QUALIFICATION OF WELDING PROCEDURES FOR DUPLEX STAINLESS STEELS

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ABSTRACT

Duplex stainless steels are being introduced into new applications within the pulp and paper industry, especially in digesters. These "new" grades have important differences in welding characteristics and construction requirements in comparison with the common austenitic stainless steels. As a Committee Activity of TAPPI, a task group of the Corrosion and Materials Engineering Committee is preparing a Technical Information Paper (TIP) on recommended practices for qualification of welding procedures. This discussion is a progress report on that activity.

The characteristics of the duplex stainless steels are reviewed, focusing on the selection of tests for qualifying weld procedures. The effectiveness of different evaluation tests is critically reviewed for the purpose of recommending technically effective and economical specifications.

INTRODUCTION

The goal of this discussion is the definition of technically and economically effective testing for qualification of weld procedures. It reviews current knowledge of welding duplex stainless steels, particularly as it affects their use in the pulp and paper industry. It introduces the currently available grades but focuses on 2205 duplex stainless steel for digesters. However, the information is generally applicable with appropriate modification to other duplex stainless steels and to other applications of duplex stainless steels within the pulp and paper industry.

Throughout the text there will be references to further discussion in the Frequently Asked Questions (FAQ) in Appendix A.

COMMERCIALLY AVAILABLE DUPLEX STAINLESS STEELS

As is true of austenitic stainless steels, the duplex stainless steels comprise a family of grades with a range in corrosion performance depending on their alloy content. Modern duplex stainless steels are often addressed in four groups:

Lean duplex, such as 2304 (S32304), which contain little or no deliberate Mo addition;
2205 (S32205), the workhorse grade accounting for more than 80% of duplex use;
25 Cr duplex, such as 255 (S32550) and S31260; and
Superduplex, with 25-26 Cr and increased Mo and N, such as 2507 (S32750).

Table I lists the duplex stainless steels covered in ASTM specifications for plate, sheet, and bar products.[1] Although few of the duplex grades are patented, many of these grades are closely associated with particular steel producers as proprietary developments. This situation is often reflected in the naming of the grades. Only one duplex stainless steel has an AISI designation, Type 329, a first generation duplex stainless steel without intentional nitrogen addition. Many of the grades have become commonly known by a number that reflects their typical chromium and nickel contents, e.g., 2205 with 22% Cr and 5% Ni. These composition-based names, used by many producers, have recently been added to A 240 and are being added to the ASTM specifications for other product forms. Trademarks of individual producers are not permitted in the ASTM specifications. All grades in the ASTM specifications are all listed by their designations in the Unified Numbering System (UNS). It is important to reference the UNS number when ordering to the standard specifications in order to get the desired grade.

Table I. Composition of Duplex Stainless Steels and Representative Austenitic Stainless Steels[a]

