1. SCOPE
At first glance, any repair, alteration or modification to an item of pressurised equipment that was originally postweld heat treated after fabrication should be postweld heat treated again after repair. This is not always possible, and efforts over the past 20 years have been aimed at finding ways around this.

This Note provides guidance on the methods available to perform temper bead welding as an alternative to postweld heat treatment for the control of Heat Affected Zone microstructure, hardness and other properties.

2. DEFINITION
The ASME Boiler and Pressure Vessel code defines temper bead welding as follows: “A weld bead placed at a specific location in or at the surface of a weld for the purpose of affecting the metallurgical properties of the heat affected zone or previously deposited weld metal”.

3. APPLICATION
It has applications in the Pressure Equipment industry for repairs and modifications. The steels to which the technique is applied are limited to those that can suffer loss of fracture toughness in the Heat Affected Zone (HAZ) as a result of welding or those that can suffer re-heat cracking. As such, the technique is generally limited to creep-resisting steels containing Chromium (Cr), Molybdenum (Mo) and Vanadium (V) with alloy contents up to 2.25% Cr and 1% Mo. Traditional pressure vessel (Carbon-Manganese) steels with carbon contents up to 0.25% and wall thickness in excess of 32mm may also be temper bead welded.

4. DEVELOPMENT OF TEMPER BEAD WELDING

Temper bead welding was developed to alleviate the need for postweld stress relief (PWSR) and to reduce as-welded HAZ hardness. But residual stress will obviously remain if PWSR is not carried out. Also the full creep strength will not be developed for many creep-resisting alloys. Temper bead welding cannot therefore be used as a substitute for postweld heat treatment in circumstances where operating conditions require a substantial reduction in residual stress levels.

However, temper bead welding techniques have been developed to *simulate the tempering effect of postweld heat treatment*. There are claims that mechanical properties in the HAZ can be improved similar to those improvements gained with conventional postweld heat treatment. The temper bead welding has been specifically developed to refine the coarse grained HAZ in the parent metal by the judicious positioning of weld beads and control of heat input. This heat treatment aims to improve the fracture toughness and reduce the peak hardness within the HAZ.

5. GOVERNING CODES AND STANDARDS

Currently clause 6.2 “Repairs, Replacements & Alterations” of AS/NZS 3788 “Pressure Equipment – In service inspection” makes a clear statement that all repairs shall be carried out in accordance with the relevant design and fabrication standards. The clause mandates that repairs must also comply with AS 4458 “Pressure Equipment – Manufacture”. Section 14 “Heat Treatment” of Australia AS 4458 provides the requirements for postweld heat treatment and includes a clause that states “….in special circumstances heat treatment may be omitted provided it can be proven that all precautions are taken to ensure the safety of equipment.”

Attempts to achieve satisfactory results from weld repairs where postweld heat treatment has been omitted are not new. Code Case N-432 for a limited range of materials under ASME III in the United

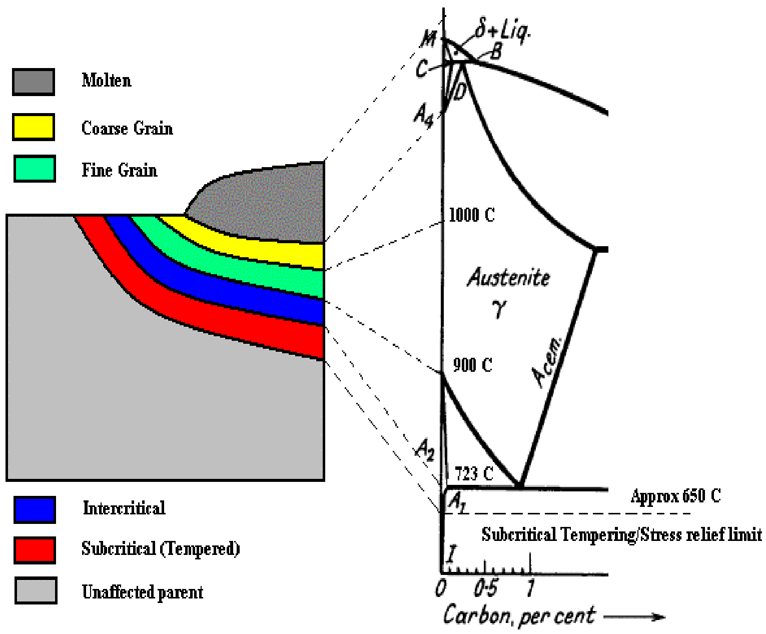
States was established in 1986. The various techniques have been refined and adopted into other standards such as ASME B 31.1 and B 31.3

