temperature plant will be subject to creep and, dependent on the operating regime and economic arguments, some stress and temperature cycling. Certain components will be at more risk than others, due to their basic mode of operation and failure, and various assessment procedures have been developed, for example, [4, 5]. Any component assessment will lead to a need for a decision. These various options may be:-.

- do nothing,
- re-inspect at defined intervals,
- repair,
- replace with identical or more advanced materials.

The decision will be taken on technical, component availability and economic grounds, based on total costs, including the need for continued plant operation, coupled with full consideration of all safety requirements. Thus, there is no one standard criterion but a full route to aid the selection process.

Repair technologies, in particular those involving a welding process, have become fully accepted over the years and the weld procedures used are identical to those for primary fabrication. However, as new technologies are developed, and older, more established procedures continue to be used, the lifetime of a weld repair becomes more important. In

particular, the life of the repair should be equal to, or greater than, the assessed component life, or sufficiently well known to allow the definition of realistic inspection periods.

In the USA, typical repair costs have been quoted as a factor of 4 times more expensive than an original weld, on a weld/unit length basis, with additional costs from the plant being unavailable, [6]. Thus, there is a need to "get it right first time", [6, 7, 8].

This paper considers the general characteristics of weld repairs, focussed on fusion welding, and the published technical developments and practical experience, thereby providing a background to the current status of weld repair.

2. Typical opportunities for weld repair

In practice, weld repair is used to renovate both homogeneous and welded components, making them fit for future safe service. Weld repair is, therefore, used to replace damaged material by sound metal, such that any new assessed life, and the actual life, is safely in excess of the expected operating time, or the time to the next full inspection.

2.1 Identification of weld repair needs

The need for repair will, unless complete failure or steam leakage has occurred, be precipitated by thorough inspection. Typical inspection methods include visual, magnetic particle, MPI, dye penetrant (DP), and ultrasonic inspection plus, in some special cases, radiography. This may be supplemented by replication techniques, to allow detection of microscopic damage.

The decision to repair will be controlled by factors such as:-

- Initial inspections, which, once defects have been detected, may be repeated using higher resolution methods.
- Defect mapping to define the size, extent and position of damage.
- Determination of the root cause of damage.
- Life assessment of the component.
- Appraisal of the time available for repair.
- Economic consideration based on the need to run, replacement availability and repair team availability and feasibility.
- Consideration and feasibility of carrying out a full design welding procedure including preheat and post weld heat treatment (PWHT).
- The determination of the correct welding procedure, taking into account local circumstances.
- The potential need for cold weld repair using Ni based or matching filler.
- Welding procedures produced, weld metal selected, weld repaired and fully inspected.
- Definition of the re-inspection period and, for an emergency repair, time for full repair set.
- Record information and appraise the possibility of a type fault involving other units.

The root cause, which leads to a need for weld repair, can be placed in one of a number of general classes as shown in Table 1, where approximate times for the detection and the need for repair are considered.

Root cause	Approximate time to weld repair *. (hours).
Primary fabrication	0 h
Fabrication defects detected by inspection	0 h
Fabrication defects not detected on initial inspection	First major inspection during operation. 30 - 40,000 h.
Defects or damage generated during service for whatever reason.	Generally in excess of 50,000 - 100,000 h.

*Assumes that steam leak has not occurred.

Table 1. Classes of damage that may require weld repair

Weld repair can have major use during primary fabrication where, typically, repair can be used for the restitution of casting defects in all forms in homogeneous bodies. In many of these cases, for example steam chests, the number of repairs frequently exceeds 200 and repairs are made both for cosmetic and defect removal purposes.

Similarly, defects can be generated during welding, [9]. Typical examples are lack of penetration and associated mechanical defects, hydrogen cracking, hot cracking and various forms of defect that are generated during stress relief. In general, these would be detected during inspection, following post weld heat treatment (PWHT), and the repair carried out if the defects are outside the code acceptance levels. Some defects may be missed by inspection following PWHT, due to their size and position, and may go into service. These can be detected at subsequent inspections if growth occurs or if improved inspection techniques are available.

Furthermore, operation in the creep regime can generate a time dependent accumulation of strain with associated creep damage. This damage can take the form of cavities or micro cracks with subsequent growth into cracks, which may require assessment and repair. Such creep damage can be associated with the parent material or the weldment. Strain accumulation, in the parent, is symptomatic of a general degradation of the whole component, which would suggest that failure was close, whereas premature cracking associated with welds, is generally repairable.

2.2 Typical components that may require repair

Studies of the operation of plant, and their temperature and stress variation, allow components, with an increased probability of damage accumulation and a subsequent need for assessment, to be defined, [10].

For the purposes of this review, a shortened list is shown in Table 2.

Component form	Root cause of damage
Tube work in boiler	Creep, oxidation, corrosion, fatigue
Headers	Creep, fatigue and creep/fatigue
Pipe work welds	Creep, additional loading
Support structures	Creep, fatigue, overload

Table 2. Typical component forms requiring damage assessment

For most purposes, the repair positions can be thought of as associated with one of three geometries; plate welds of some form; circumferential welds or, in some cases, seam welds in pipes; and cylinder:cylinder intersections such as complex header geometries and "T" junctions in pipe work.

3. Typical fusion weld procedures and positions

3.1 Conventional weld repair procedures

Historically, all weld procedures have been developed from an understanding of the effect of various parameters, such as preheat and post weld heat treatment conditions, on material behaviour, supported by a large databank of practical experience. All procedures will include advice or specification of the preheat and interpass temperature levels, which contribute to the control of hydrogen cracking. They will also specify the weld metal type, with an emphasis on matching the weld consumable to the parent material and, finally, the PWHT conditions, with the specification of the PWHT temperature and time required to reduce the residual stress and to temper the various HAZ and weld metal microstructures. These procedures were developed for primary weld fabrication and were very successful. Thus, conventional weld repair procedures are generally very similar to those previously developed for primary fabrication and would be modified only to take account of the specific circumstances of a weld repair.

A typical example, of generalised primary and conventional repair weld procedures are given below for 2.25Cr1Mo material welded with a chemically matching 2.25Cr1Mo weld metal and identifies the main parameters. These define the general welding conditions but not the form of the excavation to be used. The excavation geometry is obviously determined by the form of the damage, its position, extent etc, within the practical operating conditions. However, all of the damage must be removed before the repair is commenced. The extent to which this is achieved can depend on whether the weld is carried out under emergency conditions, where the unit is required to be rapidly back on load for subsequent full repair at a later stage, or whether the repair is expected to last for the required lifetime.

Typical excavation geometries are illustrated in Figure 1, from [11].

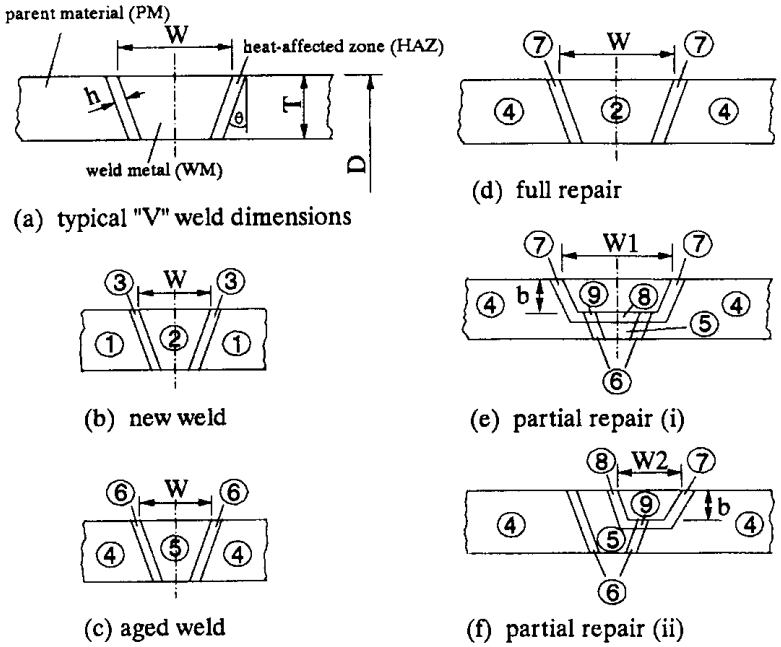


Figure 1. Model used in the studies of weld repair in pipework welds [31]
(W is the weld width, W1 is the repair weld width and the numbers 1 to 9 denote the different structures generated in the weld due to the welding and repair welding process).

The full repair weld, frw, is the most comprehensive. It would apply to welds showing damage or cracking which is associated with the HAZ, such as stress relief, extreme weld metal cracking and Type 4 cracking. In these cases through thickness damage is feasible and all the damage must be removed. In addition, complete, or near complete, removal of the weld metal may have a future cost benefit. It involves an excavation that is approximately 20mm wider than the original weld design, with the exception of the root of the weld. The excavation geometry, particularly with respect to the sidewall, must also be defined. This may be shallow or steep sided, giving ease of access or reduced weld metal volume respectively. There may also be a need for a backing bar, although this will depend on the excavation depth and the need to maintain fit up. Such repair excavation will be directly comparable with primary weld geometries but with a larger width. Note that the new heat affected zones, HAZ, will occur within the parent material.

