Practical aspects for production welding and control of duplex stainless steel pressure and process plants

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Keywords: duplex, welding procedures, production, properties, training

1 Summary

Good stainless steel practice is the basis for welding duplex and superduplex grades. However, some issues from the generalized ‘good practice’ rules must be emphasized where as other issues need only the same attention as when welding 300 series stainless steels. This paper discusses good ‘duplex and superduplex’ stainless steel practice. Issues around, for example, welding procedure design, heat input and interpass temperature are discussed. The practical application of the rules is all important. The first step is to educate the work force into thinking ‘duplex’, i.e. not just another grade of stainless steel. Specification and practical fabrication issues, as applied to reactor and pressure vessel fabrication, are described. Welding procedures are given, together with the results of procedure qualification tests and production test plates.

2 Introduction

Although duplex stainless steels are increasingly used for pressure and process plants in a wide range of industries and applications, it is still important to remember and appreciate the ‘how to weld’ issues associated with these steels. When welding the generic C-Mn steel family, the detailed grade characteristics determine the emphasis that must be placed on, e.g., techniques to avoid hydrogen cracking, heat input control etc. A similar concept of balanced emphases exists for stainless steel. General Good Practice ‘rules’ exist in various codes, e.g. EN 1011 Part 3, but the emphasis of these rules must be balanced and detailed for different generic grades of stainless steel. Duplex stainless steel is in the stainless steel family and therefore the good practice rules are the basis. However, the emphasis, balance and detail must be appreciated in terms of duplex stainless steel. This paper describes some of the more important aspects of good practice for duplex stainless steel so that welding procedures may be designed to be technically and practically correct and relevant.

3 Duplex good practice: the basis

The guidance given here is considered in relation to pipe welding where the penetration bead is the corrosion ‘active’ surface; other configurations are variations on this theme. It is assumed that the weld is to be put into service with no post-weld heat treatment.

3.1 Joint configuration

The bevel design is determined by the normal criteria of welding access in relation to joint volume. Bevel angles of 30–35º are standard for vee butts. It is very important to consider the root zone configuration. The welding consumable’s nickel content is boosted by ~2% in order to stabilize the weld bead ferrite/austenite phase balance. Care must be taken to ensure that the increased nickel content is not diluted by parent material. This is prima-
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If Root Run Heat Input is “HI\textsubscript{Root}”, HI for subsequent passes balanced accordingly

<table>
<thead>
<tr>
<th>Thin Walled Joint</th>
<th>Heavy Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passes as % of HI\textsubscript{Root}</td>
<td>Cap: ~75 &lt; 110%</td>
</tr>
<tr>
<td>Cold: ~75 &lt; 100%</td>
<td>Fill: ~75 &lt; 150%</td>
</tr>
<tr>
<td>Root: HI\textsubscript{Root}</td>
<td>Fill: ~75 &lt; 120%</td>
</tr>
<tr>
<td></td>
<td>Cold: ~75 &lt; 110%</td>
</tr>
<tr>
<td></td>
<td>Root: HI\textsubscript{Root}</td>
</tr>
</tbody>
</table>

- Based on Single Sided Welding, “Active” Root
- Which is the “corrosion active” face?
- Is it Single sided?

Figure 2. WPS design based on root run heat input.

Easily achieved by controlling the root gap. The root gap should be set and maintained at nominally 2mm (80 thou) although slightly larger root gaps can be tolerated for 22 and 23 chromium duplexes. It is well known that some welders weld ‘hotter’ or ‘colder’ than others. The root face would generally be around 2mm (80 thou) although feather edges are acceptable to welder preference. If too large a root gap or root face is used, the heat input to complete the pass may be too high or the pass would be impractically thin or incomplete penetration will occur.