The 2004 edition of Section IX of the ASME Boiler and Pressure Vessel code has addressed temper bead welding under clause QW-290 “Temper Bead Welding”. The six sub-clauses under this section provide the requirements for procedure qualification requirements, restrictions, essential and non-essential variables, test coupon preparation and testing and in-process repair welding. Additionally sub-clause QW-290.6 provides supplementary qualification requirements for the welders who will be carrying out the work.

Currently AS 4458 and AS 3992 do not directly address temper bead welding. Thus, for those wishing to qualify and implement temper bead welding for applications other than minor repairs it would be necessary to carefully review section 14 of AS 4458 and determine if the repair constitutes the special circumstance provisions. Operators of pressure plant may need to consult with their regulators prior to making modifications without postweld heat treatment. Nevertheless ASME Section IX requirements in addition to AS 3992 are recommended for those wishing to qualify and implement temper bead welding.

6. METALLURGICAL PRINCIPLES OF HEAT TREATMENT

To understand what is taking place in the HAZ due to postweld heat treatment, postweld stress relief or temper bead welding it is necessary to define these terms with reference to the iron-carbon phase diagram Figure 1. Although this Note is aimed at creep resisting steels containing chromium and molybdenum, the metallurgical principles shown in Figure 1 are the same.



Note: During welding there can be up to four sub-zones within the HAZ created according to the maximum temperature reached and the duration of time at that temperature.
These sub-zones are:

- *Sub-critical: 650 – 723°C*
- *Inter-critical: 723 – 900°C*
- *Fine Grain: 900 – 1000°C*
- *Coarse Grain >1000°C < melting point.*

Formation of these sub-zones is determined by the transformation characteristics of the steel.
The dashed lines linking the iron-carbon phase diagram on the left to the HAZ sub-zones indicates the transformation taking place during the welding process.

Figure 1. Iron–carbon phase diagram showing the transition points relating to a weld HAZ (Reference 6)

Heat Affected Zone (HAZ)
The HAZ is that portion of the parent metal adjacent to the weld that has not been melted but whose microstructure and hence mechanical properties have been altered by the heat of welding. As can be seen from Figure 1, there can be up to four sub-zones within the HAZ that all have different microstructures.

Any part of the HAZ that is heated above the lower transition temperature “A_1” as shown in Figure 1 is subjected to changes in microstructure. The key factors determining the microstructural changes for the steels discussed here are:

- Chemical Composition of the steel;
- Cooling rate;
- Welding heat input;
- Time at elevated temperature.

The chemical composition affects microstructural changes by delaying the transformation of austenite to ferrite and pearlite. The more alloy constituents, the more likely to form martensite or bainite in the HAZ.

The cooling rate has a similar effect. The higher the cooling rate, the greater the chance of avoiding the ferrite/pearlite transformation and the greater the chance of forming undesired martensite.

The welding heat input and pre-heat also influences on the cooling rate, and hence HAZ microstructure.

The portion of the HAZ that is heated above 1000^{o}C experiences grain growth. The longer the HAZ is above 1000^{o}C, the more the grain growth which in turn results in loss in toughness. Welding with high heat inputs results in the HAZ being subjected to temperatures of 1000^{o}C or above for a longer time resulting in a coarse grained HAZ with poor fracture resistance properties.

High welding heat inputs need to be balanced against low heat inputs. The latter results in faster cooling rates thus increasing the tendency for the formation of martensite.

Postweld Heat Treatment (PWHT)
In this Note, PWHT is the generic term for any thermal treatment carried out after welding including: postweld stress relief, aging or precipitation hardening, annealing, hydrogen dispersion, quench & tempering, normalising, normalising & tempering and tempering.