Parameter	Condition	Comments
Excavation method	Grinding or arc air gouging	Dependent on size and local conditions. Note the need for preheat with arc air gouging.
Excavation size	Full:- 10 mm into the parent material either side of the weld. Depth into root area to allow the fit up to be maintained. Partial:- Sufficient to ensure complete removal of damage	 This may not be possible in some cases and then a width /damage state decision is necessary.
Consumable	Matching 2.25Cr1Mo, MMA	Low C variants have been used but this is not conventional at this time.
Hydrogen control	Control and baking of consumables	Maintain temperature for period on completion of welding for hydrogen effusion. Low hydrogen consumables
Preheat	200-250ºC	
Interpass	300 C	
Bead form	Stringer bead	No HAZ control buttering
PWHT	690-720ºC	1h per 25mm thickness, minimum 3h.
Inspection	MPI and ultrasonic	As National codes

Table 3. Generalised welding conditions for 2.25Cr1Mo steel

Partial repair welds, prw1 and prw2, are similar to the full penetration weld, the main differences being a reduction in the depth of the excavation and its extent across the weld surface. In practice, the excavation depth and position will be controlled by the damage in the weld i.e. the type of cracking, the damage state and its extent. For example, local weld metal cracking could lead to a need to remove only weld metal, whereas Type 4 cracking can influence both weld/parent interfaces. The excavation will be of the order of half thickness/depth at the most, for the partial repairs prw1 and prw2. The basic difference to the full weld repair is that the outer edge of at least one side of the partial repair weld, prw2, will directly influence service exposed weld metal.

3.2 Advanced weld repair procedures - Cold Weld Repair

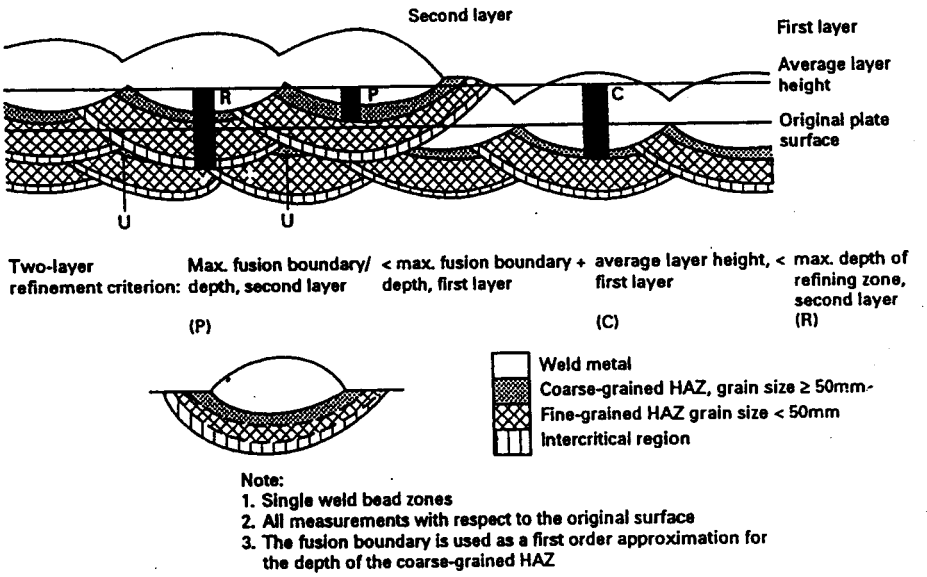
A cold weld repair is characterised by the omission of preheat and/or PWHT, while the conventional primary fabrication and repair procedures would require both. Cold weld repair has a number of major advantages, if the completed repair can be shown to have the required life. There are also economic advantages, as the welding costs, and sometimes the feasibility of the repair, are very dependent on the requirement for preheat and, especially, for PWHT. In addition, there can be practical advantages in terms of plant access, support structures and

reduced numbers of inspections. The case for austenitic repair welds, where PWHT would not be required within the primary code, is not considered here.

The basic principles of the cold repair procedure are a direct consequence of the improved understanding of microstructure features in welds and HAZ regions originally gained in the 1960-1970s, [12,13], and extended by Bhadesia and co-workers, [14]. These are best illustrated as follows; taking the MMA or SMA process as an example.

Assume that a simple weld metal stringer bead is placed on a substrate. The heat from the deposited bead will diffuse through the substrate and, for a moving heat source, will produce a temperature gradient in the parent material or, in the case of a weld repair, in the weld metal. On cooling, quasi-equilibrium structures will be produced and can be characterised using TTT, or more correctly CCT diagrams, for the relevant material. The characterisation of the temperature variation is generally obtained from the Rosenthal heat flow relationships, [15], which, in practice, allow the thermal history to be defined at any point in the parent:HAZ region. More realistic cases occur when two or more beads are used. In this case, the subsequent weld beads will generate new thermal fields that can influence both new material and interact with thermal fields from previous beads. This simplistic picture allows a generalised view of the temperature history to be generated. For recent adaptations of this approach, see [14, 16, 17]. Although variations in the energy input and material characteristics are inputs to the Rosenthal equations, a key factor is the heat input/unit length of weld, which can directly influence the depth of heat penetration for any isotherm, Figure 2a. A second factor, based on geometry, is the overlap of adjacent beads. A low degree of overlap will lead to little thermal interaction with the previously deposited weld bead and the converse with a high overlap. Thus, subsequent weld beads can temper the HAZ material and previously deposited weld metal.

Further extension of this model, with the addition of second and subsequent layers of weld beads, allow both the weld metal and the parent HAZ regions to be reheated and tempered to controlled amounts. The degree of tempering depends on the heat input, the degree of weave, the bead size, travel speed and the weld metal thickness, Figure 2b. At an increased distance from the weld metal/parent interface, the heat input during deposition of a bead does not result in sufficiently high temperatures to influence the HAZ microstructures. Thus, the technology exists, by using carefully controlled welding procedures, to generate controlled microstuctures within the HAZ and previously deposited weld material and, thus, to apply tempering during the fabrication process, [18].



Schematic representation of two-layer refinement parameters. The condition shown represents almost complete refinement with a few small patches (U) of first layer HAZ unrefined by the second layer.

Figure 2. Simplified two layer refinement models

Over the years, such techniques have been utilised in different forms and these are summarised below for completeness. They are all based on the same fundamental principles but provide the control in different ways.

3.2.1. Controlled deposition using a matching filler metal

Currently, there are a number of slightly different approaches, [18], which have been developed and these are briefly outlined for completeness here.

- **Half bead repair technique, [18]**

This was developed as an alternative to PWHT for alloys such as A508 and A533B. Preheat is applied and the preparation is buttered with 2.4mm electrodes to produce a uniform shallow HAZ. Half of the weld deposit is then ground away and a second layer is applied, using 3.2 mm electrodes. The beads are staggered to produce overlap. Finally, the third, remaining layer and fill up are added using 4 mm electrodes.

The process was used in practice, but was difficult to control. In particular it was difficult to judge the amount of the first bead to grind away and, for subsequent layers, to provide the correct stagger or overlap on the ground surface.

- **Temper bead weld repair**

This was originally developed as an alternative to the half bead technique particularly for nuclear application, as it did not involve intermediate grinding and the resulting debris, [18]. The developed version used the automated GTAW process and its use was allowed in US nuclear plant. The procedure is as follows.

Preheat is applied and a six layer buttering with controlled heat inputs, is used to develop the required refinement and tempering, without burn through. The weld fill is completed using a heat input less than that of the last buttered layer. Finally a low temperature PWHT at 450-550 F, (232-288 C), is applied for a minimum of two hours.

The procedure was initially used for pressure vessel steels, out with the creep range, where toughness was a problem. Subsequently, it has been proposed for use with creep resistant materials.

- **Consistent layer temperbead technique**

This was developed by EPRI in the 1990s, [19,20], and uses a higher degree of heat input control than previous techniques to allow both refining and tempering of the structure, using both the GTAW and SMAW processes. The procedure involves a six layer refinement. The heat input is lowest for the first layer and is gradually increased as more layers are added with the objective of tempering the HAZ and subsequent layers. Re-transformation of the microstructure is avoided and thus tempering, to improve the toughness, is the main objective. The heat input for each zone is specifically chosen to provide the required tempering.

- **Controlled deposition methods**

This was developed by Ontario Hydro, [21], and the University of Tennessee, [7,22], based on the original CEGB approaches. The primary objective is to produce both refining and tempering, again by careful selection of the heat input for each layer. The procedures are similar to those described above. They involve a three layer technique with strict control of the heat input. This heat input control can also be obtained through a change in the electrode size for the second layer, [23]. The objective is to achieve 50% overlap, which gives a high degree of refinement and, importantly, is easily achievable in practice.

- The alternative EWI/TWI procedure, [24], uses a three layer process where the first layer gives 80% refinement, the second layer gives 20% refinement and some tempering, and the third layer only gives tempering. The fourth layer weld metal thickness is such that there is no thermal effect on the HAZ produced by the subsequent fill. Preheat is used, without PWHT and it is stated that the preheat and interpass levels are essential variables.

All of these methods are acceptable and, indeed, are based on the same basic theory. The main differences are on the control of the power levels and welding speed. The procedures are complex and welder training is essential. Furthermore, the procedure must be monitored during use. The best method to use may well be that which gives the most realistic control in the operational environment.

If preheat is omitted, then very strict hydrogen controls should be used.

3.2.2. Repair without preheat and post weld heat treatment using nickel based filler metals

An alternative approach was developed in Russia, for example [25], which used a nickel-based filler metal. This required no preheat, was virtually immune to hydrogen effects, required no special controls and PWHT and has been examined by Brett and co-workers, [26, 27].

Russian consumables are not generally available and EniCrFe-2 and EcrNiFe-3 were potential options. These have high toughness, are virtually free from hydrogen cracking and have relatively low residual stress in the as welded state. On the negative side, they basically produce dissimilar welds (DMWs) with the potential for long term failure, [28], and inspection problems.