Single- or double-sided welding etc. can be used as dictated by the normal considerations of component being welded, thickness and shop fabrication practices. Double-sided welding, for example, does not require the same level of root configuration control provided 2 or more passes are deposited on each side. The root gap and face would generally be determined by more classic welding process requirements rather than alloy and metallurgical requirements. Thicker joints that can be submerged arc welded would tend to have a zero gap but a heavier face (~5mm) (~0.2”) on which to build the weld passes.

3.2 Heat input and welding procedure design

The most important elements of WPS design are heat input level and balance. The root pass heat input is dependent on the thickness and grade being welded. The “S” curve shown in figure 1 illustrates this and identifies the potential implications of welding too hot or too cold for a given thickness.

The heat input balance for a given joint is based on the root pass heat input (HI\textsubscript{root}). The cold, fill and capping pass heat inputs are taken as a percentage of HI\textsubscript{root} as illustrated in figure 2. For example, if the appropriate heat input for a thicker joint is 1.2kJ/mm (30.5kJ/in), the cold pass would be deposited at between ~0.9 and 1.3kJ/mm (22.9 and 33kJ/in), i.e. ~75% < HI\textsubscript{root} < ~110%.

The balance of heat inputs is an important factor in maximizing the metal deposition rate whilst minimizing the possibility of metallurgical damage through unacceptable intermetallic formation.
The heat input may need to be adjusted slightly if the cap is the active surface or if double-sided welding is used. In practice, changing from one welding position to another has very little influence on the root pass heat input.

3.3 Preheat and interpass temperature
Welding heat input is an important parameter that fabricators relate to. The issue is, in fact, cooling time (∆t) or cooling rate, which include heat input, thickness and 'start' temperature.

Preheating duplex stainless steel is extremely rare; to all intents and purposes assume that it is unnecessary. Interpass temperature must, however, be controlled.

Interpass temperature is the maximum temperature of the metal immediately prior to starting any welding. It should be measured in and around the area where the welding is about to start and where it is anticipated finishing. The locations to check most carefully are along the underlying weld bead or on the bevel face, not 2" away on the plate or pipe surface.

Given that interpass temperature is one of the factors determining ∆t, there is a balance between heat input and interpass. In practical terms, the interpass temperature will be in the range 100 to 150°C (210 to 300°F) dependent on the alloy and thickness being welded.

Various cooling techniques can be used to maintain productivity in relation to interpass temperature control: equally the welder can work on several joints at a time, one cooling while another is being welded.

3.4 Balanced welding
Stainless steels have a higher coefficient of expansion than carbon steels and therefore they tend to 'move' more during welding. This must be taken into account.

Production and economic factors require a maximum joint completion rate. Metallurgical factors require control of root gaps, interpass temperature etc.

These two seemingly conflicting aspects can be resolved by using a balanced welding technique. We are all familiar with the conventional approaches including double-sided weld-

![Figure 3. Balanced welding sequences.](image-url)
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In reality, plasma or laser cutting is used. The cut edge should be mechanically dressed to remove the cutting oxides and cutting HAZ.

The joint must be fitted and tacked correctly to allow welding to be completed according to the WPS. Bridge pieces and strong backs can be used as temporary attachments. Root, bridge and bullet tacks can all be used but the tack weld needs to be larger than that for C-Mn, maybe by 25–50%.

As with any welding which demands integrity, the weld zone must be properly clean and dry before starting to weld. The bevel area should be solvent cleaned.

4 Practical application of duplex good practice

4.1 Joint preparation and fit-up

Although machined joint preparations are preferred, it is not practical to use them all the time. Any thermal cutting technique results in a thermal history being retained at the cut edge. Consequently a similar thought pattern to that associated with welding heat input is appropriate, although not to the same level and extent.

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4.2 Production control and monitoring

Heat input control is very important, as previously discussed. It is obviously rather easy to set mechanized or automated welding equipment, e.g. submerged arc welding, to give the correct heat input. However, manual welding can also be controlled by using the run-out length approach.