According to AS 4458 – 1997, PWHT is intended to do either or both of the following:
a) Reduce residual stresses and improve resistance to brittle fracture, stress corrosion or in some cases, fatigue or control distortion on subsequent machining.
b) Achieve or restore the material properties required for the design and service conditions.

PostWeld Stress Relief (PWSR)
This Note refers to PWSR as one type of PWHT where the weld is re-heated to a temperature below the lower transition temperature "A_1" as shown in Figure 1. Typically the upper temperature limit for PWSR is 650^{o}C for C-Mn steels (higher for Cr-Mo steels). PWSR provides two main benefits. Firstly it reduces the residual stress built up in the weld as a result of welding. Secondly it enables tempering to take place.

Tempering
Tempering, in the context of the steels discussed in this Note, consists of re-heating HAZ hardened steel to some temperature below the A_1 with 650^{o}C again being the typical upper limit for C-Mn steels. The purpose of tempering is to improve the toughness of the HAZ microstructure. The microstructures addressed in this note are the HAZ microstructures depicted in Figure 1 with the emphasis being on the coarse grained HAZ immediately adjacent to the weld. It is this coarse grained region that has a tendency to form martensite during welding and requires postweld heat treatment.

7. TEMPER BEAD WELDING TECHNIQUES

7.1 Techniques
In temper bead welding, the heat input, preheat and weld bead sequence are closely controlled to:
a) Limit heat input and pre-heat to avoid excessive grain coarsening of the "coarse grained" HAZ of the first weld layer;
b) Increase heat input by a set amount for the second weld layer to grain refine the coarse grained HAZ of the underlying first weld layer;
c) Overlap the placement of successive weld beads to produce grain refinement of the adjacent bead.

Five temper bead welding techniques have been developed over the past twenty years:
a) Half Bead Technique
b) Consistent Layer Technique
c) Alternate Temper Bead Technique
d) Controlled Deposition Technique
e) Weld Toe Tempering Technique

All techniques are similar in the goal of tempering the coarse grained HAZ in the parent metal. The methods by which the weld beads are deposited vary from technique to technique. These are discussed below.

7.2 Half Bead Technique
The technique was originally developed for use in the nuclear industry, but has since become widely used for repairs to piping, headers and turbine casings in conventional power plant.

The MMAW technique is used and employs a series of increasing diameter electrodes, starting with 2.5 mm, then 3.2 mm and finishing with a 4.0 mm electrodes. The increasing diameters provide a sufficient increase in heat input from the first to the third layer.

The area to be repaired is cleaned and preheated to a temperature commensurate with the material and thickness (typically >150^{o}C), and a buttering technique used as a first layer with 2.5 mm electrodes. The use of 2.5 mm electrodes is to produce a small, shallow heat affected zone.

The second step is to remove approximately half of the welded layer by grinding.

The third step is the deposition of a second layer using 3.2 mm electrodes. This effectively re-transforms the coarse-grained heat affected zone and first layer.

The fourth step is again to remove approximately half of the welded layer by grinding.

The remaining steps are the deposition of third and subsequent layers using 4.0 mm electrodes with further grinding after each layer has been deposited. Each subsequent layer transforms and tempers the layers beneath it.

The disadvantage of the technique is that a lot of accurate grinding is required. This is time consuming and if too much material is removed from the first layer, the effects of the re- transformation are not successful. As a result this technique has now lost favour.

7.3 Consistent Layer Technique
This technique utilises either the MMAW or the GTAW process. The technique involves depositing weld layers that are sufficiently thick that the subsequent weld layer only tempers the heat affected zone caused by the first layer. The temperature is not intended to exceed the “A_1” temperature so no grain transformation occurs. The technique can produce a heat affected zone microstructure that consists predominantly of tempered martensite with small amounts of bainite, resulting in good toughness properties

7.4 Alternate Temper Bead Technique
This technique was developed specifically for carbon-manganese and carbon-molybdenum materials used in nuclear reactor pressure vessel components. It utilises the automatic GTAW process and is an alternative to the half bead technique for use in areas of high radiation exposure.