UNS Number	Type[b]	C	Mn	P	S	Si	Cr	Ni	Mo	N	Cu	Other
Duplex Grades												
S31200	...	0.030	2.00	0.045	0.030	1.00	24.0-26.0	5.5-6.5	1.20-2.00	0.14-0.20	...	...
S31260	...	0.03	1.00	0.030	0.030	0.75	24.0-26.0	5.5-7.5	2.5-3.5	0.10-0.20	0.20-0.80	W 0.10-0.20
S31803	…	0.030	2.00	0.030	0.020	1.00	21.0-23.0	4.5-6.5	2.5-3.5	0.08-0.20	...	...
S32001	…	0.030	4.0-6.0	0.040	0.030	1.00	22.0-23.0	1.00-3.00	0.60	0.05-0.17	1.00	...
S32205	2205	0.030	2.00	0.030	0.020	1.00	19.5-21.5	4.5-6.5	3.0-3.5	0.14-0.20	...	…
S32304	2304	0.030	2.50	0.040	0.030	1.00	21.5-24.5	3.0-5.5	0.05-0.60	0.05-0.20	0.05-0.60	...
S32520	…	0.030	1.50	0.035	0.020	0.80	24.0-26.0	5.5-8.0	3.0-4.0	0.20-0.35	0.50-2.00	…
S32550	255	0.04	1.50	0.040	0.030	1.00	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.5-2.5	...
S32750	2507	0.030	1.20	0.035	0.020	0.80	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32	0.50	...
S32760	...	0.030	1.00	0.030	0.010	1.00	24.0-26.0	6.0-8.0	3.0-4.0	0.20-0.30	0.50-1.00	c
S32900	329[d]	0.06	1.00	0.040	0.030	0.75	23.0-28.0	2.5-5.0	1.0-2.0	...	...	...
S32950	...	0.03	2.00	0.035	0.010	0.60	26.0-29.0	3.5-5.2	1.00-2.50	0.15-0.35	...	...
Austenitic Grades												
S30403	304L[d]	0.030	2.00	0.045	0.030	0.75	18.0-20.0	8.0-10.5	…	0.10	…	…
S31603	316L[d]	0.030	2.00	0.045	0.030	0.75	16.0-18.0	10.0-14.0	2.00-3.00	0.10	…	…
S31703	317L[d]	0.030	2.00	0.045	0.030	0.75	18.0-20.0	11.0-15.0	3.0-4.0	0.10	…	…
N08904	904L	0.020	2.00	0.045	0.035	1.00	19.0-23.0	23.0-28.0	4.0-5.0	0.10	1.0-2.0	…
S31254	…	0.020	1.00	0.030	0.010	0.80	19.5-20.5	17.5-18.5	6.0-6.5	0.18-0.22	0.50-1.00	…
N08367	…	0.030	2.00	0.040	0.030	1.00	20.0-22.0	23.5-25.5	6.0-7.0	0.18-0.25	0.75	…
N08926	…	0.020	2.00	0.030	0.010	0.50	19.0-21.0	24.0-26.0	6.0-7.0	0.15-0.25	0.50-1.50	…
S32654	…	0.020	2.0-4.0	0.030	0.005	0.50	24.0-25.0	21.0-23.0	7.0-8.0	0.45-0.55	0.30-0.60	…

[a] Weight percent, maximum unless otherwise noted.

[b] Unless otherwise indicated, a common name, not a trademark, widely used, not associated with any one producer, as listed in ASTM A 240.

[c] W 0.50-1.00; Cr+3.3Mo+16N=40 min.

[d] AISI designation

Table II lists the ASTM specifications that are applicable to the duplex stainless steels, both wrought and cast products.[1,2,3] In general it is true that the duplex grades can be ordered as flat-rolled products, bar products, forgings, and fittings which use the same ASTM specifications as used for Type 316L austenitic stainless steel, but there are separate specifications to be used for duplex tubular products and for castings.

Many, but not all, of the duplex stainless steels are included in the ASME Boiler and Pressure Vessel Code, either in the body of the Code or as Code cases. Users should be aware that the ASME has established additional requirements for the qualification and construction of duplex stainless steels. These requirements are detailed and complex, and the fabricator and user are advised to review these requirements before proceeding with an application of duplex stainless steels that will require certification of compliance with the ASME Code.

The mechanical properties of the duplex stainless steels, as listed by ASTM A 240, are compared to those of Type 316L in **Table III**. The duplex stainless steels typically have yield strengths about twice those of the common austenitic grades, but are less ductile. The duplex stainless steels have lower thermal expansion coefficients and higher thermal conductivities than Type 316L, with the values for duplex stainless steels more closely resembling those for carbon steel.

This discussion will focus on 2205 duplex stainless steel. It is the most readily available grade with multiple producers of virtually all product forms and good availability through common metal distribution channels. The issues regarding welding of duplex stainless steels are similar for most grades. A thorough discussion of 2205 is a sound basis for modification to cover other duplex grades of greater or lesser alloy content.

Table II. ASTM Specifications Covering Duplex Stainless Steels[A]

Product Form	ASTM Specification
Plate, Sheet	A 240
Bar Products	A 276, A 479
Pipe	A 790, A 928
Tubing	A 789
Fittings	A 815
Forgings	A 182
Castings	A 890
Testing	A 923

[A] Not all duplex grades are in each listed specification.

