Recommendations for repairs of base metal

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1.0 Introduction

This document provides general recommendations and guidelines for the design, fabrication and inspection of repairs of base metals prior to fabrication. Base metal deficiencies in fracture critical members discovered during inspection at the producing mill, and permitted by national standards, are also addressed.

These recommendations are based upon extensive practical experience and satisfactory application, with some experimental research and study.

Because the primary concern must be with structural integrity, followed closely by the economic viability of the cost of repairs (both direct and hidden), one cannot dismiss the potential loss of structural integrity caused by inappropriate repairs.

The following problems may be associated with repairs of base metal:

- Incomplete removal of defect being repaired.
- Introduction of further discontinuities associated with the repair that may be more harmful and less readily detectable than the original defect.
- Degradation of material mechanical properties (strength, ductility, notch toughness) or microstructure
- Increased residual stress and distortion.

Engineering and cost considerations should contribute to any decision to undertake a repair. The direct cost of base metal repairs and re-repairs (grinding, gouging, welding, supervision, inspection, etc.) will be significantly increased by hidden costs (loss of production space and time, penalty clauses, delays in shipment and deliveries, etc.), and may represent a considerable proportion of the overall cost of the structure.

The cost of base metal repair will increase more significantly with the increase in the depth of the discontinuities within the thickness of material than with the length of the discontinuity. The severity of base metal quality acceptance standards has a very significant influence on the cost of repairs. However, when repairs are found necessary, the problems particular to them must be fully understood and considered if the original quality of the base metal is to be restored.

2.0 Definitions

Buttering - a surfacing variation in which surfacing weld metal is deposited on one or more base metal surfaces to achieve the required dimensions.

Critical repair - repair on base material requiring direct design intervention and/or refined procedural attention and stricter quality control. This category of repair is more likely to arise for specific members or elements whose integrity, in the judgement of the designer, cannot be

compromised from the standpoint of a reliable and safe performance. Such members or elements may be subject to fatigue, brittle fracture, or some specific stress condition.

Discontinuity - an interruption of the typical structure of the base metal such as a lack of homogeneity in the mechanical, metallurgical or physical characteristics of the material.

Defect - discontinuity exceeding limits of acceptance set by the pertinent specification and hence subject to rejection and repair.

Engineer - the professionally qualified designated representative of the regulatory authority or of the purchaser, as applicable.

Fracture critical members (FCM) - members, including attachments, in a single load path structure which are subject to tensile stress and whose failure could lead to collapse of the structure.

National standard - the standard having full contractual or jurisdictional authority over any specific action or operation to which a particular reference is made in the document.

Non-critical repair - repair outside the scope of the definition for critical repair.

3. General considerations

Comprehensive repair procedures should be prepared by the base metal producer, or contractor making the repairs, for approval by the authority having jurisdiction, and should list all significant steps in the order in which they are to be performed.

For *non-critical repairs*, the repair procedure should describe in general terms the *discontinuity* and the method of repair. It is not necessary to document the nature of the *discontinuity*, its location, or the actual procedures taken for repair.

For *critical repairs*, the repair procedure should describe in specific terms the *discontinuity* and the specific method of repair. There should be documentation of the location and nature of the *discontinuity* within the base metal, the procedures taken in making the repair, the procedures taken for inspection of the repair, and the acceptance criteria for the repair.

4. Straightening

4.1 *Heat Straightening.*

When straightening members using heat, the maximum temperature of heated areas as measured by approved methods should not exceed 600^{O}C for quenched and tempered steel, nor 650^{O}C for other structural steels. These limits (including significant safety factors) are to avoid possible metallurgical changes in the steel when it subsequently cools to ambient temperature. The steel composition and prior tempering of the steel dictate the critical temperature.

Accelerated cooling of steel above 315^{O}C should not be permitted, and when used, should be limited to fine mist water spray, wet rags, or forced air . At this temperature, the moduli of elasticity and yield stress of steel are not significantly reduced from that of steel at ambient temperature.

4.2. *Mechanical Straightening*

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5. Base metal repairs by surface grinding, chipping or other methods

The material is to be free of injurious defects and have a "workmanlike finish". Structural steels are normally furnished in the as-rolled condition and visually inspected by the producing mill. Materials that exhibit injurious defects during subsequent fabrication are deemed not to comply.

Non-injurious surface or internal imperfections or both may be present in the steel as delivered and may require conditioning by the purchaser to improve the appearance of the steel or in preparation for welding, coating, or other further processing. Conditioning of imperfections may be performed by parties other than the mill at the discretion of the purchaser.

