

**Ensuring Corrosion Properties of CRA Welds**  
**Meet Requirements for the Oil and Gas Industry**

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**ABSTRACT**

This paper provides a checklist of aspects of welding procedures to highlight issues that require attention to optimise the corrosion properties of welds in a range of CRAs including duplex stainless steels and some commonly used nickel alloys. Success depends on careful handling of the material to be welded, specifying the most suitable weld preparation and filler metal, controlling heat input during welding and adopting protective measures such as shielding with backing gas. Post-weld operations can also be significant in ensuring optimum performance.

**KEYWORDS**

CRAs, welding, corrosion resistance, shielding, heat input, case histories

**INTRODUCTION**

It is an obvious requirement that welded joints in corrosion resistant alloys should have properties at least similar to those of the base material. However, the production of a weld implies a considerable thermal disturbance to the base material, which has been carefully processed and finally heat-treated to have the desired characteristics. Furthermore, the weld metal represents a chill casting and is therefore inhomogeneous. It is therefore a considerable achievement of alloy designers, filler metal developers,

and welding engineers that welded fabrications perform well in a range of applications. However, success depends on careful handling of the material to be welded, specifying the most suitable weld preparation and filler metal, controlling heat input during welding and adopting protective measures such as shielding with backing gas. Post-weld operations can also be significant in ensuring optimum performance. Since local corrosion rather than general attack is normally the limiting factor with corrosion-resistant alloys, attention to detail is of crucial importance, as is an understanding of the restrictions that may result. This paper discusses these points individually, with some examples from relevant cases where they were critical.

## **HANDLING**

While corrosion-resistant alloys – stainless steels and nickel alloys – do not suffer significant general corrosion, their susceptibility to localised corrosion not only depends on selection of the most suitable alloy for the application but also on attention to detail in handling and welding. By interfering with the integrity of the passive film, contamination of the surface of the alloy can provoke local attack. The most notable example is iron pick-up from contact with carbon steel or from tools used for both materials. Embedded particles form crevices with the base material and, in contact with some media, can initiate pitting.

The significance of contamination depends not only on the media to which the surface is exposed but also on alloy composition. In many cases the first medium that the weld will be exposed to after welding will be the water used for hydrotesting. This may be a range of qualities, from potable water to seawater, with or without chemical treatment to remove oxygen, control corrosion and inhibit bacterial activity. The temperature of the water will generally be ambient, but that can be a high temperature in hot regions of the world. Some of these grades of water, particularly at higher temperatures, can readily react with iron on the surface and form a local concentration of ferric chloride which is particularly aggressive in a crevice or pitting situation.

The sensitivity of CRA materials to ferric chloride depends upon their pitting resistance which is indicated by the Pitting Resistance Equivalent (PRE) value of the material. The PRE value is given by:

Pitting Resistance Equivalent Number = % Cr + 3.3% Mo + 16% N

Some variations to this equation with different coefficients or inclusion of other elements are sometimes used, particularly for the higher Mo content alloys. Materials with PRE values less than 40 are particularly vulnerable to pitting attack in untreated waters and these require especial care to prevent surface iron contamination. Nevertheless, good housekeeping is an important aspect of optimising the corrosion resistance in welds in all CRA materials. Weld bevelling tools and grinders should be kept strictly for CRAs and brushes should be made of stainless steel.

## **WELD PREPARATION**

The design of the weld preparation will be dictated by many factors including the thickness of the parts to be welded; the speed and process required for welding and whether there is access to both sides of the weld or only one side.

When there is access to both sides of the weld then the surface that will be exposed to the corrosive environment can be re-prepared for a capping pass that can be finished to an appropriate profile, free

from irregularities and devoid of oxides and slag. Quality can readily be checked by visual inspection and non-destructive testing.

When the weld is only accessible from one side then there will be no opportunity to correct any deficiencies in the root run, which makes the most demands on welding technique and metallurgy. The presence of physical or compositional defects may severely affect the service life of the fabrication. Root defects, e.g. lack of fusion, can be particularly dangerous if they form a crevice. Stainless steels have failed in systems carrying water containing chloride ions and oxygen because of crevice corrosion at welds, whilst the bulk of the steel has performed satisfactorily. A defect-free root run is therefore more critical in corrosion resistant alloys than in carbon steels.

The chemical composition of the weld root is inevitably affected by dilution from the base material. Since this portion of the weld is in contact with the potentially corrosive medium, careful consideration must be given to the effects of a range of dilution levels. Clearly, there is no problem when a matching composition filler metal is used but modified composition or dissimilar filler metals could require more care. For example, it is necessary to maintain an elevated nickel content in duplex stainless steel weld metal to obtain a ferrite-austenite balance within specification limits and therefore dilution should be kept to no more than 30%.