Table III. ASTM A 240 Mechanical Test Requirements for Duplex Stainless Steels

UNS Designation	Type	Tensile Strength, min MPa	Tensile Strength, min ksi	Yield Strength, min MPa	Yield Strength, min ksi	Elongation in 2 in. or 50 mm, min, %	Hardness, max Brinell	Hardness, max Rockwell C	Cold Bend
S31603	316L	485	70	170	25	40.0	217	95 (HRB)	not required
S31200	...	690	100	450	65	25.0	293	31	not required
S31260	...	100	690	485	70	20.0	290	...	...
S31803	…	620	90	450	65	25.0	293	31	not required
S32001	…	620	90	450	65	25.0	…	25	not required
S32205	2205	620	90	450	65	25.0	293	31	not required
S32304	2304	600	87	400	58	25.0	290	32	not required
S32520	…	770	112	550	80	25.0	310	…	not required
S32550	255	760	110	550	80	15.0	302	32	not required
S32750	2507	795	116	550	80	15.0	310	32	not required
S32760	...	750	108	550	80	25.0	270	...	not required
S32900	329	620	90	485	70	15.0	269	28	not required
S32950	...	690	100	485	70	15.0	293	32	not required

GENERAL GUIDELINES FOR WELDING DUPLEX STAINLESS STEELS

It is assumed that the reader already has experience in welding of austenitic stainless steels such as Type 316L in pulp and paper mill applications. This section addresses some to commonly discussed welding characteristics and procedures of the duplex stainless steels in terms of how they differ from austenitic stainless steels. Addressing each of these features is essential for the design of technically and economically effective welding procedures to be qualified.

Differences Between Duplex and Austenitic Stainless Steels

Duplex stainless steels are typically twice as strong as common austenitic stainless steels. The thermal expansion of the duplex grades is intermediate to that of carbon steel and the austenitic stainless steels. The thermal conductivity of the duplex stainless steels is also intermediate to that of carbon steels and the austenitic stainless steels.

When there are problems with welding of austenitic stainless steels, those problems are most frequently associated with hot cracking of the weld metal itself. This hot cracking tendency is aggravated by fully or predominantly austenitic solidification, and by the combination of high thermal expansion and low thermal conductivity. For the more common austenitic stainless steels, hot cracking is minimized by adjusting the composition of the filler metal to provide a significant ferrite content. For the more highly alloyed austenitic stainless steels where the use of a nickel-base filler metal is necessary, austenitic solidification is unavoidable. In these cases these problems must be managed by minimizing joint constraint and by low heat input, often requiring many passes to build up the weld.

Duplex stainless steels have good hot cracking resistance. Hot cracking of the duplex weld metal is seldom a concern. The problems most typical of duplex stainless steels are associated with the heat-affected zone (HAZ), not with the weld metal. The HAZ problems are not hot cracking but rather a loss of corrosion resistance and toughness, or of post-weld cracking. To avoid these problems, the welding procedure should focus on minimizing **total time at temperature** in the “red hot” range for the whole procedure rather than managing the heat input for any one pass. Experience has shown that this approach can lead to procedures that are both technically and economically optimal.

The data shown in the appendix of ASTM A 923 suggest how rapidly intermetallic phases can precipitate to the extent that corrosion resistance and toughness are significantly affected.

With this introduction in mind, it is possible to give some general guidelines for welding of duplex stainless steels and then to apply this background and those guidelines to specific welding methods.

Selection of Starting Material

The welding characteristics of duplex stainless steels are much more sensitive to minor within-grade variations in chemistry or processing than are austenitic stainless steels. For example, the importance of having sufficient nitrogen in the duplex stainless steel base metal has been repeatedly emphasized. Air cooling of a plate, even when rapid, through the 705 to 980°C (1300 to 1800°F) range will use up some of the “time on the clock” for the welder to complete the weld before detrimental reactions occur. Similarly, if a plate is allowed to air cool into this range during transfer to water quenching, that time is no longer available to the welder. The metallurgical condition of the material used in actual fabrication should be the same quality with regard to composition and production practice, as the material used to qualify the welding procedure. The specification of composition and testing for the starting material are discussed in Section III and in Appendix A.

Cleaning Before Welding

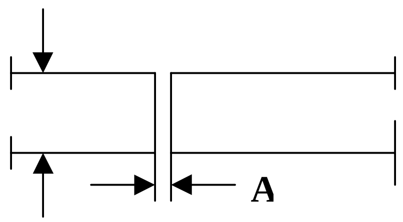
The need to clean prior to welding applies to all stainless steels. But the duplex stainless steels are more sensitive to contamination, and especially to moisture, than the austenitic stainless steels. The chemistries of the base metal and the filler metal have been developed assuming no additional sources of contamination. Dirt, grease, oil, paint, and sources of moisture of any sort will interfere with welding operations and adversely affect the corrosion resistance and mechanical properties of the weldment. No amount of procedure qualification is effective if the material is not thoroughly clean before welding.