Electrodes are characterized by their typical current, voltage and burn time. The heat input can therefore be controlled by monitoring the length over which the electrode is ‘run-out’, figure 4. A requirement to weld with (e.g.) a heat input of 1.5kJ/mm (38kJ/
in) off a 3.25mm (1/8") diam. electrode would result in a run out length of approximately 110mm (4.3"). Shorter or longer run-out lengths corresponds to higher or lower heat inputs, respectively.

Good working practice for welders is to chalk the run-out length on the joint where they can see it during welding as a benchmark for self-monitoring. Confidence to fabricate duplex correctly and economically grows with experience and being able to demonstrate a good level of production control. Production monitoring is the key.

Monitoring the welding operations, and having records to correlate with the WPS, is a very powerful and effective method of:

a. helping the welder to stay within parameter ranges and
b. building the corporate confidence that duplex can be effectively fabricated

Such records might typically include job and welder identification, WPS number, pass number and heat input. Feedback of these data help the welder to gauge travel speed in relation to WPS requirements.

The extent of monitoring is clearly dependent on many factors. It would not normally be appropriate to monitor any individual welder for more than a few passes, say, once a week. This is a supportive activity, not policing.

Other aspects of production that should be considered for monitoring include the availability and use of the equipment for checking purge gas oxygen content, cleanliness of plate and rolls, fit-up of joints.

### 4.3 Welding process issues

Welding process selection relates in the normal way to process characteristics and economics. However, there are several specific aspects that should be considered in relation to the duplex family.

The most common process for single-sided root (and cold) passes is gas tungsten arc welding (GTAW).

The fluxing processes result in a flux covering on the cap and, where single-sided, on the root pass. Flux is a very effective crevice...
former which may limit the corrosion performance of the welded component. Fluxing processes should only be used for root runs where there is adequate access to the root pass either for deslagging or for cut-out and seal welding. Submerged arc welding is a very efficient process for filling and capping. However, the efficiency is reduced dramatically in, for example, thick-walled pipe welding if the welding must be stopped after each rotation for interpass temperature requirements. Methods for effectively cooling the pipe must be implemented, taking care to avoid the obvious issues of contamination, health and safety etc. Allowance must be made for deslagging.

Flux cored arc welding (FCAW) is utilized for welding 22Cr and 23 Cr duplex grades. It is a fast economic process suitable for joints that do not have high demands for corrosion or toughness. Heat input control of mechanized FCAW is obviously straightforward but, when using the process manually, the welder has no reference points to gauge heat input in the same sense as run-out length control is available in MMA (SMAW). FCAW can be used for the two duplex grades that are most tolerant to heat input.

### 4.4 Gases

Argon and argon/helium gases are both used for shielding and purge gases dependent on national and local practices. Proprietary gas mixtures have also been developed for the duplex grades. Argon/low-nitrogen proprietary gas mixtures are available for welding particularly the duplex grades. These gases may be appropriate as shielding gas for welds that have a high corrosion requirement.

The purge gas serves two purposes: to prevent loss of nitrogen from the weld zone during welding and to prevent root pass oxidation. The purge gas is used to displace air from behind the joint. In most cases adequate oxidation protection is achieved if the purging mixture contains <~0.5% oxygen. If no nitrogen is present in this gas mixture, the nitrogen partial pressure in the weld zone will be higher than in the purge gas and there may be loss of nitrogen from the weld metal particularly. A low level of nitrogen should be retained in the purge gas to prevent this loss. Proprietary gas mixture containing 2–3% nitrogen can be used, in which case the purge gas must be ‘free of oxygen’ before starting to weld. Alternatively the oxygen content of the argon purge gas can be controlled to contain ~0.5% retained oxygen, and therefore ~2% nitrogen.