The design of the weld preparation has a role in determining the amount of dilution, though other factors such as economics and process requirements may take precedence. A J-preparation offers a combination of advantages over a simple V-preparation in reducing the number of passes to complete a joint and thus reducing the overall heat input. This reduces the extent of the HAZ in the base material and may be beneficial in minimising metallurgical reactions and formation of precipitates in the HAZ. At the same time, dilution of the root run is minimised because the amount of base metal dissolved in the root run is minimised.

The J- preparation is particularly useful in welding carbon steel which is clad with CRA. If carefully prepared it is possible to ensure that the full 'nose' of the J-preparation is made in the CRA layer, without any, or minimal, carbon steel included. This ensures that the root run picks up as little of the backing steel as possible, giving maximum corrosion resistance to the weld.

## **CHOICE OF FILLER MATERIAL**

It is a fundamental requirement that the weld metal should be at least as resistant to corrosion in service as the base material. If it is more resistant, then the possibility of intense localised attack in some environments, as the anode in galvanic corrosion, is removed. However, the consumable manufacturer has to also achieve many other requirements in producing the filler material. The production of consumables for welding corrosion resistant alloys is a specialised matter and requires the balancing of many factors. The filler material has to be manufactured either as rod or strip. It has to show a good welding characteristics, i.e. the metal has to be transferable (e.g. by spray or droplet transfer) from the consumable to the work piece using established welding processes. There has to be compatibility with fluxes in the case of flux shielded welding processes. All of these factors are critical to producing a practical welding filler metal. In addition the user demands that the weld meets requirements for both mechanical properties and corrosion resistance.

Nevertheless there are appropriate choices of filler material for the majority of corrosion resistant alloys that will provide at least matching mechanical properties and corrosion properties that are equivalent to or better than the base material itself.

Table 1 gives typical compositions of a few commonly used alloys and their corresponding weld consumables.

The composition of the duplex stainless steel consumable is adjusted, with added nickel, to ensure that as-deposited welds contain a sufficient proportion of ferrite, typically 30-50%, despite their relatively fast cooling rate. This gives mechanical and corrosion properties similar to those of the base metal. A second, commercial, consumable composition for duplex stainless steel indicated in Table 1, is designed to increase resistance to pitting corrosion by elevating the levels of chromium and molybdenum.

A similar strategy is followed in the case of alloy 825. However, careful control of minor elements is necessary to minimise a tendency to hot cracking in restrained joints because this weld metal solidifies fully austenitic and so does not have the grain refining effect of a metallurgical transformation on cooling. The standard weld consumables for alloys 625 and C-276 are similar in composition to the base material, since their corrosion resistance is more than adequate for many applications, despite a degree of segregation. There are superior alloys here, though, that can be used as filler metals in environments where exceptional corrosion resistance is required in the weld zone.

It is often more cost-effective to use the higher-nickel alloys as overlays; of these, alloy 625 has been the most widely adopted, particularly for use in sour production systems. Because there was initial concern that dilution with iron from the underlying carbon steel would be detrimental to performance, maximum iron levels of only a few per cent were specified, even though it had been shown that up to 20% iron could be tolerated for seawater service<sup>1</sup>. Consumable manufacturers therefore reduced the iron content of weld metals well below the 5% maximum of the base metal, for example to <1.5%. Current standards for overlaying are more relaxed and allow up to 10% iron<sup>2</sup> acknowledging that such layers will have equivalent corrosion resistance to other solid alloys (such as alloy 825) which are frequently used within the same environment. It is worth noting that the heat input during overlaying had to be restricted to achieve very low dilution levels and the probability of defects, particularly lack of fusion, was substantially increased. Thus, realistic weld overlay dilution levels lead to a lower level of weld defects and a better quality overall.

In circumstances where there is a genuine need for a minimum composition equivalent to alloy 625 then it is advisable to change the choice of consumable to something more highly alloyed, such as alloy 686 which can tolerate more dilution whilst still maintaining sufficient Cr and Mo in solution.

## **HEAT INPUT**

The heat input to a weld is one of the critical aspects in controlling the welding process. While there must be sufficient heat to ensure that the weld pool is fluid and that there will be complete fusion with the base metal, adjacent material will be subjected to a range of thermal cycles that may induce precipitation or phase changes that are deleterious to both mechanical and corrosion properties. Therefore, although economics demands that weld metal is deposited at as high rate as possible, heat input must be controlled to ensure that both weld metal and base metal have the required properties.