Fabricators should be aware that cracks may initiate upon bending a sheared or burned edge during the fabrication process. This is not considered to be a fault of the steel but is rather a function of the induced cold-work or heat-affected zone.

Plates may be ground to remove surface imperfections. Ground plate surfaces should be well faired without abrupt changes in contour. The amount of grinding should be limited so as to not reduce the thickness of the plate by more than 0.5 mm.

For shapes, grinding should be well faired without abrupt changes in contour, and the depression should not extend below the rolled surface of the shape by more than:

for material less than 10 mm in thickness: 1 mm
for material 10 mm to 50 mm inclusive in thickness: 2 mm
for material over 50 mm in thickness: 3 mm

Repair of bars by grinding, chipping, or other means should be well faired and the affected sectional area should not be reduced by more than that permitted by the specified national standard.

6. Welded base metal repairs - Non-critical repairs

6.1 *Recommendations for non-critical repairs*

Repairs by welding of base metal in non-fracture critical members at the production mill should be permitted when the conditions below are met. These procedures may also be used for repairs

of base metal discontinuities identified during in-process fabrication.

The producing steel mill or repairing contractor should prepare repair procedures and submit them to the engineer for pre-approval. Repairs requiring excavation of defects, including cracks and laminations, may be pre-approved. They should be made available to the inspector on request.

The engineer may, at his discretion, agree to any other arrangement proposed by the fabricator, minimizing interference with production if he judges it acceptable.

6.2 *Pre-repair inspection*

In the case of surface cracks in base metal, ascertain the extent of the crack by use of dye penetrant, magnetic particle inspection or other positive means.

When a base metal fails radiographic inspection, an ultrasonic examination prior to air carbon arc gouging is advisable in order to accurately locate the discontinuity. This is of special economic significance on the case of heavy thickness as it determines the side on which the excavation will be shallower.

6.3 *Repair welding personnel*

Welders and welding operators should be qualified in accordance with the requirements of the applicable national standard, except that any complete joint penetration groove weld qualification also qualifies the welder or welding operator to do repair welding.

6.4 *Repair weld joint preparation*

For plates, the chipped, ground, or gouged area should not exceed 2% of the area of the surface being conditioned. Depth of repair joint preparation should not reduce the thickness of the plate at any location by more than 30% of the nominal thickness of the plate. On the edges of plates, prior to welding, the depth of the removal, measured from the plate edge, should not exceed the thickness of the plate or 25 mm, whichever is less.

For rolled shapes, the total area of the chipped or ground surface of any piece prior to repair welding should not exceed 2% of the total surface area of that piece. The reduction of thickness of the material resulting from removal of imperfections prior to welding should not exceed 30% of the nominal thickness at the location of the imperfection, and the depth of the depression should not exceed 30 mm, except at shape toes and stems of rolled tees. At toes of angles, beams, channels, and zees and the stems and toes of tees, prior to welding, the depth of the depression, measured from the toe inward, should not be not more than the thickness of the material at the base of the depression or 12 mm, whichever is less.

For bars, the total area of the chipped or ground surface of any piece, prior to repair welding, should not exceed 2 % of the total surface area of the piece. The reduction in thickness of a flat bar, resulting from removal of an imperfection, prior to welding, should not exceed 5% of the

nominal dimension or thickness at the location of the imperfection. At edges of flat bars, the depth of the conditioning depression prior to welding should be measured from the edge inward and should be limited to a maximum depth equal to the thickness of the flat bar or 12 mm, whichever is less.

6.5 *Welding processes and materials*

Repair by welding should be performed using manual metal arc welding (MMAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW), or submerged arc welding (SAW) processes. Shielding gases used should be of welding quality. For SMAW, low hydrogen electrodes should be used. Electrodes and electrode-flux combinations should be selected so that the tensile strength of the deposited weld metal (after any required heat treatment) is consistent with the tensile strength specified for the base metal being repaired. Filler metal classifications with weld metal properties matching or slightly exceeding those of the parent metal should be used. Electrode classifications having known high ductility (basic electrodes) should be preferred unless other overriding conditions dictate the selection of a type of electrode more suitable to meet particular conditions (penetration, grade of steel etc.). Welding electrodes and flux materials should be dry and protected from moisture during storage and use.

6.6 *Welding procedures*

Any welding and/or rewelding should be done using approved welding procedures including preheat, interpass temperature or heat input levels as required, and including any postweld heat treatment if specified.