Although the nickel-based consumables can be more difficult to handle, they operate at lower currents than the equivalent ferritic rods. This results in a lower heat input, which is sufficiently low to produce an adequate fine grained size, in CrMoV and 2.25Cr1Mo welded with filler metal laid as a stringer bead and around 50% overlap, with no special procedures.

An appreciable number of repairs have been carried out with success, [27,29], mainly for emergency purposes.

3.3 General comparison of matching and nickel based filler metal procedures

The differences are shown in Table 4. There are advantages and disadvantages with each procedure with no perfect option. Major efforts have been made worldwide with the matching/undermatched filler approach, using controlled deposition and giving reasonable inspectability, but with a need for specialist welder training and stringent hydrogen control. However, the alternative nickel filler repair is a convenient emergency procedure, which with the correct strength filler metal, excavation design and experience on different component types, may, in some circumstances, be a viable longer term option. Possible improvements could involve lower strength filler metals and excavation restrictions.

Factor	Inconel filler metal	Matching 2.25Cr1Mo filler metal
Carbon diffusion	Limited problem	Possible in long term with chemically unmatched filler.
Hydrogen effects	Virtually no problem	Strict hydrogen control.
Creep strength differences	Major weld metal over-match. Hoop stress will offload to weld metal under pressure loading.	"Matching" so no major weld metal offloading
Coefficient of thermal expansion, CTE.	$\Delta\alpha$ is small and, based on DMW experience, limited thermal effects expected.	No expected CTE effects.
Buttering	May be necessary but heat input is low so fine grained HAZ is generated.	Necessary to temper HAZ and refine structure. Two or more layer process with heat input control through rod size, and welding speed or specific heat input controls.
Hardness	HAZ tempered if buttering techniques used.	HAZ tempered but final weld metal fill up may be of higher hardness
PWHT	None. Stress will relax at service temperatures in the more ductile HAZ and near parent regions.	None. Stress will relax at service temperature in HAZ and weld metal. Ductility/ toughness is important.
Residual stress	Potentially high at room temperature but will reduce on heating due to the alpha changes.	Probably high but will relax with service time so ductility is important.
Inspection	Difficult to detect local damage in DMWs.	Possible to standards for normal welds, typically > 3mm.
Axial loading	Sensitive based on DMW experience	Sensitivity to Type 4 cracking dependent on material combinations and stress.
Experience	Documented over 15 years. Can lead to cracking adjacent to the repair weld in parent or old weld metal. Typically emergency repairs.	More limited service experience but increasing. Note the experience with TWMC* on poorly PWHT 2.25Cr1Mo weld metal.
Research	More limited current development.	Growth area worldwide.

*TWMC = Transverse weld metal cracking

Table 4. Comparison of the use of, high Ni (Inconel) and ferritic matching filler metals

4. General characteristics of a repair weld

As the creep life of a weld, calculated using FE analysis, is directly related to the geometry, the creep property balance throughout the weld and the applied loading, [30, 31, 32], it is helpful to compare typical repair and virgin welds.

There are two basic forms of repair, where the component has seen limited service and little degradation will have occurred, and where the parent and any virgin weld metal are degraded to severe levels. The first is typical of the repair of defects during original fabrication when the parent material will have properties in excess of the design minima, although high temperature properties are not generally available for weld metals. The latter applies to repair after extended service, and plant life extension beyond original design life may be important. The various factors are summarised in Table 5.

Factor	Primary fabrication *	Primary weld	Operating times to ~120kh	Operating times to <300kh
Excavation and geometry +	No weld. Remove all damage frw, prw1, prw2 as appropriate.	L ~ thickness for pipe weld	frw, prw1, prw2 L' > L	frw, prw1, prw2 L' > L
Metallurgical structure	As fabricated	As fabricated. Meets code requirements	Degradation. Precipitate coalescence etc.	More advanced degradation
PM properties. Time independent	Meets code requirements	Meets code requirements	Reduced yield and UTS. Probably increase ductility.	Reduced yield/ UTS. Probably increase ductility.
WM properties. Time independent	Meets code requirements	Limited data but should meet code values for PM	Limited data but degraded	Limited data but degraded
PM properties. Time dependent	Meets code requirements	Meets code requirements	Limited data but degraded	Limited data but degraded
WM properties. Time dependent	Limited data, no code requirement	Limited data, no code requirement	Limited data, no code requirement	Limited data, no code requirement
WM type **	Chemically matching	Chemically matching	Chemically matching	Chemically matching
Original PM:WM ratio	Matching	Matching	Matching	Matching
Repair PM:WM ratio	Matching	Matching	Overmatched**	Overmatched**

+Excavation codes relate to Figure 1. PM = Parent metal
* May or may not include original weld metal. WM = Weld metal
** Examples of under matching exist.

Table 5. Comparison of the main characteristics of repair welds

Repair during or immediately after primary fabrication would lead to a repair weld where the property balance and material states are nearly identical to those present in any original weld, although the weld may be wider, L' > L, Figure 1. It is not always possible for the weld metal to exactly match the parent both in composition and in properties. However, repairs to components after extensive operating times will generally be with a matching composition of filler metal, as for primary fabrication, but will be severely overmatched in terms of strength due to ageing of the component. The degree of overmatching will be a function of the material, the exposure conditions and will increase with increasing degradation.

Degradation can be microstructural. The particle size and distribution are affected by the service exposure, with the possible precipitation of different carbides, formation and growth of cavities and micro cracks, or a combination of all factors.

5. Performance evaluation of repair welds

In general, there are three main methods; examination of plant damage and failures; evaluation of repair welds through the use of full size repair welded component tests; and laboratory based uniaxial/cross-weld testing of repair welds. These methods are interdependent and any viable method must reproduce the in service crack morphology.

5.1 Examination of plant damage and failures

Long term damage found on plant welds can be associated with Type IV cracking. This occurs within the low temperature region of the HAZ, which is continuous through the thickness of the component. This is generally repaired by a full weld repair, which widens the weld and regenerates new "Type IV" structural regions. Thus, unless there is an effort to minimise the root cause, such as additional loading, Type IV damage can occur again within the previous time scale. There have been no second repairs found in the published literature but an frw excavation, with a procedure similar to that for primary fabrication, should provide performance equivalent to the original weld, provided a chemically and property matched weld metal was available. In practice, this is difficult.

Failures in plant welds, which, on examination, have shown previously weld repairs are of interest. These repairs may have been made for cosmetic and/or the repair of cracking during fabrication and the earlier stages of operation, Sandstrom, Wu and Storesund, [33]. The first example, studied the creep damage distribution in a T-piece retired one year after the initial repair. Type IV cracking had occurred on one side of the weld, and was repaired using a prw2 excavation. This is a classic case, as the repair contains both new and service exposed weld metal as well as new and service exposed HAZ structures. Figure 3 shows a cross section where the grades of creep damage are shown. It is clear that damage is not uniform, even in the regions that had only been exposed for around 10,000h in service. The most heavily damaged areas were the original weld metal, with the worst damage/cracking/micro cracking in the region of the service exposed weld metal, which had been reheated by the repair weld. The importance of this weak region is further supported by studies on a seam welded 2.25Cr1Mo reheater outlet header, [34]. Four separate areas of weld repair were identified and each had led to further cracking. Once more, the use of a prw2 excavation led to a HAZ being formed in the service exposed weld metal, and some cracking had formed in the fine-grained region of the old weld metal. Test work supported the premise that the properties were reduced in this region, [34].

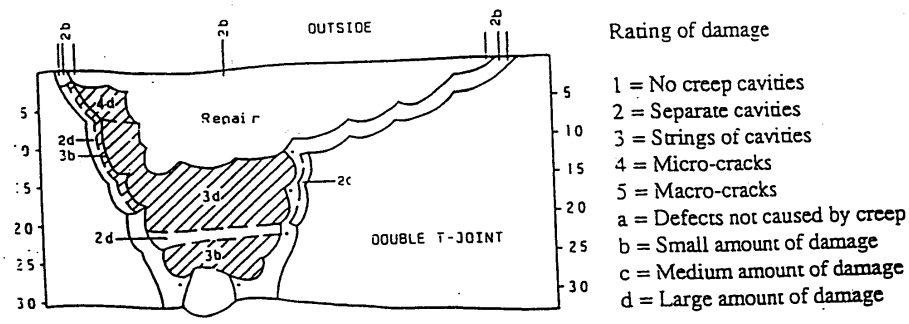


Figure 3. Damage map for the retired component one years operation after the repair, [33]

T sections are a specific case of a header assembly, which, typically, has many individual tube penetrations and a smaller number of branch connections. Experience has shown that creep loading of branch connections can cause premature damage accumulation, cracking and failure. The current welding practice for such geometries has been reviewed, [35], and involved prw2 type excavations tailored to the damage profile.

Such examinations of failed or damaged components clearly identify the weak areas. However, they also illustrate a key factor, namely, that the damage that occurs is not uniform but is directly influenced by the component geometry, the weld geometry and the more subtle local distribution of microstructures. Often, the general deformation of the component, which can be estimated by simplified methods, provides the driving force for local damage accumulation. This damage occurs at a position determined by the local stress/strain and the susceptibility of the microstructure to damage accumulation.

5.2 Controlled weld repair experiments using full size pressure vessels

5.2.1 General deformation occurring in branch components

It is helpful to initially define the general deformation occurring in header geometries in the absence of weld repairs. A 1Cr0.5Mo header, which included stub and branch connections, was removed from service after 25930h at 172 bar and temperatures between 400ºC and 600ºC. It was subjected to testing at 172 bar and accelerated temperatures of 550ºC and 575ºC, [36]. Full inspections (strain, NDT, and MPI) were carried out at regular times up to failure. The main results are:-

- The highest stressed region was associated with the branch connection, as expected, and suggested that the body and the branch will have a tendency to bulge in this region.
- The strain accumulation increased with temperature, being very low at 550ºC but increasing markedly at 575ºC.
- The general deformation was not uniform. Rather there was a bulging of the body in the vicinity of the branch with a maximum distortion at right angles to the branch penetration.
- The branch strains behaved in a similar manner with a maximum deformation in the branch normal to the header body.