Joint Design

Duplex stainless steels require good joint preparation. For duplex stainless steels, a weld joint design must facilitate full penetration and avoid autogenous regions in the weld solidification. It is best to machine rather than grind the weld edge preparation to provide uniformity of the land thickness or gap. When grinding must be done, special attention should be given to uniformity of the weld preparation and the fit-up. Any grinding burr should be removed to maintain complete fusion and penetration. For an austenitic stainless steel, a skilled welder can overcome some deficiencies in joint preparation by manipulation of the torch. For a duplex stainless steel, these techniques can cause a longer than expected exposure in the harmful temperature range, leading to results outside of those of the qualified procedure.

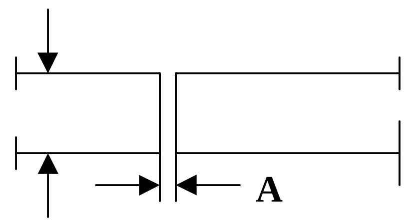
Examples of joint designs used with duplex stainless steels are shown in **Figure 1**.[4] Other designs are possible provided that they assure full penetration welds and minimize the risk of burn-through.

Figure 1. Examples of joint designs applied to 2205 duplex stainless steel.



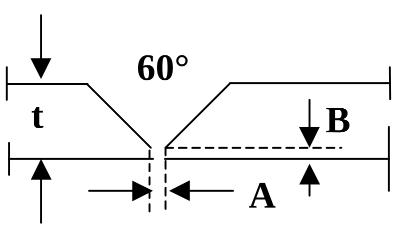
2 mm (0.08 in) $\leq$ t < 4 mm (0.16 in)
A = 1-2 mm (0.04-0.08 in)

A. Square Butt Joint - Suitable for single-sided SMAW or double-sided SMAW or GMAW.



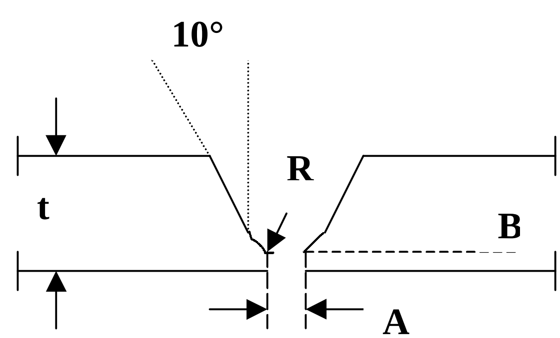
t $\leq$ 2.5 mm (0.1 in)
A = 1-2 mm (0.04-0.08 in)

B. Square Butt Joint - Suitable for GTAW from one side. Backing gas required.



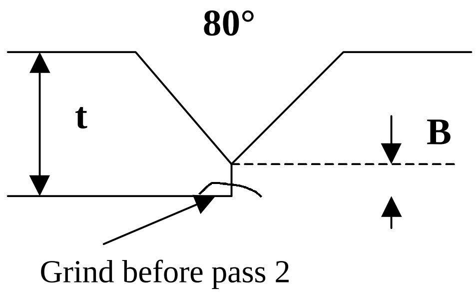
4 mm (0.16 in) $\leq$ t $\leq$ 12 mm (0.5 in)
A = 2 mm (0.08 in)
B = 2 mm (0.08 in)

C. Suitable for heavier sections with SMAW or GMAW. Increase A to 3 mm (0.12 in) for vertical-up SMAW



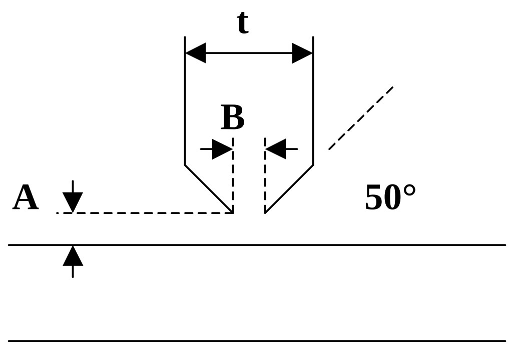
12 mm (0.5 in) $\leq$ t $\leq$ 60 mm (2.5 in)
A = 3 mm (0.06 in)
B = 2 mm (0.08 in)
Radius = 6 mm (0.25 in)

