GUIDELINES FOR PIPELINE REPAIR BY DIRECT DEPOSITION OF WELD METAL[1]

Bruce W A and Amend W E

ABSTRACT

Pipeline repair by direct deposition of weld metal, or weld deposition repair, is an attractive alternative to the installation of full-encirclement sleeves for repair of wall loss caused by corrosion on in-service pipelines. This is particularly true where the installation of full-encirclement sleeves is difficult or impossible, such as for bend sections and fittings. The results of previous work indicate that weld deposition repairs have the ability to restore the static strength of a pipeline and are resistant to pressure cycles over a wide range of applications. Weld deposition repair is attractive because it is direct, relatively inexpensive to apply, and requires no additional materials beyond welding consumables. To allow the confident use of weld deposition repair, guidelines for carrying out this technique are presented.

KEYWORDS

Pipelines, welding, in-service, repair, direct deposition, weld deposition repair, guidelines.

AUTHOR DETAILS

Mr. W A Bruce is Director of Welding and Materials Technology at DNV Columbus, Inc., in Dublin, Ohio, USA

Mr. W E Amend is an Associate with Structural Integrity Associates, Inc. in Cerritos, California, USA

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1. INTRODUCTION

Pipeline repair by direct deposition of weld metal, or weld deposition repair, is an attractive alternative to the installation of full-encirclement sleeves for repair of wall loss on in-service pipelines. This is particularly true where the installation of full-encirclement sleeves is difficult or impossible such as for wall loss in bend sections and fittings. The results of recently completed work [1-2] and previous work by others [3-8] has shown that weld deposition repairs have the ability to restore the static strength of a pipeline and are resistant to pressure cycles over a wide range of applications.

To allow the confident use of weld deposition repair, guidelines for carrying out this technique were developed [9]. These guidelines address not only the welding issues, but issues pertaining to inspection following welding, acceptance standards for discontinuities detected during inspection, and other related issues.

2. BACKGROUND

There are significant economic and environmental incentives for performing maintenance and repair welding on pipelines without removing them from service. From an economic viewpoint, a shutdown involves revenue loss from interrupted pipeline throughput, in addition to that from the gas lost to the atmosphere. Since methane is a so-called “greenhouse” gas, there are also environmental incentives for avoiding the venting of large quantities of gas to the atmosphere. The primary method of in-service pipeline repair of corrosion and mechanical damage is the installation of full-encirclement sleeves, although this is not always practical in some instances and is impossible in others.

There are two primary concerns with welding onto in-service pipelines, including pipeline repair by weld deposition. The first is for “burnthrough,” or blowout as it is sometimes referred, where the welding arc causes the pipe wall to be penetrated, allowing the contents to escape. The second concern is for the integrity of the pipeline following repair.

The concern for the integrity of the pipeline following repair includes ensuring that the deposited weld metal has adequately restored both the static and fatigue strength, allowing the pipeline to be operated safely at its maximum allowable operating pressure. In addition, it is necessary to ensure that significant discontinuities, including heat-affected-zone (HAZ) hydrogen cracking, have not been introduced as a result of the repair. The concern for hydrogen cracking comes from the extreme cooling rates and high HAZ hardness levels that tend to be produced as the result of welding onto an in-service pipeline.

Weld deposition repair is attractive because it is direct, relatively inexpensive to apply, and requires no additional materials beyond welding consumables. Potentially the most useful aspect of weld deposition repair is that it can be applied where full-encirclement sleeves cannot, such as for repair in bend sections and fittings. Weld deposition, applied externally, can also be used to repair internal wall loss.

An earlier variant of weld deposition repair, which was referred to as ”puddle welding”, was used to repair metal loss on pipelines as early as the 1920s or 30s (Figure 1). However, puddle welding was generally an uncontrolled process, without specified heat input levels, deposition sequences, or hydrogen control practices. As a result, puddle welds have achieved a reputation for having inconsistent workmanship. Several examples are known in which puddle welds had excessively hard heat-affected zones and cracks. In some cases puddle weld cracks resulted in leaks several years after the repairs were made.

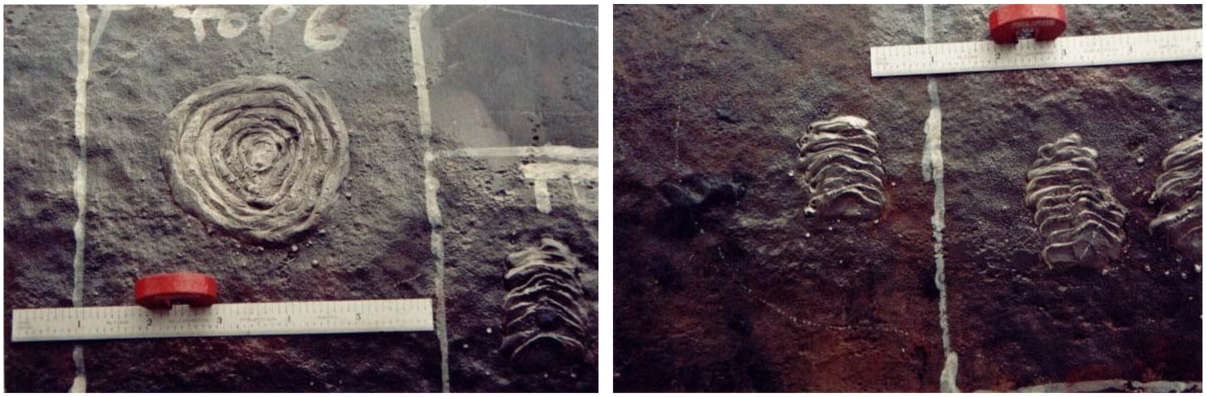

Figure 1. “Puddle welds” removed from older pipelines

3. ISSUES PERTAINING TO WELD DEPOSITION REPAIR

Issues that are relevant to welding onto in-service pipelines in general, and to weld deposition repair in particular, are discussed below.

3.1 Assessment Prior to Repair

The extent or nature of any given defect may not be apparent upon initial excavation. Sound engineering practice suggests that the pressure level should therefore be reduced until a defect assessment can be performed. Lowering the pressure is necessary to protect the repair crew since any given defect may be on the verge of failure when it is discovered. Previous work suggests that a pressure reduction to 80% or less of the level which was present when the defect was discovered is adequate [10]. Alternatively, consideration can be given to factors such as hydrostatic test history and recent peak pressure in determining a safe level of pressure reduction.