- Although these are referred to as strains, they are, in fact, distortions of the cylindrical shapes of the branch and header body. It is feasible to convert these to local strains on the pipe and branch but requires additional experimental chordal readings.
- No apparent damage was found in the branch at 550ºC during full inspection.
- At 575ºC, cracking commenced at the saddle positions, in the HAZ region of the branch weld, on the body side. Near failure, some transverse cracks were also detected in the weld metal. Final failure was from a transverse crack at the right-angled (crotch) position.

This defines a potentially general deformation and failure mode for a conventional T-junction or branch weld in a header system. The component test failure was associated with the weld and there was no major damage within the body section.

5.2.2 Component tests studying the influence of weld repair on performance

There was a major programme organised in the Netherlands at TNO as part of a multinational programme. The work, [37 - 40], involves T-pieces fabricated in 1Cr0.5Mo, 2.25Cr1Mo, CrMoV and later, X20CrMoV 12 1 and Grade 91. These tests rely on iso-stress temperature acceleration conditions (e.g. tested at operating stress with temperature increased to accelerate damage accumulation) with the test temperature ~ 40ºC above the operating temperature and, in general, the test pressure equal to the service pressure. The diameter ratio of the branch to pipe sections is in the range 0.5 – 0.7. In addition, the repair weld is applied to the branch weld such that it covers both one saddle and one right angled (crotch) position, leaving the remaining 180^{o} section for comparison with an unrepaired segment. In all cases, a prw2 excavation was used. All tests were monitored for strain and damage with frequent inspections.

5.2.2.1. The effect of repair welding excluding PWHT

Two materials were considered, a 1Cr0.5Mo vessel, (80,000h at 525ºC and 181 bar) and a 2.25Cr1Mo vessel, (91,000h at 545ºC and 168 bar) with damage at the branch weld, [37,38]. A conventional repair weld procedure was used with a prw2 excavation, no buttering or temperbead technique and a matching weld metal, but with no PWHT. The MMA process was used for both materials with the GTAW process also used for the 1Cr0.5Mo material.

Initial testing showed that the material properties in the as welded condition, although reduced by omitting the PWHT, were still acceptable to most code authorities for these materials and matching fillers.

The 1Cr0.5Mo component was tested at 181 bar and 565ºC for a total period of ~9000h and the results are summarised below.

- In all cases, the strain across the pipe section, at the centre line of the branch and the pipe, showed a general hoop dilation of the pipe and the branch with a higher hoop strain recorded in the branch than in the pipe section.
- The damage built up with time and at 8500 h, the crack in the repair was one third of the wall thickness and the unrepaired region showed a crack of one tenth the wall thickness.

Test time, h	Damage in repair weld	Damage in unrepaired weld
<2000	Cracks in repair weld metal	None
>2000	Class 4, in fg HAZ and fg WM	
8500	fg HAZ, 50% of wall	Cracking to 10% wall

fg = fine grained region of the HAZ

Table 6. Comparison of damage in a virgin and a repaired branch weld, [37,38]

- For the GTAW repair, the deformation results were similar but with higher recorded strains than for the MMA repair.
- Damage also occurred at an earlier time and mainly in the saddle position;

The 2.25Cr1Mo component was tested at increased temperatures of 585ºC and 600ºC to accelerate damage with some additional stress acceleration.

- The same general pattern of deformation was achieved.
- Damage occurred in the fine grained refined HAZ of the service exposed weld metal. The prw2 excavation could have contributed to this.
- Life estimates were made from the crack growth rates and used, with extrapolation, to define the required inspection periods as would be normal for a major repair.

Material	Crack growth, GTAW process	Crack growth, SMAW process
1Cr0.5Mo	1 mm in 4000h	1 mm in 6000h at 565 C
2.25Cr1Mo	----------	> 1mm in 7000h at 585-600 C

Table 7. Estimated crack growth rates for both repair welds

The general conclusions were that, although PWHT influenced the local properties, the material values in the as welded state were acceptable to the codes. Furthermore, the general deformation patterns of both components were similar but of differing extent. The large crack noted at the completion of the test was associated with the repair weld but lay in the HAZ region within the service exposed weld metal.

5.2.2.2. The effect of additional loading on weld repair performance

A thick walled large diameter 2.25Cr1Mo four branch header, removed from service after 130,000h at 185 bar and 540-580ºC, [40]. This was cut in two and one half, containing two branches, was constructed into a test vessel. Both branches had advanced damage present. Branch 1 was left unrepaired and branch 2 was repaired using a normal repair procedure involving preheat, PWHT and a chemically matching consumable. The test was at service pressure but with an increased temperature of 620ºC. The loading was by internal

pressurization alone, for an initial period (8000h), and then an additional load of 33.5kN was applied between the branches for a further 13,000h. The results show :-

- Damage was limited, under the pressure loading alone i.e. < 8000h.
- There was no apparent change in the diametric strain rates on applying the additional bending load.
- The presence of the system load caused time dependent deflections between the branches and tended to increase the strain accumulation at the right angled (crotch) position.
- Once the additional loading was applied, damage occurred rapidly.

    - For the unrepaired weld, the damage accumulated to macro-cracks in the old weld metal and the fine grained (fg) HAZ with similar results for the repaired weld, but with extra damage in the fine grained HAZ in the service exposed weld metal.
    - Macro cracks occurred in both branch welds, (> 11,500 h) in the fg HAZ of the weld metal for the repair and in the old weld metal for the unrepaired weld.
    - At > 15,000 h, the cracking was in the saddle position, fg HAZ of old weld metal of the repaired weld. At > 18,000h, the cracking was in the old weld metal and in the fg HAZ on the branch side.
    - Cracking also occurred on the tensile side in the right angle (crotch) position.

- The branch strains were always greater than the pipe strains suggesting that there is a clear geometry effect, irrespective of the type of weld present and the repair state, and supporting the importance of the component deformation in controlling local cracking.

.
Different assessment models were used to define the life and the R5 approach, in particular, gave encouraging results, [40].

5.2.2.3. A study of the effect of specific variables on the performance of weld repairs

This work, [41], studied the effect of specific factors on repair weld performance in 1Cr0.5Mo, 2.25Cr1Mo and CrMoV branch connections.

- **The effect of grinding without weld repair**

Often, defects may be ground out and this is normally carried out if the remaining cross section of the component, after grinding, exceeds the minimum design thickness. The results from a sharp, 25mm radius, and a smooth, 500mm radius excavation, both showed that the blending out of a damaged area, with a smooth radius, was acceptable as long as the minimum thickness criteria were met.

- **The use of undermatched consumables and the need for PWHT where controlled buttering/temperbead techniques are used**

Van Wortel and co-workers, [39,41], considered seven different filler metals of different creep strengths.

Weld metal	**Creep property.**
New 0.5 Mo No PWHT	Group 1.
New 1Cr0.5Mo No PWHT	Group 1.
New 1Cr0.5Mo + 1h at 680 C	Group 1.
New 2.25Cr1Mo + 1h at 680 C	Group 2.
New 2.25Cr1Mo, low C. + 1h at 680 C	Group 2.
New CrMoV + 1h at 680 C.	Group 2.

Table 8. Typical filler metals used

In general, chemically matching fillers were overmatched in terms of strength, where matching relates to a comparison of the creep life, not strain rate, at 535ºC. To obtain an undermatched weld metal, in terms of strength, composition changes such as reduced Cr, Mo and carbon were necessary.

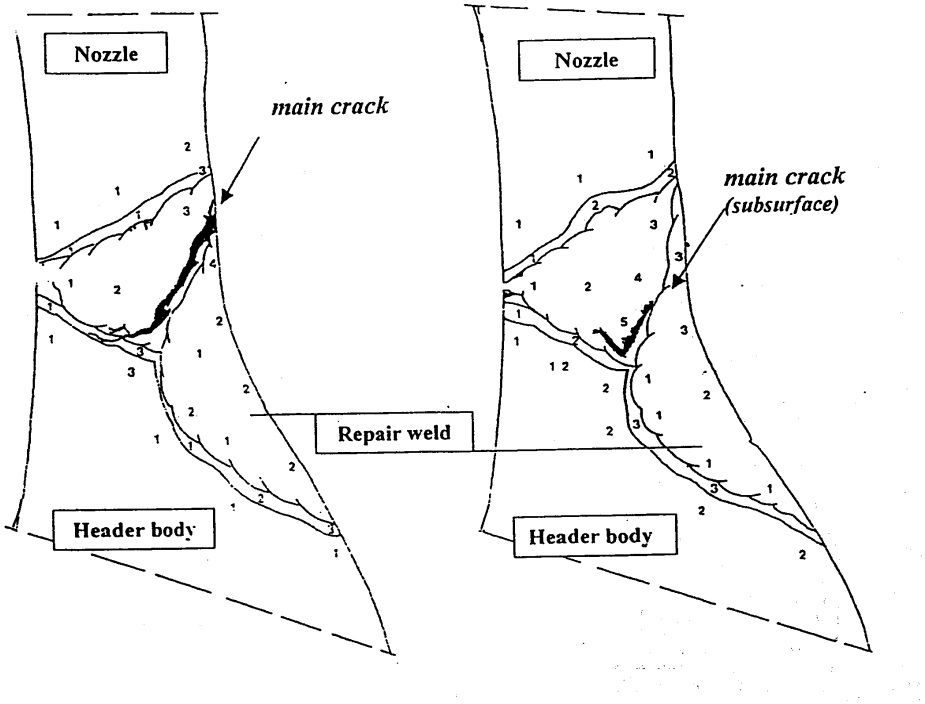
Material and conditions	**Chemically undermatched, no PWHT and buttered/ temper bead.**	**Chemically matched. PWHT**
1Cr0.5Mo. 565ºC. 181 bar at 15400 h	No macro cracks. Small cracks in fg HAZ of old weld metal for ~ 20% thickness.	Micro-cracks in fg HAZ of old weld metal.
2.25Cr1Mo. 600ºC. 180 bar at 7600h 12400 – 13500 h 13500 h	Fg HAZ of old weld metal, 25% of wall	Macro crack, fg HAZ on body side, 10% wall thickness crack at end of test. New longer crack ~ 75% of wall, fg HAZ of old weld metal.
CrMoV. 575ºC, 125 bar. 2900 h ➢ 2900 h 9000 h	Micro-cracks, reheat, in cg HAZ but no growth at 9000 h. Fg HAZ damage at < class 3B.Other positions < Class 3A.	Micro-cracks, reheat, in CG HAZ but no growth at 9000 h. Fg HAZ on body side, micro-cracks. Macro crack of 3mm.