D. Suitable for very thick base metal with SMAW or GMAW.



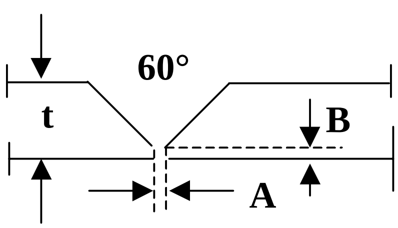
9 mm (0.36 in) < t < 12 mm (0.5 in)
B = 5 mm (0.2 in)

E. Suitable for SAW. Grinding after first pass facilitates full penetration.



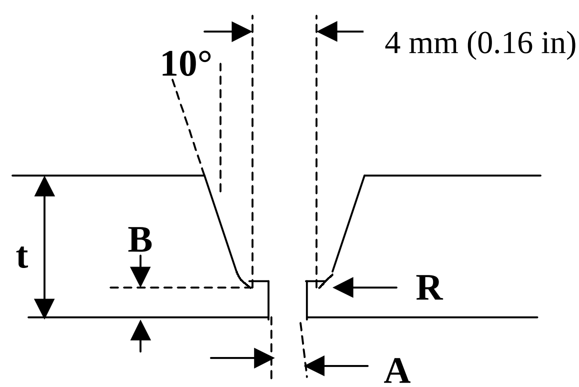
4 mm (0.16 in) < t < 12 mm (0.5 in)
A = 2.5 mm (0.1 in)
B = 5 mm (0.2 in)

F. Full penetration Fillet. Suitable for SMAW. Tack weld with SMAW or GMAW.



4 mm (0.16 in) ≤ t < 12 mm (0.5 in)
A = 2.5 mm (0.1 in)
B = 2.5 mm (0.1 in)

G. Single V Joint. Pipe welding. Suitable with SMAW.



3 mm (0.12 in) ≤ t < 12 mm (0.5 in)
A = 1-2 mm (0.04-0.08 in)
B = 2 mm (0.08 in)

H. Single U Joint. Pipe Welding. Suitable with GTAW.

Preheating

As a general rule, preheating of duplex stainless steel is not recommended because it slows the cooling of the heat-affected zone. Preheating should not be a part of a procedure unless there is a specific justification.

Preheating may be beneficial when used to eliminate moisture from the steel as may occur in cold ambient conditions or from overnight condensation. When preheating to remove moisture, the steel should be heated to about 95°C (200°F) uniformly and only after the weld preparation has been cleaned.

Preheating may also be beneficial in those exceptional cases where there is a risk for forming a highly ferritic HAZ because of very rapid quenching. Examples include welding a thin sheet to a plate, as with a liner to a vessel or a tube to a tubesheet, or any very low heat input weld where there is exceedingly rapid cooling. (See FAQ 13.)

Heat Input and Interpass Temperature

Compared to austenitic stainless steels, duplex stainless steels can tolerate relatively high heat inputs. The duplex solidification structure of the weld metal is resistant to hot cracking, much more so than that of highly austenitic weld metals. Duplex stainless steels, with higher thermal conductivity and lower coefficient of thermal expansion, do not create the same high intensity of local thermal stresses at the welds of austenitic stainless steels. While it is prudent to avoid severe restraint, hot cracking is seldom a common problem.

To avoid problems in the HAZ, the weld procedure should allow rapid (but not extreme) cooling of this region. The temperature of the work piece is important because the plate itself provides the most effective cooling of the HAZ. Typically, the maximum interpass temperature is limited to 150°C (300°F). That limitation should be imposed when qualifying a weld procedure, and production welding should be monitored to assure that the interpass temperature is no higher than that used in the qualification. Electronic temperature probes and thermocouples are the preferred instruments for monitoring the interpass temperature. When a large amount of welding is to be performed, planning the welding to provide enough time for cooling between passes is good, economical practice.

The size of the test piece used in qualifying a weld procedure may affect the cooling rate and the interpass temperature. There is a risk that the test piece for qualification of a multipass weld procedure may come to a lower interpass temperature than can be reasonably or economically achieved during actual fabrication. Therefore, the qualification might not detect the loss of properties that can occur the higher interpass temperature slows the cooling and increases the time at temperature for the HAZ in actual practice. (See FAQ 5, 6.)