Many contracts require that the welding oxidation is removed from penetration and capping beads. This should certainly be regarded as the norm. It is not possible to

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>AS SAF 2507</th>
<th>Welding consumable</th>
<th>2507/P100</th>
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</thead>
<tbody>
<tr>
<td>Wall thickness</td>
<td>10mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root gap</td>
<td>1–2mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root face</td>
<td>2mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welding position</td>
<td>1G</td>
<td></td>
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</tr>
<tr>
<td>Interpass temp.</td>
<td>125°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWHT</td>
<td>None</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pass &amp; process</th>
<th>Consum. diam. (mm)</th>
<th>Heat input (kJ/mm)</th>
<th>Properties achieved</th>
<th>To contract requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root SMA</td>
<td>3.25</td>
<td>1.0–1.2</td>
<td>Bends (R&amp;F)</td>
<td>180³</td>
</tr>
<tr>
<td>Cold SMA</td>
<td>3.25</td>
<td>0.8–1.0</td>
<td>G48A @</td>
<td>35³</td>
</tr>
<tr>
<td>Fill SMA</td>
<td>4.0</td>
<td>0.7–1.2</td>
<td>CVN: weld metal &gt;56</td>
<td>J @</td>
</tr>
<tr>
<td>Cap SMA</td>
<td>4.0</td>
<td>0.8–1.2</td>
<td>CVN: weld metal</td>
<td>J @</td>
</tr>
<tr>
<td>(10×7.5mm CVNs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Welding procedure qualification data for SMA welded AS SAF 2507 superduplex stainless steel.
absolutely relate the color of the oxide interference film to the performance of the joint but any oxide on the root pass that is darker than ‘light straw’ should be removed. It is also advisable to investigate why a higher level of oxidation has occurred. It is not possible to be dogmatic about which gases should be used as every fabricator and country has its own practices. Notwithstanding the comments above, the gases should be clean, dry and inert. The only exception to this is the possible inclusion of a low level of oxidizing species for the gas shielded wire processes. There is a strong positive argument for using the same gas as both shield and purge gas. However, each fabricator’s shop’s facilities and practices must be respected.

5 Procedures

It is very important that the required levels of properties are achieved in qualification and that those levels are sustained in production. The outline results of welding procedure qualification are shown in tables 1 and 2. Both of these procedures reflect the basis of sound procedure design, show the inevitable ranges in parameters that are used and result in properties that are achieved to meet contract requirements. Production test plate data, tables 3 and 4, demonstrate how the qualification data relates to actual production. Notch toughness and microstructural phase balance are numerical data that may be sensitive to changes in welding practice. The submerged arc welding data in table 3 shows these data to be reasonably consistent across a number of welds, over a period of 4 months and for a range of applied thicknesses. The maximum hardness and tensile strength are also consistent; no accelerated corrosion testing failures were experienced in these or any other of the production test pieces. Table 4 shows the data for a rather difficult production weld, a compensating plate to shell weld. This production weld was welded as a prolongation to the strake, not as a stand-alone test piece. The production weld is covered by two PQRs as shown. All the properties achieved in production reflect the qualification welds.

6 Specifications

It is extremely important to every one that realistic specifications are used. They must be technically accurate and relevant and, importantly, they must be accurately applied. There are several difficult areas still being debated, not least of which is the significance of different product and fabrication tests. For example, most specifications state that the phase balance shall be within limits and no deleterious phases shall be