fg = fine grained CG = coarse grained

Table 9. Comparison of the chemically matched/PWHT and the undermatched/no PWHT repairs, [39,41]

The results of the chemically matched and PWHT'd repairs and undermatched repairs, made by buttering or temperbead techniques with no PWHT, is summarised in Table 9. Both types

of repair showed similar damage locations, with cracking detected in the fg region of the service exposed weld metal and evidence of damage in the fg HAZ region on the body side. In general, the use of undermatched weld metal, with temperbead and no PWHT, showed no major deleterious effects. In fact, the damage was similar or less than that for the chemically matched PWHT'd option. Again, however, the use of the prw2 excavation has exacerbated damage in the reheated regions of the service exposed weld metal, Figure 4.



a. b.

Figure 4. Macroscopic crack positions in the branch weld repair after test, [41]
a. *Chemically matched with PWHT.* b. Chemically undermatched, no PWHT.

- **A comparison of the performance of high nickel repairs without PWHT and a standard chemically matched filler with PWHT**

The repairs were compared for the weakest material, 1Cr0.5 Mo, and no details are given of the weld procedure other than that the interface was not buttered, [41]. The results, Table 10, clearly show the poor performance of the nickel filler metal, with HAZ micro cracking on the body side and in the old weld metal, again associated with the prw2 excavation. Based on this evidence, the authors do not recommend its use. However, such procedures have been used on power plant for short-term repairs, though not for all geometries, [27,29], and have performed well.

Conditions, Time h.	Nickel filler metal	Chemically matched + PWHT
1Cr0.5Mo 565ºC 181 bar 6100h 15400 h	Several microcracks in HAZ, body side, and old weld metal. 50% wall thickness crack in CG HAZ.	Micro-cracks, fg HAZ of old weld metal.

Table 10. Comparison on the crack growth for high Ni repairs without PWHT and a standard chemically matched consumable with PWHT

5.3 Weld repair performance evaluation using uniaxial testing

Laboratory based studies generally rely on test programmes involving cross weld geometries under uniaxial loading. Several major programmes have chosen this route for evaluation of weld repairs. Typically, this route involves removal of a damaged weld/component from service, development of weld procedures, repair welding and a full metallurgical examination. The mechanical and time dependent properties of the repair are then used to assess the life. Such procedures normally involve homogeneous material and cross weld creep testing using iso-temperature (test at service temperature with increased stresses) or iso-stress (test at estimated service stress with increased test temperatures) accelerated conditions. Extrapolation then defines the remaining life of the repair, following procedures generally applied to homogeneous specimens. This approach has been used to evaluate the effect of numerous welding parameters.

Various workers, [42-47], have reviewed the published case histories for 1Cr0.5Mo and 2.25Cr1Mo weld repairs, which can evaluate the influence of certain welding parameters.

Typically, property tests include examination of metallurgical structures, using both optical and electron microscopy, hardness measurement to define weak areas, Charpy impact tests to define a "toughness", room temperature and typical operating temperature tensile tests, for procedure evaluation, and finally cross weld creep testing. These are all established procedures. The cross weld creep test, although relatively simple to manufacture and test, is complex to analyse, [48]. The specimen takes a sample of the cross section of the weld and, including weld, HAZ and parent microstructures is an ideal test section. However, the specimen and weld sizes are obviously different. The thickness of any weld structure, relative to the specimen diameter, is an additional variable and the final failure position may be influenced by the loading. The following criteria are important.

- Specimen should be large enough to include representative sections of all of the relevant structures but small enough to test.
- Any failures that occur must be relevant to the practical cases. Failure maps for cross weld geometries can be generated experimentally, identifying the failure mode as a function of stress and temperature, [49] and can aid the choice of loading. The cracking is dependent on the stress direction relative to the individual structures. The cross weld sample can be used to consider any failure process normal to the maximum stress, as typified by stress relief and Type IV cracking.

- There is no defined test specimen geometry for creep studies although there have been suggestions, primarily based on specimen diameter and length criteria. Specimens are generally cut parallel to the sample surface or cut normal to the weld/parent interface. Such samples will include parent, HAZ and weld metal segments and may include one or both weld interfaces.

Despite these potential problems, the use of such tests has been shown to be relevant to an initial comparison of the effect of various welding parameters, [50,51]. These workers clearly showed that the strength of the weld, as defined by the cross weld test, is consistently less than that for the homogeneous material, and that the magnitude of the difference is a function of the material combination and other parameters.

5.3.1 Effect of material combination on the creep life

Ettienne and Heerings,[51], reviewed the available data for cross weld data, relative to the parent material, and clearly defined a series of factors, on stress, for failure in a cross weld, relative to failure in the homogeneous parent material. Typically such factors are less than unity but generally greater than 0.5 and can give guidance for the use of these welds in practice. Although generated for welds that have not been repaired, they are obviously also of relevance for frw type repairs, where the only differences between the repair and the virgin weld are the balance of the strength properties across the weld and the weld width.

5.3.2 Effect of conventional repair on the life of welded joints

A number of workers have examined the expected life of weld repaired components taken from service after long exposure times. Data, relevant to repairs that have been subjected to a full PWHT, are given here.

Arnswald, Blum, Neubauer and Poulsen, [50], examined a 2.25Cr1Mo welded pipe taken from service after 170,000h at 538ºC and a mean diameter hoop stress of 60 MPa. The results, based on iso-stress testing of cross weld samples, with temperature acceleration for extrapolation purposes, can be summarised as :-

- The remaining life of the parent was estimated to be around 200,000h.
- The cross weld life was estimated to be around 150,000h. Thus, the weld life was reduced by around 25% of the parent life.
- Typical failures were of the Type IV form and were reproduced in the tests.

The authors highlighted the fact that, for the optimum results, all damaged material should be removed from the weld before repair was attempted.

A number of other examples of such results are available, typified by DeWitte and Coussement, [49], with data from a 2.25Cr1Mo pipe weld taken from service after 123,000h at 565 C, (mean diameter hoop stress of 27MPa). Again, iso-stress testing of cross weld samples was used with temperature acceleration, in addition to slow strain rate testing. In this case, the repair life was in excess of the parent life, 100,000h as against 72,000h. They also noted that the effect of PWHT was small.

Nonaka, Ito, Ohtsuki and Takagi, [52], extended this approach by considering repairs of prw2 and prw1 type excavations, using data from a MMA welded 2.25Cr1Mo header taken from

plant after 19,500 h at 577 C. The original weld had been made by the MMA process and was post weld heat treated for 3.2 h at 720ºC. Repair welds were made to this weld. The first was a prw2 excavation at one of the original weld interfaces and the second, the equivalent of a prw1 excavation, was made in exposed parent pipe away from the original weld area. Cross weld and parent specimens were tested at 575C to 650ºC. Although short term, these tests allowed the evaluation of the direct influence of specific structures as outlined below.

Position	**Test structures**
A	Across exposed WM:new WM interface
C	Across exposed PM:new WM interface
E	Across exposed WM:exposed PM interface
D	Exposed PM only

WM = weld metal. PM = parent metal

Table 11. Positions studied within the repair welds.

Although the differences were not large, positions A, E, C and finally D showed increasing lives, respectively, at stresses of 34-40 MPa and temperatures of 625ºC and 650ºC. Thus, the suspect areas are those containing exposed material, especially weld metal. The parent material, in the absence of a weld, shows the longest life. A very small effect was found on creep life, by increasing the specimen diameter from 6 to 10 mm at 40 MPa and 625 C. At higher stresses and lower temperatures, (55 MPa, 625ºC and 75 MPa, 575ºC), position A had the lowest life, and the other structures had lives around the same values. Nonaka et al also used fatigue and creep:fatigue loading to test material from positions A and C at 550ºC and strain ranges of 0.7 % and 1% with a 10 minute hold period. The results were dependent on the strain range, with there being no apparent effect at a strain range of 1% but a reduction in life at position A for the strain range of 0.7%, Table 12.

Strain range, %	Temperature, ºC	Cycles to failure Position A*	Cycles to failure Position C*.
0.7	550	~700	~1200
1.0	550	~400	~400

* See Table 11.