Postweld Heat Treatment

Postweld stress relief is not necessary or useful for duplex stainless steels. Unlike the L-grade austenitic stainless steels, the duplex stainless steels are sensitive to even relatively short exposures to temperatures in the 300 to 1000°C (600 to 1800°F) range. Thermal stress relief in the 300 to 700°C (600-1300°F) range may cause precipitation of alpha prime phase ("475°C (885°F) embrittlement"), causing a loss of toughness and corrosion resistance. Stress relief in the range of 700 to 1000°C (1300 to 1800°F) leads to rapid precipitation of intermetallic phases with moderate to severe loss of toughness and corrosion resistance. Any heat treatment of a duplex stainless steel for whatever reason, should be a full solution anneal, meeting the minimum temperatures specified for the mill product in the ASTM specifications, followed by water quenching. For 2205 that minimum temperature is 1040°C (1900°F) in most cases.

Some types of equipment manufactured from duplex stainless steel require a full anneal. For example, the forming of large heads or the fabrication of some valve and pipe assemblies may require annealing. When there is a full solution anneal and quench subsequent to welding, that heat treatment is a part of the welding procedure. Annealing can restore the equilibrium phase balance and eliminate the problems associated with excessive ferrite and intermetallic phases. If the common duplex filler metals are used, typically overalloyed with nickel, phase balance in the fully annealed weld may shift toward austenite. Water quenching is essential after the final anneal, but air cooling from intermediate thermal exposures, such as in hot forming, have been found to be practical and economical. (See FAQ 12, 18.)

Phase Balance in the Weld

Modern duplex stainless steel mill products are balanced to have about 40-50% ferrite with the balance being austenite. It is generally agreed that the characteristic benefits of duplex stainless steels (strength, toughness, corrosion resistance, resistance to stress corrosion cracking) are achieved when there is at least 25% ferrite with the balance austenite.

The ferrite in the weld metal is typically in the range of 25 to 60%. In some welding methods, particularly those relying upon flux shielding, the phase balance of the filler has been adjusted toward more austenite to provide improved toughness, offsetting the loss of toughness associated with oxygen pickup from the flux. There have been no reports of problems associated with the ferrite contents at the lower end of this range, typically seen in SMAW (shielded metal arc, or stick) or SAW (submerged arc) welds. (See FAQ 16, 17.)

Rapidly quenched autogenous welds, e.g., arc strikes, repair of arc strikes, small GTA repair welds, etc., tend to have high ferrite, greater than 60%. Such welds can have low toughness and reduced corrosion resistance. (See FAQ 4, 10, 13.)

Metallographic evaluation of the phase balance in the HAZ is an appropriate test for welding procedure qualification. However, metallographic evaluation is not technically or economically effective for evaluation of annealed mill products or production welds. Magnetic evaluation of the phase balance is widely used but has serious accuracy limitations when used on welds or HAZ.

Dissimilar Metal Welds

Duplex stainless steels can be welded to other duplex stainless steels, to austenitic stainless steels, and to carbon and low alloy steels.

Duplex stainless steel filler metals with increased nickel content relative to the base metal are most frequently used to weld duplex stainless steels to other duplex grades.

When welding duplex stainless steels to austenitic grades, the austenitic filler metals with low carbon and a molybdenum content intermediate between the two steels are typically used. AWS E309LMo/ER309LMo is frequently used for these joints. The same filler metal or AWS E309L/ER309L is commonly used to join duplex stainless steels to carbon and low alloy steels. Because austenitic stainless steels have lower strength than duplex grades, welded joints made with austenitic filler metals may not be as strong as the duplex base metal.

When welding the highly alloyed austenitic stainless steels, nickel-base fillers are used. The nickel-base filler metals are not normally used for duplex stainless steels, but if they are, they should be free of niobium (columbium). Although not thoroughly documented, there have been suggestions that the ENiCrMo-3 filler (625) has been less than satisfactory, possibly because of interaction of the niobium from the filler with the nitrogen from the duplex base metal.

Table IV summarizes filler metals frequently used to weld duplex stainless steels to dissimilar metals. These examples show the AWS bare wire designation (ER), but depending on the process, joint geometry and other considerations, electrodes (AWS designation E), and flux-cored wire may be considered.

Table IV. Welding Consumables Used for Dissimilar Metal Welding.