Upon detection of a defect, it is necessary to determine if a repair is indeed required. If the predicted failure stress of the defect, including hoop stress caused by internal pressure and secondary stresses, exceeds 100% of SMYS, then there is no reason to perform a repair. Repair, particularly by welding, can lead to the introduction of additional and sometimes more significant defects than the defect being repaired. Welding can also result in the introduction of significant residual stresses. Common corrosion assessment methods used in the pipeline industry include the ASME B31G criteria [11] and RSTRENG computer program [12].

Aside from lowering the pressure to protect the repair crew, it would appear from the results of previous work [1-2] that weld deposition repairs can be made at pressures as high as the RSTRENG predicted safe pressure (i.e., RSTRENG predicted failure pressure multiplied by the design factor) for the defect, up to 900 psig (6.2 MPa).

Experiments conducted in the previous program [1-2] primarily addressed repair of corrosion damage, although this technique can also be used to repair locally-thinned areas that result from grinding to remove mechanical damage, such as a gouge produced by excavating equipment. This technique should not be used for the repair of crack-like defects or for mechanical damage that has resulted in a dent in the pipeline however, as re-rounding of the dent upon pipeline re-pressurization could produce excessive strains in the vicinity of the repair. Also, this technique should not be used to repair selective corrosion in or adjacent to ERW seams that may have low ductility and toughness, which is often the case for older ERW line pipe material.

3.2 Practical Limits for the Maximum Size of Repair

No technical limits were established in the previous work [1-2] for the size of an area that can be effectively repaired using weld deposition. However, it would not be practical to use weld deposition repair for an area that extends around nearly the entire circumference for several pipe diameters in length. This size of an area would be more effectively repaired using an alternative method, such as a full-encirclement sleeve. Individual companies may want to establish limits, based on practicality, for longitudinally, circumferentially and spirally oriented areas. Exceptions to these limits could be made for extenuating circumstances (e.g., larger areas in bend sections that cannot effectively be repaired using a full-encirclement sleeve). Similarly, individual companies may want to establish practical limit for the proximity of one weld deposition repair to another. Again, exceptions could be made for extenuating circumstances.

3.3 Determination of Remaining Wall Thickness

The ability to perform weld deposition repair depends on there being at least enough remaining wall thickness present to avoid burnthrough. The results of previous work [1-2] have shown that weld deposition repair is feasible down to 0.125 inch (3.2 mm) remaining wall thickness provided that proper steps are taken to prevent burnthrough. Prior to repair, it is necessary to determine the remaining wall thickness and to unequivocally establish that there is at least 0.125 inch (3.2 mm) of remaining wall thickness present.

Remaining wall thickness can be determined by measuring the depth of the corroded area, using a “pit gage" or the combination of a bridging bar and a depth micrometer, and subtracting this from the actual local wall thickness of the pipeline. The actual local wall thickness of the pipeline should be verified using an ultrasonic thickness gage. The remaining wall thickness can also be measured directly using an ultrasonic thickness gauge, provided that the diameter of the transducer is small enough to provide an accurate measurement in the bottom of the corroded area. “Pencil-probe” -type transducers are available for this purpose.

More sophisticated methods for determining the remaining wall thickness of a corroded area include mechanized ultrasonic scanning systems that use a water column couplant and laser-based systems that use laser range sensors. While mechanized ultrasonic scanning systems measure wall thickness directly, the laser-based system infers wall thickness by subtracting corrosion depth from the nominal wall thickness, which must be checked using an ultrasonic thickness gauge.

3.4 Surface Preparation

Prior to weld deposition repair, it is necessary to remove corrosion products from the damaged area and, in some cases, to grind the damage to a favorable profile for welding. Before grinding, the length and width of the expected boundaries of the ground area should be evaluated to ensure that the combination of the surface area and depth of the ground area do not become unsafe. In the previous program [1-2], preparation of corroded areas for welding began using an angle grinder with a 4-1/2-inch (114.3-mm) -diameter disk to remove the steep-sided areas. Grinding was also applied to the bottom of the corroded area to remove the corrosion product while taking care not to significantly increase the depth of the corrosion (i.e., decrease the remaining wall thickness). Corrosion product was removed from portions of the corroded area that were inaccessible to the grinder using a rotary file (burr grinder). Abrasive grit blasting may be used to remove corrosion product prior to welding if the remaining pipe wall thickness is sufficient to prevent abrading through the pipe wall in areas of deep pits. Note that in some cases corrosion product can obscure the presence of localized deep pitting.

3.5 Selection of Welding Parameters to Prevent Burnthrough

3.5.1 Factors Affecting Burnthrough

A burnthrough will occur if the unmelted area beneath the weld pool has insufficient strength to contain the internal pressure of the pipe. The occurrence of burnthrough is governed primarily by the pipe wall thickness and the penetration of the welding arc into the pipe wall. Weld penetration is primarily a function of the welding heat input and the ability of the pipeline contents to remove heat from the pipe wall. For a given welding process and electrode type, as heat input increases, penetration into the pipe wall increases, and for a given heat input level, penetration increases as the welding current increases. The ability of the pipeline contents to remove heat from the pipe wall, or the heat sink conditions, is a function of the temperature and thermal properties of the contents, and flow parameters such as pressure (for gases only) and flow rate.

Previous research by Battelle and others concluded that a burnthrough will not occur unless the inside surface temperature exceeds 1800ºF (982ºC) when using low-hydrogen electrodes [13-15] and that this temperature is unlikely to be reached if the wall thickness is 0.250 inch (6.4 mm) or greater, provided that normal welding practices are used [16]. The risk of burnthrough is, therefore, extremely remote under these conditions if the wall thickness is 0.250 inch (6.4 mm) or greater. For areas that are thinner than 0.250 inch (6.4 mm), proper steps must be taken to prevent burnthrough.

The pipeline wall thickness is not normally a parameter that can be changed for a given in-service welding operation, but should be checked using appropriate ultrasonic testing equipment and techniques, such as ultrasonic mapping as described in Section 3.3.