The characteristics of the duplex stainless steels derive from the balanced structure of austenite and ferrite, which is formed when the initial totally ferritic structure decomposes on cooling. If the cooling rate is too high, particularly in the range 1200 – 800 °C, the austenite reaction is suppressed and the weld deposit will consist mainly or completely of ferrite. An example concerns cracks in longitudinal welds in pipes which were found to have been “dressed” with a GTAW torch, without using filler metal, in order to improve the weld surface appearance. The effect was to introduce a rapid cooling cycle with the metal transforming to ferrite at high temperature and then quenching giving welds with >70% ferrite. These areas in the weld cracked due to delayed (hydrogen) cracking which was fortunately detected during X-ray inspection of a girth weld <sup>3</sup>.

On the other hand, if the heat input is too high, thermal cycles in the heat-affected zone will allow time for precipitation to occur, especially of sigma phase within the existing ferrite. Since this phase is rich in chromium and molybdenum, it depletes the surrounding ferrite of these elements and thereby reduces corrosion resistance as well as reducing the toughness. For duplex stainless steels, therefore, there are both minima and maxima for heat input and interpass temperature is correspondingly limited. These restrictions result in an increase in the cost of making weld joints in duplex stainless steels as compared with similar joints in carbon steels. In practice, the general guidelines are as given in Table 2.

The arc energy throughout the joint should be balanced. The arc energy of the “hot pass” (second pass) should be about 80% of the root pass while the arc energy of subsequent passes may be relaxed, say up to 130% of the root pass<sup>4</sup>.

Duplex stainless steel welds should not normally be repair welded because of the risk of precipitate formation from the additional heat input. For this reason it has been normal practice for repairs in duplex stainless steel welds to require a full weld cut-out. This is particularly in the case where super duplex stainless steel flowlines have been laid.

Although nickel alloys remain austenitic, intermetallic phases can precipitate in the heat-affected zone. For example, a complex intermetallic  $\gamma$  phase and secondary carbides form in alloy C-276 in the temperature range 650-1040 °C and have a sensitising effect <sup>5</sup>. While this potential problem was overcome in later developments it did not necessarily disqualify the alloy from performing satisfactorily in many applications, as experience shows. Grain boundary precipitation occurs during ageing of alloy 625 <sup>6</sup> but the kinetics are such that sensitisation is not a significant issue at the operating temperatures of the oil and gas industry. Susceptibility of nickel alloys to intergranular attack is more associated with faults in production processes than welding. It is nevertheless generally recommended that heat input should be limited to avoid hot cracking, to which some nickel alloys are susceptible.

## **BACKING GAS**

While stainless steels and nickel alloys are characterised by a stable passive oxide film, welds and heat-affected zones oxidise rapidly at the very high temperatures generated during deposition. As a result, there is a zone denuded of chromium under the oxide that is less resistant to attack than the unaffected base material. It is necessary to prevent such oxidation by providing an inert backing gas, which not only prevents oxidation of the root run but also ensures that penetration is uniform and not affected by oxide formation. The importance of this backing gas shield cannot be overestimated. It must be formed before welding commences and maintained by a continuous flow of gas during insertion of the root run and subsequently until at least a further two runs have been deposited.

Inert gases, typically argon (lowest cost) or argon-helium mixtures, are normally used for purging. The oxygen content is measured and welding is not commenced until it is below a level, e.g. 500 ppm, specified according to the degree of oxidation that can be accepted in the completed joint.

Excessive purging of the backing gas to very low levels of oxygen was found to result in weld zones with low pitting resistance in duplex stainless steels because the nitrogen was removed from the weld zone. This was overcome by some fabricators using Formier gas (90% N<sub>2</sub>/10% H<sub>2</sub>), the added nitrogen content being claimed to improve the pitting corrosion resistance of the weld root. Nitrogen should not be used in the arc shielding gas as it can cause porosity. An alternative practical approach which is more commonly applied is to commence the welding of duplex stainless steels as soon as the oxygen level registers the relatively high oxygen limit of 500 ppm, whilst continuing to flow the backing gas purge. This ensures that there is sufficient air present in the backing gas to prevent loss of nitrogen from the weld and consequent reduction of weld austenite content and pitting resistance.

There are many examples of systems where corrosion failures have initiated on the heat-affected zone of stainless steel systems where this heavier oxide film is present.