	2304	**2205**	**25 Cr**	**Superduplex**
2304	2304 ER2209	ER2209	ER2209	ER2209
2205	ER2209	ER2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
25 Cr	ER2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
Superduplex	ER2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
304	ER309LMo ER2209	ER309LMo ER2209	ER309LMo ER2209	ER309LMo
316	ER309LMo ER2209	ER309LMo ER2209	ER309LMo ER2209	ER309LMo ER2209
Carbon steel **Low alloy steel**	ER309L	ER309L	ER309L	ER309L

Applicable Welding Methods

Second-generation (nitrogen-alloyed) duplex stainless steels saw rapid development in the early 1980s. With only limited understanding of the formation of intermetallic phases, early views of welding duplex grades focused on limiting heat input, possibly because this approach is what is typically applied to special austenitic grades. With such severe limitations on heat input, many of the more economical welding methods with high deposition rates, such as submerged arc welding, were thought to be inappropriate for the duplex stainless steels. However, the final properties of the duplex stainless steels are of such interest that much effort was directed to learning how to use the more economical processes. Now virtually all welding processes, except for oxyacetylene with its associated carbon contamination of the weld, are applied to duplex stainless steels. Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Flux Core Arc Welding (FCAW), Submerged Arc Welding (SAW), and Plasma Arc Welding (PAW) have all seen practical application. Electric Resistance Welding and Electron Beam Welding, although much less common, have also been qualified and used in particular fabrications. There are important differences among the welding procedures. For example, the decision to use a flux-shielded weld and selection of flux for that weld effect toughness. (See FAQ 15, 16.)

Welding Procedure Qualification

"Qualification" of welding procedures for duplex stainless steels must be considered in a broad sense, i.e., demonstration that the welding procedure that will be used in fabrication will have acceptable engineering properties, especially toughness and corrosion resistance. For other types of stainless steels, qualification testing for weld procedures is fairly simple, with only a limited amount of testing to qualify a material, filler metal, and weld method. With hardness tests and bend tests, looking for martensite and hot cracking, respectively, these qualification tests reflect long experience for what can go wrong when welding ferritic, martensitic or austenitic steels. Duplex stainless steels are unlikely to have difficulty meeting these requirements, because these standard tests are unlikely to find intermetallic phases or excessive ferrite, the most likely problems for duplex stainless steels. A bend test may still be useful and economical, but it is not conservative in the sense of always detecting problems if present. Because of the limitation on total time at temperature for the HAZ, the properties of duplex grades will be sensitive to section thickness and details of actual welding practice. So the qualification of procedures for duplex stainless steels is specific to particular geometries of welding, much more so than for austenitic stainless steels.

It would be desirable to qualify a weld procedure for every thickness, geometry, and method of welding because minor differences in setup may be significant in the results achieved in production. However, the complex nature of actual constructions makes such testing costly. Savings are achieved by qualifying the procedures (defined by section, filler, and method) determined to be the most demanding on the duplex stainless steel. It is also prudent to test welds in the most critical joints in a construction, even when those joints might be exempt from testing of production welds under a strict reading of the ASME requirements. For example, ASME UHA 51 does not require testing for thickness of 3/8-inch or less, or for minimum design metal temperature above -29°C (-20°F).[5] The temperature for toughness tests will depend on whether the purpose of the test is to check the metallurgical condition of a mill product or to demonstrate the suitability for use of a construction. (See FAQ 15, 16.)

Issues to be Addressed

Starting material. It is ideal when the welding procedure qualification is performed on material that is essentially identical in specification and actual production to the material that will be used in fabrication. For example, if material used in the qualification is of significantly higher nitrogen or has been quenched much more rapidly than the material that is used in fabrication, then one cannot rely solely upon the use of the qualified procedure to produce a weld of acceptable properties. Unfortunately, from a practical standpoint, it is generally true that weld procedure qualifications are made on different heats of material compared to the actual fabricated equipment. Therefore it is essential to have sufficient control and testing of both the starting material and the weld for fabricated equipment.

For the starting material, the ASTM specifications that cover duplex stainless steels require testing of each heat lot of material. The ASTM definition of heat lot for a continuous heat treatment system permits all material of a given heat and size, processed within the same operating period and under the same time and temperature, to be represented by a single sampling. However, ASTM specifications do not address the possibility for an individual plate of duplex stainless steel to dwell in the temperature range below the specified minimum annealing temperature, as may occur during "rapid air cooling" or in the transfer of product from the furnace to the quenching operation. The time for the quenching operation will vary from one producer to another and will vary by size range for an individual producer. Therefore, the most conservative approach is to require testing of each piece even within a heat lot.