Penetration of the welding arc into the pipe wall is a function of the welding parameters and, to a lesser degree, the welding process. Penetration increases as heat input increases and as the hydrogen potential of the welding process increases. A low-hydrogen process, such as shielded metal arc welding (SMAW) using basic-coated electrodes (e.g., EXX18-type) in conjunction with a low heat-input level results in the least amount of penetration. Conversely, a high-hydrogen potential process such as SMAW using cellulosic-coated electrodes (e.g., EXX10-type) at a high heat input level results in much greater penetration. For a given heat input level, penetration increases as the welding current increases [17]. The level of welding current required for a given electrode tends to increase proportionally with electrode diameter (a general rule of thumb is that the current level required for a given electrode diameter is the diameter in inches times 1000 [e.g., 125 amps for a 0.125-inch diameter electrode]). When welding with direct current, electrode polarity can also effect weld penetration. Straight polarity (electrode negative) produces less penetration than does reverse polarity (electrode positive).

Steps required to prevent burnthrough when welding onto in-service pipelines with a wall thickness of less than 0.250 inch (6.4 mm) include minimizing the penetration of the arc into the pipe wall by using small diameter low-hydrogen electrodes and a low heat-input procedure. This may conflict with other requirements, such as the need to use a high heat-input procedure (if the procedure does not rely on tempering) to avoid hydrogen-induced cracking. However, the heat input required to avoid cracking is typically lower for weld deposition repairs than for sleeve fillet welds or branch groove welds. In the absence of a sleeve or branch, the heat from the welding arc is dissipated only by the pipe, therefore the weld cooling rate tends to be slower. For some applications, the heat input required to avoid cracking may be greater than the heat input allowed to avoid burnthrough, prohibiting the use of this type of procedure. As an alternative to using a high heat-input procedure to avoid hydrogen cracking, a procedure that uses a temper bead deposition sequence can be used. The application of this type of procedure to weld deposition repairs is described in Section 3.7.1.

Common misconceptions pertaining to operating practices required to prevent burnthrough are that some level of flow must always be maintained to prevent burnthrough and that the operating pressure must always be reduced. While maintaining flow does result in lower inside surface temperatures, it can be shown that inside surface temperatures are often less than the 1800ºF (982ºC) limit established by Battelle due to the thermal mass of the pipe wall itself and the thermal properties of the contents, even at little or no flow.

While a pressure reduction may be justified to prevent a defect from rupturing during the repair process on the basis of protecting the repair crew, pressure has a relatively small effect on the risk of burnthrough. When the unmelted area beneath the weld pool has been heated to a sufficient temperature (i.e., significantly above 1800ºF [982ºC]), a burnthrough will occur even at very low pressures. Because the size of the heated area is small, the stress in the pipe wall is redistributed around the heated area, as it does similarly around a small corrosion pit. Pressure reductions are, therefore, relatively ineffective at preventing burnthrough and are often unnecessary.

While this has certainly been shown to be true for thicker materials [0.250 in (6.4 mm) thick and greater], it may not be true for thinner materials. The results of recent work [18] indicate that pressure does have an effect on the ability to make safe welds on thinner materials [0.188 inch (4.8 mm) thick and less], particularly for welds made in the longitudinal direction. Therefore, when welding on areas with thin remaining ligaments, the initial layer of weld metal should be deposited in the circumferential direction (i.e., perpendicular to the hoop stress direction).

Interestingly, thermal analysis modelling can be used to show that, since flowing gas more effectively conducts heat at higher pressure (assuming a constant linear flow rate greater than zero), pressure reduction results in higher inside surface temperatures and an increase in burnthrough risk. The effect of pressure is secondary to that of other factors, and this phenomenon does not occur for liquid pipeline contents, as the thermal conductivity of liquids do not vary greatly with pressure.

3.5.2 Experimentally-Derived Heat Input Limits

In the previous work [1-2], experiments were conducted on reduced wall thickness, pressurized pipe to develop limits for the maximum allowable heat input as a function of remaining wall thickness. These experiments also considered the effect of electrode size (current level) on the maximum allowable heat input. These heat input limits, for various diameters of how-hydrogen (EXX18-type) electrodes, are shown in Figures 2 and 3.

The limits shown in Figures 2 and 3 are for a worst-case condition in terms of heat sink conditions, since the experiments were conducted with nitrogen gas under no-flow conditions. Methane gas and most typical liquid pipeline contents remove heat from the pipe wall more effectively than does nitrogen gas, adding some conservatism to the use of these limits for typical applications. It should be noted, however, that these limits are based on nominal current levels of 50, 80, and 110 amps for 5/64-, 3/32-, and 1/8-inch (2.0-, 2.4-, and 3.2-mm) -diameter electrodes, respectively. The use of these limits for higher current levels may be non-conservative.

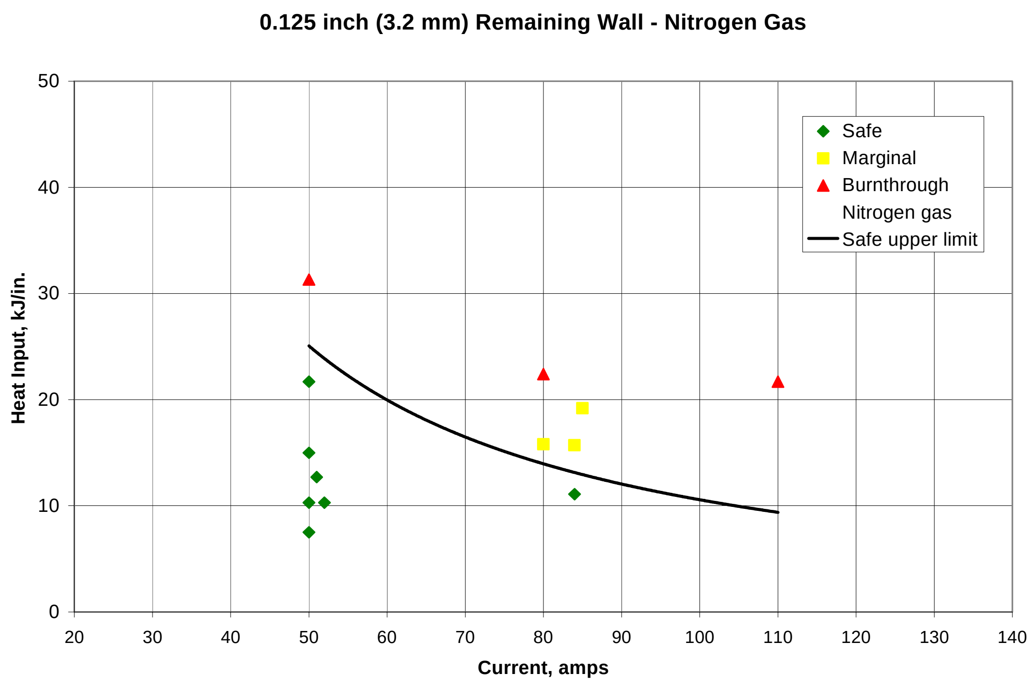

Figure 2. Heat input limits for 0.125 inch (3.2 mm) remaining wall thickness areas