Table 12. Fatigue life for materials including exposed weld metal, [53]

The general results identified that the exposed weld metal, particularly where it had been reheated by the repair weld, could be the weakest structure under certain loading conditions. Generally, a smaller effect was found at high stress levels and strain ranges, which is not unusual. The data from the other positions sampled for creep suggested that the repair weld life was approximately equal to the exposed parent material life. This effect can be seen with other workers, where the relevant tests have been made, and could suggest that the repair life, in positions of high restraint, may be dominated by deformation in the parent material.

Croker Finlay and Law,[53], have examined the important commercial effect of good and bad practice, relating to electrode size and heat input. Repair involved carbon steel, 2.25Cr1Mo and CrMoV service exposed materials with the 2.25Cr1Mo material removed from service after 190000h at 565ºC and showing no visual cavitation damage. The first repair involved a fast process with a high heat input and the second repair was a controlled butter low heat input procedure. Both were subjected to PWHT. Iso-stress temperature acceleration testing plus other remaining life assessment techniques were used and the initial published work suggests, from the limited data available at this stage, that the remaining life of the repair welds was around 100,000h and that the controlled buttering process repair showed longer life.

5.3.3 The effect of post weld heat treatment on weld repair life

There has been increasing studies on the influence of PWHT on repair life, due to the many potential economic advantages. There are a number of basic options that can be used to minimise the need for PWHT. These are:-

- To manufacture the repair using the normal weld procedures.
- To use a controlled deposition process to allow for heat treatment during the repair procedure.
- To modify the weld metal to an undermatched ferritic consumable, thereby improving the high temperature property match to the exposed parent material.
- To modify the weld metal to a high nickel variant.

Preheat is an important parameter and is generally used to ensure that the possibility of hydrogen cracking is minimised. Indeed, the major economic implications arise from PWHT rather than preheat. The need for preheat can be minimised, through the use of strict hydrogen control of the consumables and of the welding process itself, [9].

When considering the influence of PWHT, it is also essential to consider the deposition method used.

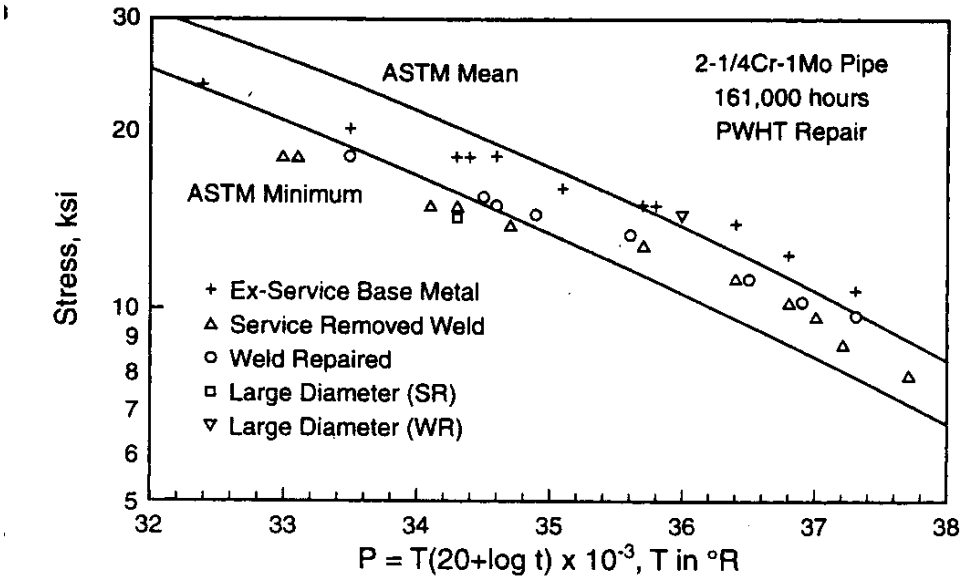
The earliest work, [54], considers a 2.25Cr1Mo header material taken from service after 91,000h at 545ºC and a mean diameter hoop stress of 45MPa. The repairs, made using a matching 2.25Cr1Mo filler metal without controlled deposition, showed that the lack of PWHT had not led to any deterioration of the repaired material in both low and high damage states and, indeed, iso stress temperature accelerated testing suggested lives of 100-200,000h for the repairs. This result was supported by other work, [49], again for 2.25Cr1Mo material and cross weld testing using similar techniques, which suggested repair lives of around 100,000h and a general conclusion that, for this material, PWHT was not essential. Again, there was support from Lundin and Wang, [55], for similar material after185,000h at 565 C. In this case, the absence and presence of a PWHT of 1h at 718ºC, after a conventional weld repair, showed that both the repair and the service aged parent material gave similar lives, around the lower bound value for the ASME design codes. This was corroborated by a further series of tests, where a full re normalisation and temper was carried out, and the material reverted to the mean design value, [55].

A major programme in this area has been reported, [42-47], for both 2.25Cr1Mo and 1.25Cr0.5Mo materials. This programme involved materials classified as low damage, 161,000h at 538ºC and 22.75 bar, and high damage, 244,000h at 565ºC and 168 bar, from service exposure and the fabrication of a series of repairs, with a frw type excavation, around

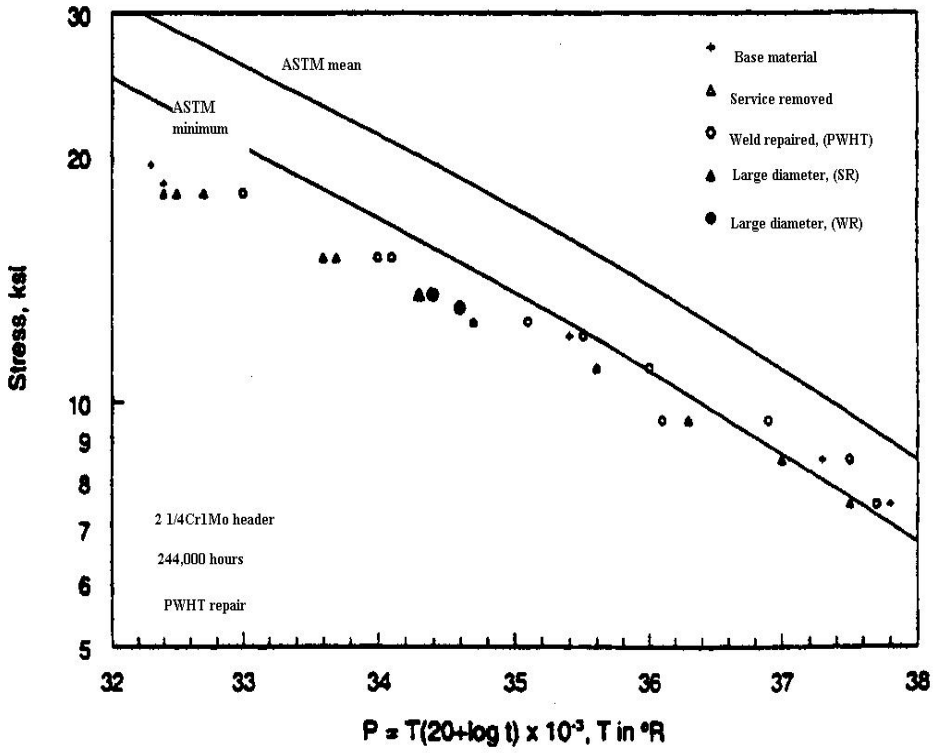
the complete circumference of the pipe. The repair was sectioned and half was subjected to PWHT while the other half was left in the as welded state. It should be noted that the repair procedures involved either 3 layer 50% overlap and fill, or a three layer temperbead technique with a temperbead fill. It is important to note that a three layer 50% overlap procedure is similar to the controlled deposition method used in the UK and allows a high degree of microstructural refinement in the HAZ. Furthermore, the frw excavation removes any possibility of reheated regions of the service exposed weld metal, which has been shown to be a problem area, remaining after repair. The welding process was generally SMAW though one repair was carried out using the GTAW process to provide the buttering layers with a SMAW fill. Chemically matching consumables were used in all cases. A very comprehensive series of property tests was carried out. The results of laboratory tests generally showed:

Mechanical and Charpy properties met the normal code requirements and, indeed, the Charpy value for the temperbread weld metal was higher.

- The creep properties of the exposed parent materials were at, or above, the lower bound values for an annealed 2.25Cr1Mo material, for example see Figure 5.



Level 1. 161,000 h service exposure.



Level 2, 244,000h service exposure

Figure 5. Larson Miller representation of the parent and cross weld creep data following repair and PWHT at level 1 and level 2 prior exposure levels, [46]

- No cavitation/crack damage was present in the original materials.
- Hardness variations were realistic although there were a number of exceptions.
    - The PWHT repairs showed reproducible hardness levels typically 140 - 180 VPN.
    - The repairs not subjected to PWHT were typically 260 - 280 VPN.
    - However, there was no obvious hardness reduction at the low temperature HAZ region after temper bead repair.
    - The GTAW process temper bead repair showed no difference with the PWHT option and the weld metals were typically around 180 - 200 VPN.
- The cross weld data for all types of weld showed realistic lives for all repairs, based on stress accelerated tests data, with no major differences for the repairs not subjected to PWHT. A limited number of large cross weld specimens did not always show the expected life increase.
- Extrapolation of the expected cross weld life to operating stress levels did produce a wide range of data, dependent on the extrapolation method used and this is problem area.
- Typical cross weld rupture data, extrapolated to operating levels are shown below.

Code	LM extrapolated life, h	Iso stress extrapolation approach using 1/temperature, h	Iso-stress extrapolation using linear temperature, h.
TC9 WR	498000	278384	133598
TC10WR	693000	280517	139559
TC8WR	434000	369273	167521

LM = Larson Miller parameter.