The technique involves preparing the area to be repaired so that at least six buttering layers can be performed. A preheat of 150^{0} C minimum is applied, and the heat input of each layer is controlled to within 10% of that measured in the procedure qualification test.

7.5 Controlled Deposition Technique
This technique resulted from special cases where creep embrittlement and re-heat cracking were potential problems during repair, and was aimed at specific materials used in conventional fossil-fired stations. It is also a MMAW technique, and uses strictly controlled ratios of heat input between one weld layer and the next. The heat input for the second layer is 1.3 to 1.8 times higher than for the first layer, and is designed to produce grain refinement and tempering in the original heat affected zone. The ratios need to be experimentally verified for each material to be welded

The increase in heat input should be 30 to 70% for each subsequent layer, and for MMAW, increasing the electrode size by one size whilst keeping the welding technique the same generally achieves this.

It is not necessary in production to use exactly the same heat input as in the procedure test, but the ratio between layers must remain the same.

Part of the weld metal and HAZ of the first bead is re-melted by the second bead. How much is re-melted depends on the overlap, but typically, a 50% overlap is the aim. The temper bead technique usually involves completing the first layer first.

The heat input for the second layer runs is increased so that the heat re-melts some of the first layer but re-transforms the coarse-grained area of the HAZ while tempering the inter-critical region. Extreme care is needed with placement of the final run. The third layer is a repeat of the second layer with increased heat input.

7.6 Weld Toe Tempering Technique

This technique involves the placement of a sacrificial capping using beads, runs or weld sequence to temper the underlying HAZ at the toe of butt or fillet welds. The bead placement sequence is crucial to achieve the desired effect. The temper capping beads are usually ground off to bring the weld reinforcement back to acceptable limits.

Whilst the virtues of temper bead welding techniques are debatable, there is no doubt that the HAZ at the weld toe is one of the hardest areas when left in the as-welded condition. The weld toe tempering technique provides a simple method to temper this area without resorting to PWHT. It has been applied for many years.

8. QUALIFICATION OF TEMPER BEAD WELDING PROCEDURES

ASME Section IX has provided full details on temper bead qualification testing in accordance with the ASME code. The qualification process for temper bead welding must establish that the welding technique produces the required heat treatment of the HAZ in addition to meeting the traditional welding procedure qualification requirements.

To determine if the temper bead welding procedure produces the required HAZ the following four supplementary tests are generally applied:

1) Microstructural assessment of Weld and HAZ This assessment will determine the presence of un-tempered martensite, regions of excessive grain growth and the presence of any undesirable microstructures.

2) Hardness Testing A systematic hardness survey across the weld and HAZ will provide rapid evidence of undesirable hard microstructures. A micro-hardness testing survey across the HAZ using a Vickers or Knoop hardness testing methods provides a good indication of whether the desired microstructures in the HAZ was achieved.

3) Charpy Vee Notch Impact Testing Charpy Vee Notch testing of the as-welded HAZ provides a well recognised determination of the notch toughness of the HAZ.

4) Bend Test The traditional side bend test provides a rapid and inexpensive method of determining the ductility and strain capacity of the HAZ.

In order to determine the effectiveness of the temper bead welding procedure it will be necessary to compare the temper bead HAZ results with:

a) The same results obtained from the conventional welding procedure qualification test after the traditional postweld heat treatment;

b) The same test results obtained from the conventional welding procedure without postweld heat treatment.

Both comparisons are required to determine if the applied temper bead welding technique provides the required results.

9. QUALIFICATION OF TEMPER BEAD WELDERS

In addition to the usual welder qualification requirements of AS3992 and ASME Section IX, it is necessary for welders to complete a supplementary proficiency demonstration. This demonstration mimics the actual welding to be carried out with a sufficient amount of welding to show competency.

The complexities of most temper bead welding techniques require the welder to be supervised by a competent person for the duration of the welding. Weld toe tempering can be achieved by a competent welder in a satisfactory manner without full time supervision.