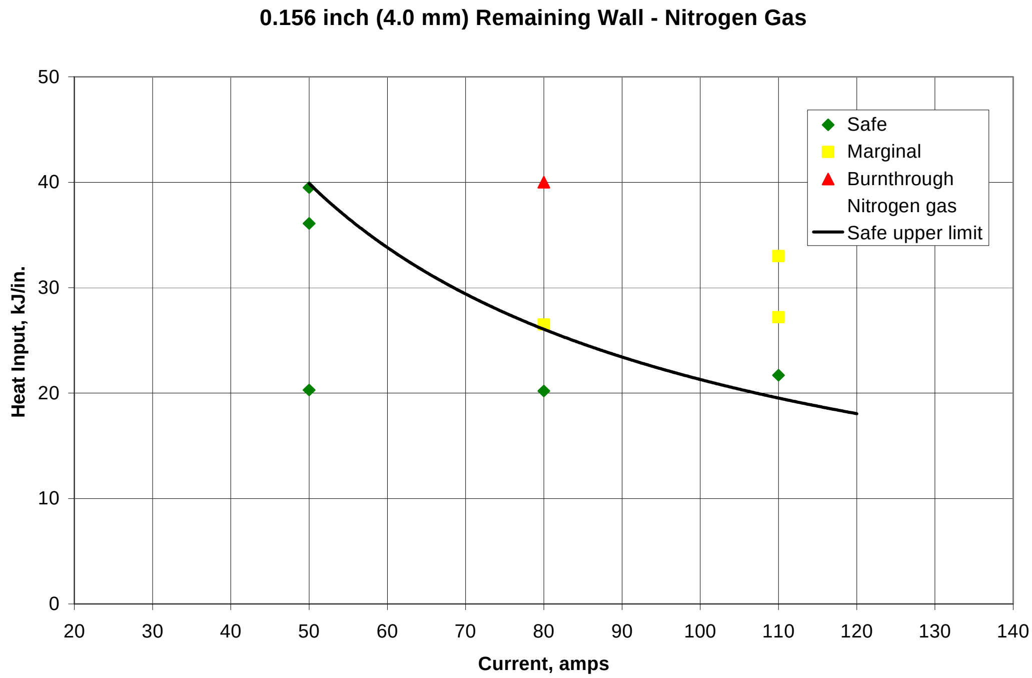

Figure 3. Heat input limits for 0.156 inch (4.0 mm) remaining wall thickness areas

3.5.3 Thermal Analysis Model-Derived Heat Input Limits

A useful tool in evaluating the risk of burnthrough is thermal analysis computer modeling [19-21]. These models, in addition to predicting weld cooling rates, predicts inside surface temperatures as a function of the welding parameters (current, voltage and travel speed), geometric parameters (wall thickness, etc.) and the operating conditions (contents, pressure, flow rate, etc.). The risk of burnthrough for a given application can be evaluated or the limiting welding parameters for a given set of operating conditions can be determined. While the PRCI Thermal Analysis model can provide results for the bead-on-plate configuration of a weld deposition repair, the Battelle model cannot, although a fillet weld geometry can be used as an approximation.

These models define safe parameters as those which produce an inside surface temperature of less than 1800ºF (982ºC) when using low hydrogen electrodes. This limit was based on the observation that burnthroughs tended to be produced when the inside surface temperature exceeded 2300ºF (1260ºC) in a series of previously-conducted experiments [22-23]. The 500ºF (278ºC) temperature difference was introduced as a margin for safety.

3.6 Qualification of Procedures and Welders

The purpose of qualifying a welding procedure is to demonstrate that the procedure is capable of producing sound welds under production conditions. The purpose of a welder qualification is to show that a particular welder is capable of executing a qualified procedure under production conditions. Requirements for qualifying procedures and welders for in-service welding are given in a variety of codes and standards. CSA Z662 contains requirements specifically intended for the qualification of procedures and welders for weld deposition repairs, whereas Appendix B of API 1104 does not. ASME B31.8 indicate that procedures qualified under Appendix B of API 1104 for either branch or sleeve welds are suitable for weld deposition repair, provided the procedure is appropriate for the remaining wall thickness to which it is being applied. Work is currently underway to incorporate requirements for qualifying procedures and welders for weld deposition repairs into Appendix B of API 1104.

3.7 Deposition of Repair

3.7.1. Factors Affecting Hydrogen Cracking

The conditions under which weld repairs to in-service pipelines are made favor the production of high hardness levels. Fast cooling rates result from the presence of the pressurized, flowing contents which tends to remove heat from the pipe wall, and from heat input limitations needed to control the risk of burnthrough. These fast weld cooling rates combined with high CE material of older pipelines tend to result in the development of hard, crack-susceptible weld microstructures. The development of these microstructures tends to make repair welds made onto in-service pipelines particularly susceptible to hydrogen cracking. For hydrogen cracking to occur, three primary independent conditions must be satisfied simultaneously. These conditions are:

- Hydrogen in the weld,
- The development of a crack-susceptible weld microstructure, and
- A tensile stress acting on the weld.

To prevent hydrogen cracking, at least one of the three conditions necessary for its occurrence must be minimized or reduced to below a threshold value. The first step taken towards avoiding hydrogen cracking in welds made onto in-service pipelines is to minimize the hydrogen level by using low-hydrogen electrodes or a low-hydrogen process. As added assurance against hydrogen cracking, since low hydrogen levels cannot always be guaranteed, procedures that minimize the formation of crack-susceptible microstructures are also used. A significant amount of residual tensile stress acting on the weld cannot be avoided and must always be assumed.