Table 13. Comparison of the extrapolated cross weld test lives using different methods, [44]

The following points can be made:

- Based on the Larson Miller (LM) approach, temperbead with no PWHT gives a major life improvement. Note that the lives are all very long and even greater than the design life of the pipe, which would be unusual.
- Using the iso stress, 1/T extrapolation, the temperbead and PWHT options showed the same life but that of the GTAW repair was highest. Note that the extrapolated life was reduced in all cases, relative to the parent material, but still would be around the pipe design level.
- Using the T extrapolation approach, the GTAW life was highest with limited differences between the temperbead and PWHT options. Note that the extrapolated life is further reduced and now is less than the expected design life of the pipe.

In all cases, the minimum repair life was acceptable, relative to the expected life of the parent material and bearing in mind that a welded component generally has a lower life than a homogeneous component.

Similar studies have been carried out for service exposed 1Cr0.5Mo and 1.25Cr0.5Mo material with generally similar results, [20,43,56,57]. These results show realistic cross weld rupture lives for repair welds, in both the PWHT and as welded states. Furthermore, similar extrapolation problems are present.

5.3.4. The use of under matched weld metals for weld repair

Such an approach is logical, as it minimises the differences in creep properties between the weld and service exposed parent materials. A number of workers have considered this. Newell and co-workers, [58,59], examined a series of case histories where lower strength weld metal was used in the repair process. Of the eight cases considered, only one operated in the creep regime and the survey showed that generally, ASME rules would call for matching filler metals for primary construction. Hence, for consistency, a service exposed material should be of lower strength. Thus lower strength fillers should be used for weld repair. The case history operating in the creep range was a weld in 1.25Cr0.5Mo which had seen 164,000h at 538ºC. An E9018B3 weld metal was used for the repair and the tensile strength was approximately equal to that of the exposed parent material. Cross weld creep tests failed outside the weld within the parent material, suggesting a limited effect of the repair weld on the parent life under these test conditions. The work of Lundin et al, [60], is quoted by Lundin and Prager, [61]. Here a low carbon filler metal is used for the repair and the toughness and weldability were completely acceptable. Cross weld testing of the

combination, virgin 1.25Cr0.5Mo and weak low carbon weld metal, in the as welded, PWHT and renormalised and tempered states provide lives at or above the minimum ASTM D50 value for 1.25Cr0.5Mo.

The definition of material matching could be important for creep loading and Newell generally used yield behaviour whereas Lundin et al could also relate this to a creep rate comparison from their data.

5.3.5. The use of high nickel weld metals

Generally, the use of high nickel weld metals outside of Russia, for weld repair of components in the creep range, has been limited to emergency repair or repairs where there is a possibility for a later repair using more conventional filler metals. Within the UK, this has been used with large economic benefits and success, [26, 27, 29]. Initially it was used with controlled deposition procedures but later, [27], was found to be equally acceptable using a stringer bead deposition pattern with a 50% overlap, which gave the necessary HAZ refinement. The cross weld data reported are limited but generally show realistic lives with failure in the Type IV position. The depth of operational service experience is excellent, see [27,29] and is used to validate the continued use of this approach.

6. Concluding remarks

A survey of the literature and experience clearly illustrates that there is evidence for the build up of damage and cracking in components subjected to high temperature creep loading and of defects generated through the primary fabrication processes, be they welding or casting. In addition, the generic microstructures present in all welds, but particularly ferritic welds, produce weld lives less than the design life calculated for the homogeneous parent material. Thus, there is a need for realistic, reproducible and reliable weld repair procedures. The repair procedures, based on primary welding procedures are realistic and can, if produced to high quality standards, which include PWHT when required, give reliable service.

However, there are major economic benefit if welding, particularly in-situ welding at site, is carried out without preheat and PWHT. This also has advantage in situations where component size or location does not permit in-situ heat treatment. This has led to a number of major studies to investigate this specific aspect, including controlled plant application. The current techniques, which generally use a complex controlled deposition process to both temper the weldment microstructures generated and to reduce residual stress, are based on technical understanding and are becoming more generally accepted. However, there are a number of areas where the on-going work is essential and where further work is needed, to provide the level of assurance required for general application of these techniques. In addition, Dong and co-workers, [62], are studying residual stress build up during the welding process and for repair welds, [62], with promising results. Further investigation of methods for minimising such stresses, by variation of any applied cooling, are required.

Major areas where further work is required are:

- A need to define, as a comparison standard, the life of a weld repair made to conventional primary fabrication best practices.

- A need to improve the understanding of the controlled deposition processes and the possible generation of more easily controlled and user-friendly procedures.
- A need to confirm the reliability of cross weld testing, for the realistic evaluation of weld repair procedures, through the use of large scale feature tests.
- To determine the optimum conditions of excavation geometry, weld metal and parent material matching or the use of under or overmatched electrodes from a detailed understanding of how these factors influence the high temperature behaviour of weld repairs.
- A need to take account of any residual stress variations that are generated with advanced weld procedures, where some degree of stress relief and tempering occur during fabrication.

Much of this work is ongoing and it is clear that, over the next five years, it will be possible to select fully validated repair techniques and procedures, from a range of possible options, thereby providing major economic benefits, with due account taken of safety considerations.

7. Acknowledgements

The authors wish to thank colleagues within the project for assistance and comments on the various documents, particularly Dr. A Klenk, MPA, Germany;, Dr. G Fedeli, ENEL, Italy; Dr. A Thomas and Dr. U Gampe, SPG, Germany; Ing. Roland, Laborelec, Belgium; Dr. H Rantala and Dr.-Ing F Hukelmann, JRC, Petten, The Netherlands; Dr. S Marie, CEA, France; Ing Margarida Pinto and Ing. Sandra Estanislau, MT, Portugal; and Professor D. Smith and Dr. D George, The University of Bristol, UK. This work was carried out as part of the EC Project No. 10886, INTEGRITY of Repair Welds and the EC is gratefully acknowledged for funding.

8. References

[1]. Ambrose, S., Moss, C.J., Croker, A.B.L. and Harrison, R.P., 1995, A perspective of pressure plant life management in Australia., Conf. “Failures, repairs and life assessment of pressure vessels and pipework”, Melbourne, March, 1995, Inst. Metals and Materials Australia Ltd.,

[2]. Brett, S.J., 1994, Cracking experience in steam pipework in National Power, VGB Conf. “Materials and weld technology in power plants”, Essen, Germany, March, 1994.

[3]. Cheetham, D., Fidler, R., Jagger, M. and Williams, J.A., 1977, Relationships between laboratory data and service experience in cracking of CrMoV welds, Conf. “Residual stresses and their effect on welded constructions”, London, TWI, Cambridge, UK.

[4]. Ainsworth, R.A., 1990, R5. Assessment procedure for the high temperature response of structures. British Nuclear plc, UK.

[5]. TRD 507. 1992, Guideline for assessment of microstructure and damage developed in creeping materials for pipes and boiler components, VGB-TW507. NORDTEST 302, Auerkari, P, Salonenm J. and Borggren. K., 1995, Guidelines for evaluation of service damage.

[6]. Lundin, C., 2001a, Weld repairs are costly, . Conf. “Repair Welding and serviceability”, San Diego, Ca., USA., Jan. 2001, PVRC, NY, USA.

[7]. Lundin. C., 2001, Controlled deposition welding, . Conf. “Repair Welding and serviceability”, San Diego, Ca., USA., Jan. 2001, PVRC, NY, USA.

[8]. Doty, W.D., 2001, Challenges and solutions in repair welding of ferritic materials-Keynote, Conf. "Repair Welding and Servicability", San Diego, Ca. Jan. 2001, PVRC, New York, USA.
[9]. Stout, R.D., 1987, "Weldability of Steel", Welding Research Council, New York, USA.
[10]. Kiessling, L. and Johansson, N., 1999, Lifetime analysis of a steam boiler in Hasselby power plant in Sweden, Conf. "CAPE 99", Wilderness, South Africa.
[11]. Sun, W., Hyde, T.H., Becker, A.A. and Williams, J.A., 2000, Comparison of the creep and damage failure prediction of the new, service aged and repaired thick walled circumferential CrMoV butt welds using materials properties at 640 C., Int. J. Press. Vess. and Piping., 77, 389.
[12]. Alberry, P.J., Myers, J. and Chew, B., 1977, An improved welding technique for HAZ refinement, Welding and Metal Fabrication, Nov.
[13]. Clarke, J.N., 1985, MMA weld modelling, Parts 1 - 3, Mats. Sci. & Tech., 1, 1069.
[14]. Reed, R.C. and Bhadesia, H.K.D.H., 1994, A simple model for multi pass welds, Acta Metall. Mater., 42, 11, 3663.
[15]. Rosenthal, D., 1941, Mathematical theory of heat distribution during welding and cutting, Welding J., Res. Suppl., 220, 220s.
[16]. Grong, O. 1997, Metallurgical Modelling of Welding", 2nd. Edition, Institute of Materials, London, UK.
[17]. Suzuki, R.N., Trevisan, R.E. and Trevisan O.V., 2000, Analytical solutions for heat flow in multipass welding, Sci. & Technology of Welding and Joining, 5,2, 63.
[18]. WRC 412., Challenges and solutions in repair welding for power and process plant, Bulletin 412, Welding Research Council, NY, USA,
[19]. Gandy, D.W. and Smith, R., 2000, Shielded metal arc welding temperbead repair without grinding, 4th. RRAC Conf. “Welding and repair technology for power plants”, Marco Island, Naples, Fa., USA, EPRI, Palo Alto, Ca., USA.
[20]. Lundin, C.D., 1996, Overview of results from PVRC programmes on half bead / temperbead / controlled deposition techniques for improvement of fabrication and service performance of CrMo steels. WRC 412., Challenges and solutions in repair welding for power and process plant, Bulletin 412, Welding Research Council, NY, USA.
[21]. Lau, T.W., Lau, M.L. and Poon, G.C., 1996, Development of controlled deposition welding at Ontario Hydro, Conf. “Challenges and solutions in repair welding for power and process plant”, San Diego, WRC Bulletin 412, 1996.
[22]. Lundin C.D. and Wang, Y., 1989, Repair welding of service exposed Cr-Mo steel weldments, Welding Research Counciil Bulletin 348, Nov. 1989, WRC, New York, USA.
[23]. Allen, D.J. and Kelly, T.W., 1995, Cold weld repair- development and application, Conf. Welding and repair technology for power plant, Daytona Beach, Fa. USA, EPRI, Palo Alto, Ca., USA
[24]. Friedman, L.M., 1996, EWI/TWI controlled deposition repair welding procedure for 1CrMo and 2.25Cr1Mo steels, Conf. “Challenges and solutions in repair welding for power and process plant”, San Diego, WRC Bulletin 412, 1996.
[25]. Zemzin, V.N., Titiner, Z.K., Shron, R.E., Bukin, Yu, Krechet, L.E. and Bereznev, A.T., 1978, Reliability of welds to repair defects in cast components made from CrMoV steel, Energomashinstroenie, 12, 25.
[26]. Brett, S.J., 1987, The long term creep rupture of nickel based cold welds in CrMoV pipework, Conf. “Refurbishment and life extension of power plant”, London., IMechE, UK.
[27]. Brett, S.J., Abson, D.J. and Jones, D.L., 1998, The repair welding of plant without PWHT, Conf., “Integrity of High temperature welds”, Nottingham, UK, Professional Engineering Publishing, UK.