Repair welding should be in accordance with a welding procedure specification (WPS) meeting the requirements of the applicable national standard, with the following exceptions or clarifications:
(a) The WPS should be qualified by testing a complete joint penetration groove weld, except a prequalified complete joint penetration groove weld WPS is acceptable without qualification. When so specified, the WPS should include qualification by Charpy V-notch testing,
(b) The geometry of the surface groove weld need not be described in other than a general way.

Prior to repair welding, the surface to be welded should be inspected to verify that the imperfections intended to be removed have been removed completely. Surfaces at the weld should be dry and free of scale, slag, rust, moisture, grease, and other foreign material that would prevent proper welding.

The repair area should be maintained at a sufficiently high temperature by preheat and heat input by arc to prevent fast cooling rates which may potentially result in high local hardness and embrittlement.

Welds should be comparatively small and should be multipass welds when their throat is greater than 5 mm. The thickness of passes or layers should not exceed 3 mm. Any additional weld metal used to compensate for any deficiency in member size should be deposited using a manual metal arc electrode, preferably smaller than that used to make the original weld but not more

than 4.0 mm in diameter for mild steel, 3.2 mm in diameter for low-alloy and high-strength steels, and 0.9 mm in diameter for gas metal arc welding processes.

6.7 *Repair weld quality*

The weld and adjacent heat-affected zone should be sound and free of cracks. The weld metal should be thoroughly fused to all surfaces and edges, and free of undercut and overlap. Visible cracks, porosity, lack of fusion, and undercut in any layer should be removed prior to deposition of the succeeding layer. After welding, weld metal should project at least 2 mm above the rolled surface, and the projecting metal should be removed by chipping or grinding, or both, to make it flush with the rolled surface, and to produce a workmanlike finish.

6.8 *Inspection during repair welding*

It should be the responsibility of the producing mill or repairing contractor and inspector to:
(a) ensure all welders are qualified in all respects for the welding envisaged for the repair operations; it may be advisable in some specified cases to qualify them additionally in simulated repair joint assemblies,
(b) ensure the supervisory personnel is well acquainted with the details of procedures and the requirements for documentation,
(c) ensure that defects have been completely removed,
(d) ensure that the limitations on the extent of the repair area have not been exceeded,
(e) ensure that the exact provisions of the repair procedure are strictly implemented, including preheat, interpass and postheat temperatures as specified in the welding procedure,
(f) monitor continuously the repair process and provide data for corrective action when such appears warranted (e.g. adjustment in rest periods to allow for cooling down to specified interpass temperatures)

6.9 *Inspection after repair welding*

It should be the responsibility of the inspector to:
(a) conduct a final and comprehensive visual inspection to check for full compliance with the requirements.
(b) If nondestructive examination was used prior to repair, the repaired area should be re-examined by the method originally used or as specified by the engineer to the same quality acceptance criteria.

The inspection report should include detailed information on the following:
(a) the names of welders and supervisory personnel,
(b) the environmental conditions and the condition of the base material,
(c) the parameters of the welding procedure including welding sequence,

6.10 *Document of acceptance*

It should be the responsibility of the inspector to document that the base metal, as repaired, meets the applicable acceptance criteria.

7. Welded base metal repairs - Critical repairs

Critical repairs include repair of surface or internal defects in rolled products. Critical repairs should include the provisions described in section 6 for non-critical repairs, plus the provisions of this section.

Repairs by welding of base metal in fracture critical members at the production mill should be permitted only when the following conditions are met, as applicable. These procedures may also be used for repairs of base metal discontinuities identified during in-process fabrication.

7.1 *Pre-repair inspection and testing*

Preparation for repair welding includes visual inspection and/or nondestructive testing to ensure complete removal of the defects.

7.2 *Qualification of welding procedures*

Repair procedures are to be approved by the engineer and repairs made using welding procedures approved by the appropriate national certification agency and welders or welding operators qualified by the same body. If the mill cannot meet this condition, it may subcontract repair welding to the fabricator-purchaser, or to any other fabricator, provided that either has nationally recognized certification or is otherwise considered qualified to do welded work.

If Charpy V-notch (CVN) impact testing or any other toughness testing is required for the base material, the welding procedure qualification testing should also include Charpy or the other impact tests of the weld. The results of these tests should be shown in the test report. The Engineer of Record should specify the location and orientation of test samples. Samples may be cored, flame cut, or saw cut.