The most commonly used options for preventing hydrogen cracking in welds made onto in-service pipelines, beyond the use of low-hydrogen electrodes, are; specification of a minimum-required heat input level, and the use of a temper-bead deposition sequence.

The minimum-required heat input levels predicted by thermal analysis modeling can be used to achieve acceptable weld cooling rates. Faster cooling rates can result in the formation of undesirable microstructures (e.g., martensite) that are susceptible to cracking. Hardness is typically used as an indicator that an acceptable microstructure has been achieved. However, the use of high heat input levels represents a greater risk of burnthrough than do lower heat input levels, particularly for thin areas. As an alternative approach, HAZ hardness levels can be minimized by using procedures designed to make use of tempering from subsequent passes or tempering from subsequent layers of a multi-layer repair. These procedures are generally referred to as temper bead procedures.

A temper bead procedure generally involves depositing a first layer or "buttering" layer using stringer beads that are deposited in such a way as to maximize the amount of grain refinement and tempering by subsequent passes within the layer. For repairs requiring multiple layers, higher heat input levels are used for the second layer and subsequent layers to further refine and temper the HAZ of first layer.

3.7.2 Weld Deposition Sequence

The results of the procedure development experiments in the previous work [1-2] indicate that the use of the temper bead technique is well suited for weld deposition repairs. The most effective technique for making weld deposition repairs was found to be a series of perimeter welds that are followed by layers of consecutive parallel fill passes that are deposited in a "stringer bead" manner. This technique is illustrated in Figure 4.

The initial perimeter weld defines the boundary beyond which no subsequent welding is allowed. The intent is to avoid any inadvertent un-tempered heat-affected zones beyond the perimeter. This initial perimeter pass also allows starts and stops of the first layer to be made on weld metal as opposed to base metal, which results in completed repairs that are a bit neater than those made using other techniques. Following the completion of the first layer (described below), grinding is performed on the initial perimeter pass so that a corner is produced at approximately 1/16 inch (1-2 mm) from the toe of the perimeter pass. A second perimeter pass is then deposited prior to depositing the second layer, the toe of which just consumes the corner that was produced by the grinding step. The second perimeter pass is intended to temper the HAZ at the toe of the first perimeter pass. In previous work [24], it was found that, for a tempering pass to be effective, a toe separation of approximately 1/16 inch (1-2 mm) is required. The use of the grinding step facilitates proper weld toe placement (i.e., the welder can see the corner produced at the intersection of the ground surface and the perimeter pass).

The first layer of fill passes must be deposited using established heat input limits to minimize the risk of burnthrough. If the remaining ligament is less than 0.250 inch (6.4 mm), the first layer should be deposited using low hydrogen electrodes that are 3/32 inch (2.4 mm) diameter or less. If the remaining ligament is less than 0.188 inch (4.8 mm), the first layer should be deposited in the circumferential direction. The fill passes of both layers are deposited using stringer beads in a parallel, consecutive, or buttering layer, manner. During deposition of the buttering layers, the electrode is aimed at the toe of the previous pass, resulting in a bead overlap of approximately 50%. Cosmetic grinding between layers is performed only to remove layer height irregularities (i.e., a "half-bead" technique is not used). Higher heat input levels are used for the second layer to refine and temper the HAZ of the first layer. Higher heat input fill passes can be used for the second and subsequent layers since deposition of the first layer increases the remaining wall thickness.