[28]. Williams, J.A., 1998, The high temperature performance of austenitic:ferritic dissimilar welds, Conf. "Integrity of High Temperature Welds", Nottingham, UK, Professional Engineering Publishing, UK.
[29]. Mitchell, K.C., 1994, Cold weld repair applications in the UK, EPRI Conf., Weld repair technology for fossil fired plant", Williamsburg, Va., USA. EPRI, Palo Alto, USA.
[30]. Samuelson, L.A., Segle, P. and Storesund, J., 1994, Life assessment of repaired welds in high temperature applications, EPRI Conf., "Welding and repair technology for fossil fired plants", Williamsburg, Virginia, USA, EPRI, Palo Alto, Ca.
[31]. Sun W., Hyde, T.H., Becker, A.A. and Williams, J.A., 2001, A study of weld repairs in a CrMoV service exposed pipe weld, Conf. Proc. 9th. Conf. "Creep and Fracture of Engineering materials and Structures", Swansea, UK, Institute of Materials, London.
[32]. Hyde, T.H., Sun, W. and Becker, A.A., 2000, Effects of end loading on the failure behaviour of CrMoV welds in main steam pipe lines, Conf. "Computer aided assessment and control, (Damage and Fracture Mechanics 2000), May, 2000, MONTREAL, Canada.
[33]. Sandstrom, R., Wu, R and Storesund, J., 1992, Through thickness distribution oof creep damage in a service aged double T joint of CrMoV steel, Conf., ICPVT-7.
[34]. Bissell, A., Scully, S. and Small, R., 2000, A case history of creep crack growth in a seam welded reheater outlet header, 2nd. HIDA Conf. "Advances in defect assessment in high temperature plant", Stuttgart, Germany.
[35]. Storesund, J., 1998, Guidelines for repair welding, IIW WG "Creep", Budapest, Hungary.
[36]. Day, R., Rowley, T.R. and Williams, J.A., 1979, Examination of deformation and failure modes of an overheated 1CrMo boiler header assembly of complex form, CEGB Report RD/M/R277.
[37]. Van Wortel, H., Heerings, J.H. and Arav, F., 1995, Integrity of creep damaged components in power generation plants after welding without post weld heat treatment, Conf. Baltica III, Helsinki, VTT.
[38]. Van Wortel, H. and Arav, F., 1996, Effectiveness of repair welding without PWHT of creep damaged 1Cr0.5Mo and 2.25Cr1Mo components. Int. Conf. Pressure Vessel Technology, ASME., New York, USA.
[39]. Van Wortel, J. and van Vulpen, R., 2000, Time and cost effective method for in situ repair of creep exposed high temperature components, 4th. RRAC Conf. "Welding and repair technology for power plants", Marco Island, Naples, Fa., USA, EPRI, Palo Alto, Ca., USA.
[40]. Rotvel, F, Sampietri, C., Verelst, L., van Wortel, H. and Zhi, L.Y., 1998, Header Integrity Assessment, Conf. Baltica IV, Helsinki, VTT.
[41]. Van Wortel, H., 1999, Effectiveness of repair of in service exposed components by grinding or by welding without PWHT, Conf. "Langzeitverhalten warmfester Stahle und Hochtemperaturwerkstoffe", Dusseldorf, Nov. 1999, VdeH.
[42]. Viswanathan, R., 1995, Weld repair of aged piping- a literature survey, EPRI 2nd. Conf., Daytona Beach, Fa, USA
[43]. Viswanathan, R, Gandy, D. and Findlan, S.J., 1999, Weld repair of 1.25Cr0.5Mo piping girth welds, PVP-Vol 388, "Fracture, Design, Analysis of pressure vessels, heat exchangers piping components and fitness for service, 1999.
[44]. Viswanathan, R. and Gandy, D., 1998, Performance of repair welds in aged CrMo piping girth welds, Conf., "Integrity of High temperature welds", Nottingham, UK, Professional Engineering Publishing, UK.
[45]. Viswanathan, R. and Gandy, D., 1999, Performance of repair welds in aged CrMo piping girth welds, J. Mats. Eng. and Performance, 8, 579-
[46]. Viswanathan, R, Gandy, D. and Findlan, S.J., 1997, Performance of repair welds on service aged 2.25Cr1Mo girth weldments, J. Pressure Vessel Technology, Nov., 119, 414-

[47]. Viswanathan, R, Gandy, D. and Findlan, S.J., 1999, Weld repair of 2.25Cr1Mo service aged header welds, J. P.V. Technol., 121, Nov, 345-
[48]. Hyde, T.H. and Tang, A., 1998, Creep analysis and life assessment using cross weld specimens, Int. Mats. Rev., 43, 6, 221.
[49]. De Witte M. and Coussement, C, 1992, Behaviour of 2.25Cr1Mo base matertial and repair weldments at high temperatures, "Creep Characterisation, Damage and Life Assessment", Ed. D.A.Woodford, C.H.A.Townleey and M. Ohnami, ASM International, Metals Park, OH.
[50]. Arnswald, W., Blum, R., Neubauer, B. and Poulsen., K.E., 1986, Remaining life affected by repair welds, Conf. “Creep”, Tokyo, Japan, Japan Soc. Of Mech. Engrs.
[51]. Ettienne, C.F. and Heerings, J.H., 1993, Evaluation of the influence of welding on creep resistance, IIW Doc. IX-1725-93
[52]. Nonaka, I., Ito, T., Ohtsuki, S. and Takagi, Y., 2000, Performance of repair welds on aged 2.25Cr1Mo boiler header welds., 2nd. HIDA Conf. “Advances in defect assessment in high temperature plant”, Stuttgart, Germany.
[53]. Croker, A.B.L., Finlay, M.R. and Law, M., 1996, Weld repair of creep damaged pressure vessels and piping steels, Conf. Welding and repair technology for power plant, Daytona Beach, Fa. USA, EPRI, Palo Alto, Ca., USA.
[54]. Ettienne, C.F., Heerings, J.H. and van Wortel, J.H., 1992, Weldability and assessment of residual life of repair welds in thick walled headers., VGB Conf. “Residual Life”, Mannheim, Germany.
[55]. Lundin C.D. and Wang, Y., 1989, "Repair welding of service exposed CrMo weldments", Welding Research Council Bulletin 348, WRC, New York, USA.
[56] Viswanathan, R., Gandy, D. and Findlan, S., 1999, Weld repair of 1.25Cr0.5Mo steel piping girth welds, PVP. Vol. 388, Fracture, Design, Analysis of Pressure Vessels, Heat Exchangers, Piping Components and Fitness for Service, ASME, USA.
[57]. Gandy, D.W., Findlan, S.J. and Viswanathan, R., 1999, Weld repair of steam turbine casings and piping-an industrial survey, PVP Vol. 388, Fracture, design, analysis of pressure vessels, piping components and fitness for service,
[58]. Newell Jr., W.F., 2001, Component repair using undermatching weld filler metals to avoid cracking problems, . Conf. “Repair Welding and serviceability”, San Diego, Ca., USA., Jan. 2001, PVRC, NY, USA.
[59]. Newell Jr., W.F. and Scott, J., 2000, Properties and fabrication experience with SA welding of P91 piping systems, 4th. RRAC Conf. “Welding and repair technology for power plants”, Marco Island, Naples, Fa., USA, EPRI, Palo Alto, Ca., USA.
[60]. Lundin. C., Liu, P., Zhou, G. and Khan, K.K., 1999, Efficiency of low carbon 1.25Cr0.5Mo weld metal for repair welding., WRC Bulletin No. 439, PVRC, NY., USA.
[61]. Lundin, C. and Prager, M., 2001b, Repair weld issues for high temperature service, . Conf. “Repair Welding and serviceability”, San Diego, Ca., USA., Jan. 2001, PVRC, NY, USA.
[62]. Dong, P., 2001, Residual stress in repair welds and local PWHT effects, Conf. “Repair Welding and serviceability”, San Diego, Ca., USA., Jan. 2001, PVRC, NY, USA