<table>
<thead>
<tr>
<th>Prod test plate I/D</th>
<th>PQR</th>
<th>901542</th>
<th>902906</th>
<th>809205</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQR no.</td>
<td>PQR</td>
<td>616</td>
<td>616</td>
<td>616</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td></td>
<td>16</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>UTS (weld) (MPa)</td>
<td></td>
<td>785</td>
<td>762</td>
<td>775</td>
</tr>
<tr>
<td>CVN J W/M @ –50ºC</td>
<td>&gt;58</td>
<td>&gt;57</td>
<td>&gt;42</td>
<td>&gt;61</td>
</tr>
<tr>
<td>CVN J F/L @ –50ºC</td>
<td>&gt;79</td>
<td>&gt;64</td>
<td>&gt;78</td>
<td>&gt;104</td>
</tr>
<tr>
<td>Ferrite %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld (Av)</td>
<td>42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld cap</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td>48</td>
</tr>
<tr>
<td>Weld root</td>
<td>46</td>
<td>48</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>HAZ root</td>
<td>52</td>
<td>51</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>HAZ hardness (max.)</td>
<td>Hv10</td>
<td>279</td>
<td>272</td>
<td>274</td>
</tr>
<tr>
<td>G48A @ 22ºC</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Table 3. Summary of AS 2205 production welding (SAW) data obtain for contract requirements.
detected during microstructural evaluation. However, the significance of low levels of intermetallic is, in general terms, almost certainly doubtful. Additionally, the significance is related to application. It is noticeable that, in recent years, industry is moving from accepting low levels of intermetallic on concession to actually allowing low levels in application and project specifications. Given this situation, the question arises regarding how to accurately quantify low levels of intermetallic content; it is very difficult and expensive.

Specifications must be applied accurately. ASTM A923 is a case in point. This standard was written as a wrought product acceptance specification and as such it is very valuable. However, it does get applied erroneously to fabrication acceptance. The requirements and implications of product and fabrication ‘qualification’ should not be confused. This specification is good for the intended purpose, product specification: do not abuse it.

Accelerated corrosion testing of parent material or welds is only as relevant to stainless steel as notch toughness testing is to carbon manganese steels (or stainless steels). It is no more, no less a QC test. ASTM G48A and CVN testing are, at best, broad brush indicators of service performance. They must not be over-specified or, indeed, over-interpreted.

There must be a distinction between qualification plates and production test plates. There is no doubt that qualification plates should be thoroughly examined and characterized. However, the purpose of the production test plate is to ensure that the procedure is achieving the properties obtained in qualification. Testing regimes should be kept in this context. It is rarely necessary to complete the same level of testing on a production test plate as has been completed on a qualification plate. Common sense and engineering judgement should be used to consider what a particular test is measuring, why it is being measured and how does it relate to other tests that may be completed for this quality control operation. It does seem unnecessary to duplicate all the qualification tests on the production test plates if, of course, the results are satisfactory.

7 Education

The education and awareness of the workforce, at all levels, is very important. The whole of the shop floor must be made aware that whilst the principles of 300 series welding are relevant (crater filling techniques, tack weld condition etc.), the detail of duplex must be applied and procedures must be followed. The welders must be allowed time and facilities to ‘convert’ from welding 316 to welding duplex grades. They must practice the almost certainly unfamiliar technique of stringer bead welding and continuous filler addition. Controlled heat input must become second nature for duplex as it is for many high-grade C-Mn steels.

The company’s management must be aware that the material be welded is rather

Table 4. Summary of AS 2205 production welding (SMAW) data obtain for contract requirements.
more sophisticated than, say, 304 and that it requires greater attention to detail. Everyone must know stainless steel confidently and think duplex absolutely.

8 Conclusions

Stainless steel good practice is the basis for welding duplex grades. However, different emphases must placed on various aspects for Duplex Stainless Steel Good Practice. Welding procedure design and control is central to successful fabrication and application. Experience and confidence is very important. Heat input, interpass temperature and balanced welding techniques are three of the factors to which detailed attention must be paid.

Attention to detail is carried through to practical application by good production control and supportive process monitoring. Specification of technical parameters is obviously appropriate but the specifications should not be over-prescriptive or mis-applied. One of the keys to successful duplex fabrication is education, at all levels of the company. It is important that the shop floor understand the practical issues of duplex fabrication, maybe also having a level of appreciation of the technical background. However, the CEO or President must also understand that a sophisticated material is being fabricated and greater attention to detail is necessary. There is no substitute for experience in the successful supply of fabricated duplex process plant.