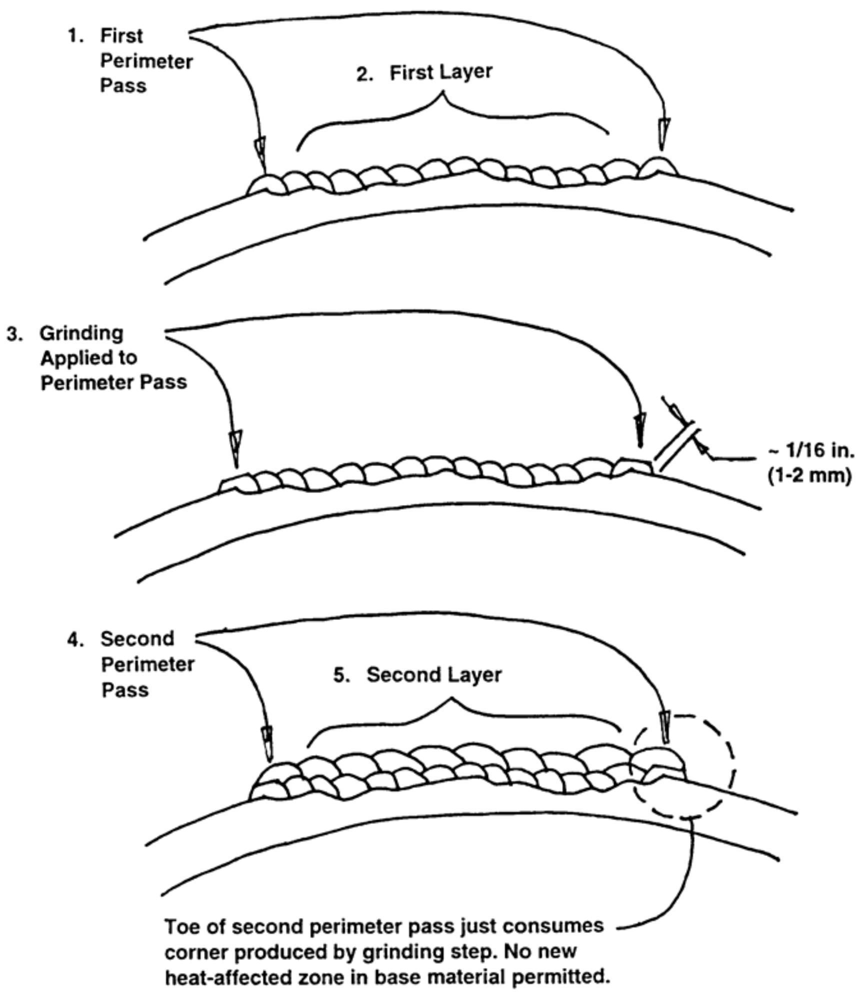

Figure 4. Illustration of typical weld deposition repair sequence

Multiple layer repairs result in the highest amount of tempering. Multiple layers are not ideal for shallow repairs, however, as excessive reinforcement may result. The need for either one or multiple layers of weld metal depends on the depth of corrosion and the need for tempering. The results of the previous work indicate that multiple layer repairs were appropriate for simulated corrosion depths of 0.125-inch (3.2-mm) or greater. An area of simulated corrosion that was 0.94 inch (2.4 mm) deep could be filled using a single layer and bead overlap could be adjusted slightly to insure proper filling. Additionally, the choice of electrode size, whether for a single or a multiple layer repair, can be used to achieve proper reinforcement height. Since multiple layers result in more tempering than single layers, the deletion of multiple layers should be considered an essential variable for procedure qualification (i.e., requalification should be required if a multi-layer procedure is to be used for a single layer repair).

The use of this sequence results in the most consistent weld profile, the least amount of welder induced discontinuities and the highest amount of tempering from subsequent passes. This tempering, combined with the use of low hydrogen electrodes and the relatively low level of restraint inherent with weld deposition repairs, minimizes the risk of hydrogen cracking. The results of the previous work indicate that the developed procedure could be executed in all positions around the pipe circumference with consistent quality.

The factors that render this technique effective are believed to be as follows:

- The first layer of fill passes is deposited using established heat input limits to minimize the risk of burnthrough.
- Depositing these passes in a buttering layer manner maximizes tempering by subsequent passes within the first layer.
- Higher heat input fill passes used for subsequent layers, if used, tend to further temper the initial passes.
- Welder induced discontinuities are minimized by the use of small diameter electrodes. These electrodes permit the welder to maintain a low heat input level comfortably, minimizing the inherent risk of burnthrough.

Where necessary, the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) can first be applied to the deepest areas of wall loss until a uniform remaining depth is established. The general technique can then be applied again to the entire area of wall loss until the desired amount of weld metal is deposited. A typical completed weld deposition repair is shown in Figure 4.

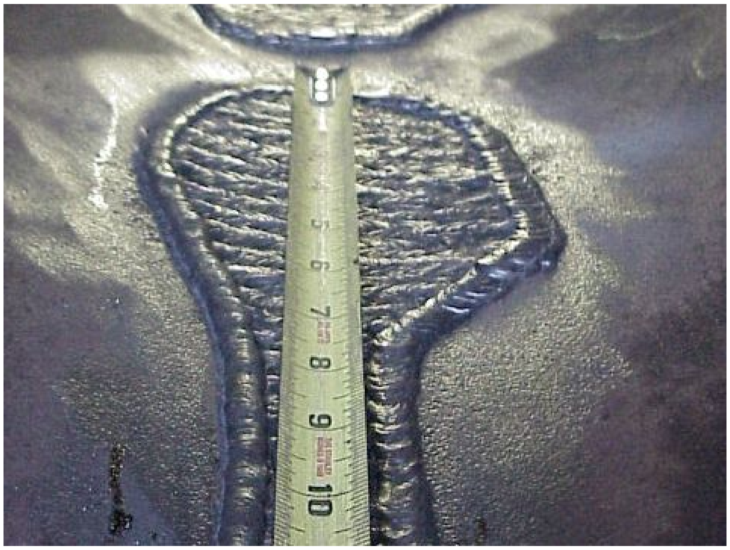

Figure 5. Appearance of typical completed weld deposition repair

In the previous work,(2) some repairs were limited to restoring just enough of the wall thickness to meet the RSTRENG criterion (partial repairs); in other cases the welding was continued until the full-thickness was restored. During cyclic pressure testing of these repairs, fatigue cracks first reached through-thickness from initiations at the toe of the partial repairs. These partial repairs (Figure 6) concentrated the stress not only by providing a smaller cross-sectional area, but also by causing additional bending stresses in the thinner area. These results indicate that partial repairs are not appropriate for high-cycle applications (e.g., a liquid petroleum pipeline that batch feeds a refinery).

Figure 6. Illustration of a partial repair

3.7.3 Amount of Reinforcement Required for External Repair of Internal Wall Loss

An adaptation of the previously-developed technique was developed for external repair of internal wall loss [25]. The amount of reinforcement required was determined using finite element analysis. The adaptation of the previously-developed technique involved applying the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) to an area larger than the area of wall loss (as mapped out using an ultrasonic thickness gauge) by at least one wall thickness in all directions. This was followed by a second perimeter pass and a second layer. If this did not restore the wall thickness to at least the nominal thickness (as determined using the ultrasonic thickness gauge), the technique was applied again to an area larger than the area of less-than nominal-thickness by about one wall thickness in all directions. This process was repeated until all areas were restored to at least the nominal thickness. This adaptation is illustrated in Figure 7. The results of a series of full scale experiments indicate that the static strength of straight sections of pipe, elbows, and tees can be fully restored when after-repair minimum wall thickness is equal to or greater than the nominal wall thickness. The repair should overlap the perimeter of the wall loss by at least one nominal wall thickness in all directions and the weld metal strength should be at least equal to the parent material strength.

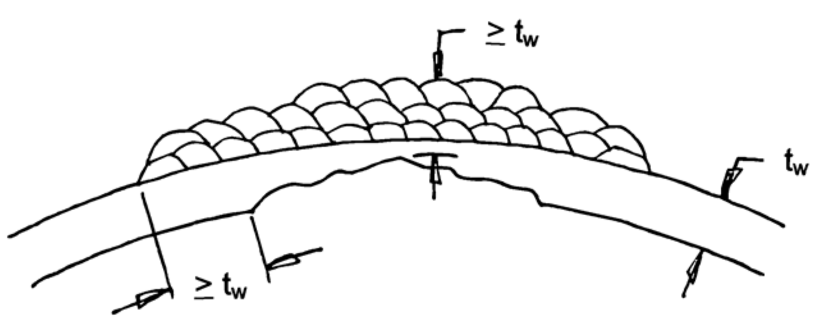

Figure 7. Adaptation for external repair of internal wall loss

3.7.4 Avoidance of Welder-induced Discontinuities

Weld discontinuities, including those that can occur in weld deposition repairs, can be classified into two separate categories: welder-induced discontinuities and hydrogen-induced cracking. Welder-induced discontinuities are those that can be controlled by the skill of the welder and include slag inclusions, porosity, undercut, lack of fusion, etc. When welding onto an in-service pipeline, welder-induced discontinuities can be controlled by the welder maintaining good practice with regard to procedural aspects and welding technique. Welder comfort and ambient conditions can also greatly influence the occurrence of welder-induced discontinuities. In production, efforts should be made to protect the welder from inclement conditions and to provide for the comfort of the welder.