10. EXAMPLE TEMPER BEAD WELDING REPAIR TECHNIQUE

The following example demonstrates the controlled deposition technique applied to a repair weld situation using 2.4 mm and 3.2 mm hydrogen controlled MMAW electrodes. The welding parameters would be the actual parameters measured during the repair. Pre-heat must be maintained at a minimum of 150°C with a maximum interpass temperature of 200°C.

The controlled deposition is achieved by following the specific bead deposition sequence shown in each figure to complete each layer. Note the increase in Heat Input from an average of 0.67 kJ/mm on the first layer to an average of 1.14 kJ/mm for the second layer and 1.4 kJ/mm for the third layer. A final layer is required to temper the underlying layer. However, this typically results in excess reinforcement which is subsequently removed by grinding.

The application of weld pass 14 over weld pass 7 and weld pass 16 over weld pass 9 is the traditional weld toe tempering technique. With such welding it is important for the final weld pass(es) to be deposited in the centre portion of the weld.

11. BIBLIOGRAPHY

1. ASME IX 2004 Edition
2. AS/NZS 1200:2000 Pressure Equipment
3. AS/NZS 3788:2001 Pressure Equipment – In-service inspection
4. AS 3992:1998 Qualification of Welders and Welding Procedures
5. AS 4458:1958 Pressure Equipment - Manufacture
6. Exploring Temper Bead Welding, Walter J. Sperko Welding Journal July 2005, pp37 to 40
7. Weldability of Steels, Stout and Doty;
8. AWS Welding Handbook, Vol 4 8th Ed
9. Inspection and Welding Repairs of Pressure Vessels, S.V. Gupte Arcraft Plasma Pvt Ltd.
10. Carbide and Hardness Development in HAZ of Tempered and PWHT 2.25-1Mo Steel Weldments, Peddle B.E. & Pickles C.A. Journal of Materials Engineering & Performance, Vol 9 #5 Oct 2000
11. X-ray diffraction based residual stress analysis of repair welds of Cr-Mo steels, S. Rai, S. Sujith, T. Jayakumar, WCNDT '96 – New Delhi
12. Creep –fatigue properties of 2.25Cr.-1Mo Repair Welds, Y. Takagi, S. Otsuki, T. Ito I. Nonaka. OMNI Vol 2 Issue 1 April 2003

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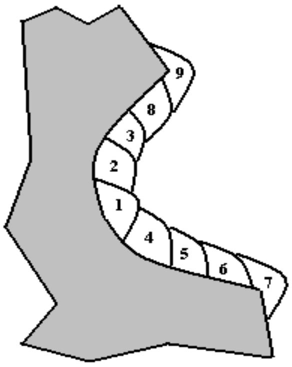
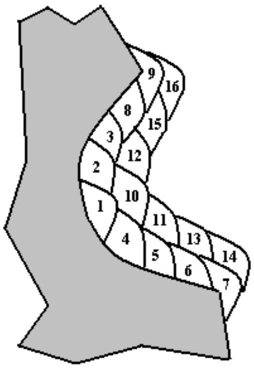


Welding Parameters 2.5 mm electrodes

Run	Volts	Amps	Speed mm/min	Heat Input KJ/mm
1	20	100	173	0.69
2	21	95	156	0.76
3	21	95	153	0.79
4	20	95	174	0.67
5	20	95	174	0.66
6	20	95	180	0.63
7	20	95	180	0.63
8	20	95	192	0.59
9	21	95	180	0.67
				0.67

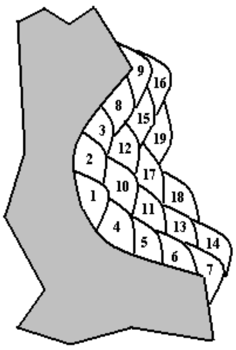
FIRST LAYER



Welding parameters 2.5 mm electrodes

Run	Volts	Amps	Speed	Heat Input
10	21	100	132	1.19
11	21	95	132	1.19
12	21	95	140	1.13
13	21	95	146	1.10
14	21	95	146	1.09
15	21	95	138	1.14
16	21	95	140	1.13
				1.14