When an applicable and previously approved welding procedure is available but does not include CVN or the other tests, a new test assembly should be prepared solely to provide the required CVN or the other test data. However, when a valid previously qualified and approved welding procedure including the pertinent impact testing is available, a new qualification by test need not be provided.

7.3 *High-strength steels*

For steels with specified minimum tensile strength of 690 MPa or higher, prior approval for repair by welding should be obtained from the purchaser. The surface to be welded should be inspected using magnetic particle or liquid penetrant methods to verify that the imperfections intended to be removed have been completely removed. Where magnetic particle inspection is used, the surface should be inspected both parallel and perpendicular to the length of the area to be repaired. Repairs that are not subsequently heat-treated at the mill should receive final inspection no sooner than 48 hours after completion of welding. Following repair, the location of the weld repairs should be marked on the finished piece.

7.4 *Quenched and tempered steels and heat-treated steels*

Quenched and tempered steels must be repaired prior to heat treatment. If the base metal is subjected to quenching and tempering, the welding procedure qualification test plates and the repaired base metal member should be subjected to the same thermal heat treatment as the original base metal.

If the base metal is subjected to normalizing, the welding procedure qualification test plates and the repaired base metal member should be subjected to the same thermal heat treatment as the original base material.

When weld repairs are to be post-weld heat-treated, electrodes appropriate for postweld heat treatment should be selected to avoid those that embrittle as a result of the heat treatment. Repairs that are subsequently heat-treated at the mill should be inspected after heat treatment using magnetic particle or liquid penetrant methods. Where magnetic particle inspection is used, such inspection should be made both parallel to and perpendicular to the length of the area repaired. Following repair, the location of the weld repairs should be marked on the finished piece.

7.6 *Post-repair inspection and quality*

Repair welds are to be inspected and meet the quality requirements of the applicable national standard.

7.7 *Procedural recommendations for fracture critical repairs*

Repair procedures should include at least the following provisions and list steps in the order in which they should betaken:

(a) Surfaces should be cleaned and/or ground as necessary to aid visual and nondestructive tests to enable the contractor and inspector to identify and quantify the discontinuity(s).

(b) The discontinuity should be shown in a drawing in size and location established on the basis of visual inspection and nondestructive examination (NDE).

(c) Air-arc gouging, if required, should be part of the approved welding procedure. The method and extent of excavation should be completely described, giving the sequence of progressive excavations. Preheat prior to arc-air gouging should be shown. Oxygen gouging should not be used.

(d) All air carbon-arc gouged and thermal-cut surfaces that form a boundary for a repair weld should be ground, when accessible to form a smooth, bright surface.

(e) Magnetic particle or dye-penetrant inspection, or other inspection method(s) approved by the engineer should be used to verify that the discontinuity was removed as planned.

(f) Run off tabs and backing, when used, should be shown in detail.

(g) The minimum preheat and interpass temperature required by the applicable code should be increased because of the additional restraint of the repair area. Preheat and interpass temperatures should be maintained without interruption until the repair is completed. The maximum preheat and interpass temperature for quenched and tempered steels should not exceed that recommended by the steel manufacturer.

(h) The repair procedure should include the applicable welding procedure specification. If both were approved by the appropriate national agency prior to fabrication, they need not be qualified by test for the specific method of repair unless a change in essential variables has been made or unless otherwise required by the engineer.

(i) If the geometry of the repair joint or of the excavation is similar to the geometry of a prequalified joint preparation as defined in an applicable national standard and permits good access to all portions of the repair weld during the proposed sequence of welding, it should not require qualification by test unless required by the engineer.

(k) Postheat is recommended, and when used, should continue without interruption from the completion of repair welding to the end of the minimum specified postheat period.

(l) Faces of repair areas should have at least the same surface quality and should be blended to the same contour and dimension as the original base metal.

(m) If postweld heat treatment (PWHT) is required, it should be completely described. Final acceptance NDE should be performed after PWHT has been completed.

8. Residual Stresses from Repair

Research indicates that residual stresses due to mill rolling practice and welding only have an effect on member capacity for some specific structural functions. Because of offsetting tensile and compressive residual force levels, residual stresses result in no quantifiable degradation of a member's flexural capacity. A similar condition exists for tensile members, provided that the heating or welding affects only a portion of the member's cross-sectional area. Compression members are more sensitive to residual stress distribution because of overall and local buckling possibilities. Balanced flame heating or welding about the neutral axis may be essential to avoid this type of problem.

9. References

ASTM A6

ASTM A709