As noted in Section 3.6, a welding procedure qualification is used to demonstrate that a procedure is capable of producing sound welds under production conditions. Welder qualification is used to show that a particular welder is capable of executing the qualified procedure. Proper use of welding procedure and welder qualification, combined with close monitoring in the field to ensure that the welding procedure is being followed, should minimize the occurrence of welder-induced discontinuities.

3.8 Inspection of Completed Repairs

To insure that significant discontinuities have not been produced as the result of a weld deposition repair, a thorough nondestructive inspection following repair should be carried out. Based on the results of previous work [26], the optimized inspection method for weld deposition repairs would involve the use of a combination of magnetic particle inspection and angle beam ultrasonic testing for the weld toes and straight-beam ultrasonic testing or radiography for volumetric inspection. Ultrasonic testing for volumetric inspection requires that the weld reinforcement be removed or ground smooth. The results of experiments in the previous work [1] indicate that removal of the weld reinforcement does not adversely affect the integrity of the repair.

Surface techniques such as liquid penetrant testing (PT) and magnetic-particle inspection (MPI) rely on discontinuities being slightly below (direct current MPI) or open to the surface (PT or alternating current MPI), which is not necessarily the case with all significant discontinuities that can occur in weld deposition repairs. Magnetic particle testing can be effective for the detection of toe cracking, provided that proper procedures are used and that the weld toe has a favorable profile. A favorable weld profile can be produced using a high-speed rotary file (i.e., a burr grinder) to clean up the weld toes. In the previous program, it was concluded that MPI performed significantly better than PT. Both the wet fluorescent and visible (black) ink over white contrast paint techniques performed equally well. The choice of the optimum technique depends on illumination conditions available.

Radiography is well suited for volumetric inspection of weld deposition repairs, except for difficulties caused by the presence of liquid pipeline contents. The alternative for a full-volumetric examination is ultrasonic testing. Inspection procedures, reference standards and reporting criteria that have been developed for the specific weld geometries of interest should also be employed.

There may be psychological benefits of any NDT requirement in the form of increased welder performance with respect to welder induced discontinuities. If a welder knows that a completed weld will be subjected to thorough NDT, regardless of how effective the NDT method might be, he is more likely to ensure that welder induced discontinuities are avoided.

It is important to note that hydrogen-induced cracking can occur following a substantial time delay after welding. Therefore, inspection should not occur immediately. At present, there is no industry-accepted method for predicting delay intervals for specific applications.

3.9 Acceptance Standards

There are presently no industry-accepted workmanship-based acceptance standards specifically intended for discontinuities located during inspection of weld deposition repairs. Therefore, the use of a workmanship-based criteria that is based on Section 6 of API 1104 is proposed. Other workmanship-based acceptance criteria, such as those found in CSA Z662, BS 4515, etc., could be similarly adapted to weld deposition repair.

The adaptation of the workmanship-based criteria in Section 6 of API 1104 must consider the requirements imposed by the geometry of weld deposition repairs and the types of discontinuities that these repairs are likely to contain. To develop this criteria, Section 6 of API 1104 was evaluated in terms of how each paragraph applies to weld deposition repair. Tables 2 through 5 contain a summary of this evaluation. Some items do not apply to weld deposition repair and can be ignored when using Section 6 to evaluate discontinuities located during inspection of weld deposition repairs. Other items can be directly applied to weld deposition repairs. The acceptance limits for some discontinuities are given both as an absolute length and as a percentage of the weld length. These items can be directly applied to weld deposition repairs provided that the "weld length" for a weld deposition repair is defined. A reasonable definition of weld length might be the maximum length of the repair along the longitudinal axis of the pipeline.

3.10 Repair and Removal of Defects

If a discontinuity in a weld deposition repair that is detected by nondestructive testing is found to be unacceptable according to the acceptance criteria, it should be removed and repaired. Care should be taken during the removal of the defect to ensure that the wall thickness is not reduced to less than that which is acceptable for the operating pressure of the pipeline and the length of the defect (i.e., the RSTRENG-predicted safe pressure of the repair cavity should be greater than the operating pressure of the line). The defect should be entirely removed to sound metal prior to repair. Defects other than cracks should be repaired using a procedure similar to the one used to deposit the original repair. A procedure for the repair of cracks should account for the deficiencies in the procedure and/or technique used to deposit the original repair that resulted in the crack (e.g., insufficiently-low hydrogen levels caused by improper electrode handling, etc.). Following repair, the repaired area should be re-inspected using the same method used previously.

4. DEVELOPMENT OF GUIDELINES

The information presented in the previous section can be used by individual companies to develop a guideline or specification for carrying out weld deposition repair in the field. An example company specification was developed and is contained in Appendix B. This specification addresses the major topics of scope, policy, definitions, application, inspection and documentation, repair and removal of defects, and recoating and backfilling. The requirements outlined in Appendix B are for a hypothetical pipeline company. Individual pipeline companies may want to alter these requirements and/or add additional requirements.

5. SUMMARY AND CONCLUSIONS

The guidance presented here is based on the results of the most recent research and development in the area of weld deposition repair. This information was used to develop an example guideline, in the form of a generic company specification, which is contained in Appendix B. This guidance will allow the confident use of this repair technique, which is an attractive alternative to the installation of full-encirclement sleeves, and provide a foundation for regulatory acceptance where it is not already accepted.

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Appendix – Example Weld Deposition Repair Specification

XYZ Pipeline Company
Weld Deposition Repair Standard
No. XXX

1. Scope

This document outlines the requirements for carrying out repair of damaged or defective pipelines and related components by direct deposition of weld metal, or weld deposition repair. The use of this document is limited to external defects in carbon steel pipelines and components within the following ranges:

• Diameter	2-3/8 inch through 48 inch
• Wall thickness	0.156 inch through 0.750 inch
• Grade	B through X70

This document is limited to repairs made using the SMAW process using low-hydrogen (EXX18-type) electrodes.