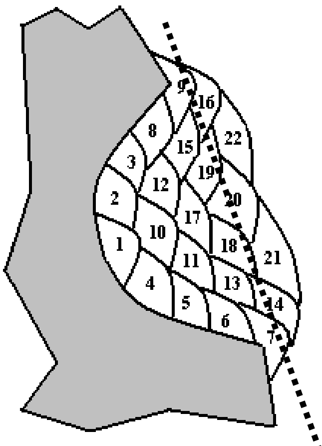
SECOND LAYER



Welding Parameters with 3.2 mm electrodes

Run	Volts	Amps	Speed	Heat Input
17	21	125	113	1.39
18	21	125	118	1.33
19	21	125	105	1.50
				1.40

THIRD LAYER



Welding Parameters with 3.2 mm electrodes

Run	Volts	Amps	Speed	Heat Input
20	21	125	140	1.13
21	21	125	142	1.11
22	21	125	150	1.05
				1.10

FINAL LAYER
NORMALLY GROUND OFF ALONG DOTTED LINE

Notes:
HEAT INPUT RATIO LAYER 1 TO 2 = 1.7
HEAT INPUT RATIO LAYER 2 TO 3 = 1.22
AIM IS TO INCREASE HEAT INPUT 30% TO 70% WITH EACH LAYER
Note how weld pass 14 tempers the HAZ at the toe of weld pass 7 and weld pass 16 tempers achieves the same purpose with weld pass 9. Correct placement of beads 14 and 16 is crucial to a successful outcome.

Figure 2. Temper Bead Examples

NDNP TECHNOLOGY DIFFUSION ACTIVITY # 27	Welding Technology Institute of Australia ABN 69 003 696 526 **NATIONAL DIFFUSION NETWORKS PROJECT** **TECHNOLOGY QUESTIONNAIRE** **Pressure Equipment Industry Group** **"Temper Bead Welding"**	**Document No:** 9.4.4 – QR - 001 **Revision No:** Rev 0 **Page 1 of 2** **Date:** 18 Nov 2005

As part of the WTIA National Diffusion Networks Project the Pressure Equipment Industry Sector has identified the need to increase understanding of temper bead welding techniques for pressure equipment repairs. The WTIA has prepared a Technical Guidance Note "Temper Bead Welding" to explain the features, use and applications of temper bead welding. As a valued technology expert in this area we would like you to be part of the Technology Expert Group to review this note. Please complete this questionnaire so that we can gauge the success of meeting this need.

Objective 1: Identify the need to increase understanding of temper bead welding

There is an increasing need to carry out in-situ weld repairs to aging pressure equipment. Traditionally post-weld heat treatment is required on such equipment. This guidance note is intended to provide the Pressure Equipment Industry with the features of temper bead welding in repair situations so an informed decision can be made on whether to use PWHT. How well does the document explain the temper bead welding technique?

poor ☐ average ☐ good ☐ very good ☐

Comments: ______________________________

Objective 2: Identify appropriate technology receptors in the Pressure Equipment Industry

This document was written for Welding Coordinators and Maintenance Engineers in the Pressure Equipment Industry. Are these people the appropriate individuals we should be targeting?

yes ☐ no ☐

What other types of companies and/or personnel do you suggest we target? ______________________________

____

Objective 3: Identify current best practice for temper bead welding

The document was written to reflect current best practice for temper bead welding. Do you envisage opportunities for the use of this technology in the industry?

yes ☐ no ☐

If yes, what and where, if no why not? ______________________________

____

Objective 4: Is the information provided clear, concise and accurate?

yes ☐ no ☐

If not, why? ______________________________

Objective 5: Broad dissemination of technology to the Pressure Equipment Industry

Please indicate how best to disseminate this Technical Guidance Note to the appropriate Pressure Industry Recipients

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If poster, what size? A1 ☐ A2☐ A3 ☐ Laminated ☐ What selling price? $

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Other format? ______________________________

Objective 6: Continuous Improvement

Please Identify areas where the document can be improved or return the document with your recommended additions/amendments. Alternatively, please use the area below to provide any additional comments.

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Please Fax (02 9748 2858) or E-mail (j.baker@wtia.com.au) your response.

Your prompt response is appreciated.