In the early 1980s, a duplex stainless steel pipeline was laid for the Ijsselmonde project using the SMAW process and basic electrodes for girth welding <sup>7</sup>. The finished welds had the typical features of SMAW welds with oxidation of the heat-affected zone causing blackening of the surface and the weld bead itself having an adhering flux layer. A section of the line was laid on land and hydrotested using the most readily available water source, canal water, without any chemical treatment. The water was left in the line for a period of some months before being flushed out. During subsequent testing of the complete line, this section was then found to be leaking at many of the girth welds. Severe crevice corrosion had initiated at the welds and oxidised heat-tinted zones, where the surface condition reduced the resistance to corrosion. This experience highlighted the importance of avoiding oxidation during welding and also of the effect of residual slag on the interior of the pipe. As a result, gas-shielded processes replaced the SMAW process for weld roots and quality guidelines were established on the amount of discoloration which would be allowed in the heat-tinted area <sup>8</sup>.

It is not always recognised that internal oxidation can occur when welds are made on the outside of a pipe or vessel, for example fillet welds for attachment of supports. This can only be avoided by a rigorous purging procedure similar to that used for pipe joints. This is not a trivial matter and must be judged against the possibility of failure in service in the particular corrosive environment. Recent experience in the early production period of the Shell Shearwater project <sup>9</sup> has indicated that pitting attack initiated internally at heat darkened regions of piping associated with external support welds, despite a specified requirement for internal purging during support welding. In this case the internal environment was particularly severe with chloride ion concentrations estimated to be well in excess of 200,000 ppm due to flashing off of the gases, but it still highlights the influence of these regions in initiating the attack.

## **POST WELD TREATMENT**

It is normally impracticable to remove any heat tint that is formed within a pipeline but welds within vessels may be accessible. In tests on super duplex stainless steel samples <sup>10</sup>, pickling in a nitric/hydrofluoric acid mixture produced a substantial increase in critical pitting temperature while more a modest improvement was gained by prolonged exposure in aerated seawater. Other investigations <sup>11</sup> gave no indications that heat tint has any influence on the corrosion resistance of alloy

C-276 or, by inference, other nickel-base high-molybdenum alloys. A similar conclusion was drawn from tests with alloy 625 in simulated high-chloride scrubber environments<sup>12</sup>. Purging with an inert backing gas is thus the main defence against failures due to heat tint in duplex stainless steels and alloys with comparable or lower pitting resistance, while removal of slag and mechanical cleaning is a general requirement for all accessible welds.

## CONCLUSIONS

Welding of CRA materials requires care to ensure that the weld zone matches the corrosion resistance of the base material. If proper consideration is given to the weld preparation, welding procedure, choice of weld consumable, heat input, backing gas and post-weld clean up and handling then satisfactory results can be obtained. Whilst the literature shows that there have been some failures of CRA materials at welds there are also many success stories. By drawing attention to some key aspects, this paper aims to reduce the re-occurrence of past failures.

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Table 1 - Typical compositions of alloys and weld consumables (mass %)

|                        |          | Cr   | Ni   | Mo   | Fe   | Nb  | N    | Other  |
|------------------------|----------|------|------|------|------|-----|------|--------|
| Duplex stainless steel | Alloy    | 22,0 | 5.5  | 3.0  | Bal. | -   | 0.14 | -      |
|                        | Weld (1) | 22.5 | 9.0  | 3.0  | Bal. | -   | 0.17 | -      |
|                        | Weld (2) | 25.0 | 9.5  | 3.4  | Bal. | -   | 0.17 | -      |
| 825                    | Alloy    | 21.5 | 42.0 | 3.0  | 30.0 | -   | -    | 2.0 Cu |
|                        | Weld     | 28.0 | 38.0 | 3.5  | 27.0 | 0.3 | -    | 2.0 Cu |
| 625                    | Alloy    | 21.5 | 61.0 | 9.0  | 2.5  | 3.6 | -    | -      |
|                        | Weld     | 22.0 | 65.0 | 9.0  | 0.8  | 3.5 | -    | -      |
| C-276                  | Alloy    | 16.0 | 57.0 | 16.0 |      | -   | -    | 4.0 W  |
|                        | Weld     | 16.0 | 57.0 | 16.0 |      | -   | -    | 4.0 W  |

Table 2. Guideline heat input restrictions for welding duplex stainless steels

|              | Heat Input<br>kJ/mm | Max Interpass Temp.<br>°C |
|--------------|---------------------|---------------------------|
| Duplex       | up to 2.5           | 250                       |
| Super duplex | up to 1.5           | 150                       |