2. Policy

The overriding concern addressed by this document is safety. Safety in this context includes, but is not limited to insuring that no harm comes to any person or persons during the application of a repair, and that the repair adequately restores the integrity of the damaged or defective pipeline segment.

3. Definitions

Company - Refers to the owner company or its authorized representative

Defect - Refers to an area of external wall loss caused by corrosion or by grinding to remove mechanical damage.

4. Application

4.1 Pressure Reduction - Prior to the commencement of any repair activities, the pipeline operating pressure should be reduced to 80% or less of the level which was present when the defect was discovered. Following assessment (see Section 4.2 below) the pressure may be increased to the RSTRENG-predicted safe pressure (i.e., failure pressure multiplied by the design factor).

4.2 Assessment Prior to Repair

4.2.1 Remaining Strength - B31G, RSTRENG or another Company-approved method should be used to determine the remaining strength of the defect. If the predicted failure pressure exceeds 100% of SMYS, then no repair is necessary.

4.2.2 Maximum Permissible Size of Repair - The maximum allowable size of an area for which repair is permissible is shown below. Prior Company approval is required for repair of larger areas.

4.2.2.1 Longitudinal length - 6 inch (150 mm) or 25% of the pipe diameter (whichever is larger).

4.2.2.2 - Circumferential width - 3 inch (75 mm) or 12-1/2% of the pipe diameter (whichever is larger).

4.2.3 Proximity to Seam and Girth Welds and Other Repairs - Prior Company approval is required for weld deposition repair of an area that impinges upon a seam or girth weld. Individual repairs should be separated by at least 1 inch (25 mm).

4.2.4 Dented Areas - Weld deposition repair of an area that is associated with a dent in the pipeline is prohibited.

4.3 Determination of Remaining Wall Thickness - The remaining wall thickness should be measured using appropriate equipment and techniques. Care should be taken to ensure that the remaining wall thickness is measured in the thinnest area. The minimum remaining wall thickness on which a repair should be attempted is 0.156 inch (4.0 mm). Prior Company approval is required for repair of thinner areas (down to 0.125 inch [3.2 mm]).

4.4 Surface Preparation - The surface of the area should be prepared to produce a favorable profile and to remove corrosion products from the area. Care should be taken to ensure that the surface preparation does not significantly increase the depth of the area.

4.5 Selection of Welding Parameters - If the minimum remaining wall thickness is less than 0.25 inch (6.4 mm), a value for the maximum allowable heat input level should be established to minimize the risk of burnthrough.

4.6 Qualification of Procedures and Welders

4.6.1 - Procedure Qualification - Welding procedures should be qualified to the requirements of API 1104 Appendix B. Pipeline operating conditions that affect the ability of the flowing contents to remove heat from the pipe wall, where applicable, should be simulated by filling the test section with water and allowing water to flow through the test section while the test joint is being made. The pipe material carbon equivalent level for which the procedure applies replaces the specified minimum yield strength as an essential variable. The macro-section test from API 1107 should be added to the procedure qualification test requirements.

4.6.2 - Welder Qualification - Welders should be qualified to the requirements of API 1104 Appendix B. Pipeline operating conditions that affect the ability of the flowing contents to remove heat from the pipe wall, where applicable, should be simulated by filling the test section with water and allowing water to flow through the test section while the test joint is being made. Welders should be able to demonstrate the ability to maintain a heat input level within the specified range of the procedure for which he is being qualified.

4.6.3 - Other Requirements - All welders performing weld deposition repair work should be familiar with the safety precautions associated with welding onto in-service pipelines.

4.7 Deposition of Repair

4.7.1 Sequence - A weld deposition sequence that is suitable for the geometry of the area being repaired, and that results in a significant amount of tempering from subsequent passes, should be used. A perimeter pass should be used to establish a boundary beyond which no subsequent welding is allowed. The first layer of fill passes should be deposited using established heat input limits to minimize the risk of burnthrough. If the minimum remaining wall thickness is less than 0.250 inch (6.4 mm), the first layer should be deposited using low hydrogen electrodes that are 3/32 inch (2.4 mm) diameter or less. If the minimum remaining wall thickness is less than 0.188 inch (4.8 mm), the first layer should be deposited in the circumferential direction. A second perimeter pass should be used to temper the HAZ at the toe of the first perimeter pass. Higher heat input fill passes should be used for subsequent layers to further temper the initial passes, again observing established heat input limits to minimize the risk of burnthrough if necessary. Additional layers should be deposited, as necessary, for proper filling.

4.7.1.1 Areas with Irregular Depth - Where necessary, the general technique (i.e., a perimeter weld followed by consecutive parallel fill passes) can be first applied to the deepest areas of wall loss until a uniform remaining depth is established.

4.7.2 Control of Heat Input Levels - If the minimum remaining wall thickness is less than 0.250 inch (6.4 mm), the heat input level should be monitored using appropriate equipment and techniques. The heat input level should not be allowed to exceed the maximum allowable level established to minimize the risk of burnthrough.

4.7.3 Clean-Up - The completed repair should be cleaned-up by grinding or using rotary files, as necessary, to facilitate inspection and recoating.

5. Inspection and Documentation

5.1 Inspection of Completed Repairs - The toe area of the completed repair should be inspected using magnetic particle inspection or angle beam ultrasonic testing, or a combination of these. Volumetric inspection of the completed repair should be carried out using straight-beam ultrasonic testing or radiography.

5.2 Acceptance Standards - The disposition of discontinuities detected during inspection should be determined using Section 6 of API 1104. For weld deposition repairs, weld length is defined as the maximum length of the repair along the longitudinal axis of the pipeline.

5.3 Documentation - Following acceptance of the repair, pertinent information concerning the repair should be recorded.

6. Repair and Removal of Defects -

Repair and removal of defects should be carried out in accordance with the requirements in API 1104 Appendix B.

7. Recoating and Backfilling

After the repair has been inspected and accepted, the pipeline should be recoated with an approved coating material and backfilled. Care should be taken to assure that the pipeline is properly supported prior to backfilling.