In the ASTM specifications, the S32205 version of 2205 has narrower (the upper half) ranges on chromium, molybdenum, and nitrogen than does S31803. These ranges reflect the experience accumulated over almost twenty years that consistent, favorable results are obtained by tight control of these elements. Furthermore, the heat treatment requirements for S32205 include water quenching except for coiled product heat treated in a continuous annealing line. This exception to water quenching is applicable to the thin product, sheet, where consistent rapid air cooling is effective and essential to operation. Imposing a similar restriction on the quenching required for other duplex stainless steels would be an appropriate and conservative requirement.

All duplex stainless steels should be ordered as complying with ASTM A 923. Not all duplex grades are presently listed in A 923, but at least Method A can be applied as an acceptance test. The acceptance criteria for Methods B and C for grades not specifically covered are subject to agreement between producer and user. For S32205 (and S31803), specification of both Methods B and C may not be necessary, incurring extra cost, but is conservative. A 923 permits the use of Method A as a screening test, where acceptance replaces the need to complete Methods B and C. The user may require reporting of actual test results for Methods B and C as a way of removing the permission to use Method A for screening. As noted below, the impact tests for the ASME requirements may be done at the more stringent condition of A 923 in order to save on testing costs.

The ASME toughness testing addresses the suitability for use of a particular construction, and the requirements depend on section thickness and minimum design metal temperature. The ASME specification for duplex stainless steels, when applicable to a particular construction, require the more common set of three specimens for the Charpy test, and use lateral expansion rather than energy absorption as the acceptance criterion. The impact test requirements of the ASME specification are less stringent than those of A 923, unless the minimum design metal temperature is below –40°C (-40°F). It is possible that the ASME required testing would not detect the early stages of formation of intermetallic phases. But as noted in ASTM A 240, performing the ASME tests at the more stringent test temperature of A 923, with measurements of both impact energy and lateral expansion, is permitted and allows for cost saving by avoiding redundant testing. (See FAQ 15, 16).

Hardness tests of the starting material are of little value, but fortunately hardness tests are also of little cost. If hardness testing is required, as is the case for most duplex grades in the ASTM specifications, the maximum should be that listed in the specifications.

Sampling. It is important to qualify both the heat-affected zone and the weld metal itself for a duplex stainless steel. However, the testing procedure and acceptance criteria are likely to differ for the HAZ and the weld. In the case of austenitic stainless steels, there are seldom problems associated with the heat-affected zone, other that the possibility of sensitization, relatively unusual for the low carbon versions of these grades.

Acceptance criteria. The appropriate acceptance criteria for welds, applicable to as-welded fabrications, vary widely from those applicable to annealed mill products, especially with regard to toughness measurements for flux-shielded welds. (See FAQ 9, 15, 16.)

GUIDELINES FOR TESTING FOR PROCEDURE QUALIFICATION

For the qualification of the welding procedure, it is recommended that the following tests be performed for each significant geometry and thickness. Some judgment must be applied with regard to the differences in the proposed procedures with respect to total time at temperature and the rate of quenching that will be seen for the last pass of welding. For example, it is convenient but possibly unrealistic to weld plates in the flat, downhand position to qualify a procedure if it is known that the actual welds will be made with less than perfect fit-up or with substantially out-of-position welding.

It is common for a skilled welder to overcome minor deviations in fit-up with welding technique and local rework, and these may lead to extended time at temperature for the HAZ. Accordingly, it is prudent to qualify procedures for reasonably anticipated repairs or rework of welds. For example, when welds are to be radiographed, it is obviously the intention that any defects found will be repaired. Therefore, it is appropriate and economical to qualify a repair procedure for one or two successive repairs to be performed on piece that has been welded by the qualified fabrication welding procedure. Qualification of the major repairs should use the same tests as the qualification of the procedure for the fabrication weld. For minor repairs, it may be sufficient to perform only limited confirmation tests, such as the tests of ASME UHA-51 or ASTM A 923 Method C.

For the welding procedure qualification, the following materials and tests are typically specified:

Starting Material (Mill Products)

1. Material should meet the appropriate ASTM product form specification (or ASME specification, as noted below, for Code-qualified construction). For 2205, the S32205 should be specified. For other duplex stainless steels it is recommended that the listed composition be accepted, but with consideration for further limits on composition. For those grades with nitrogen content range (max-min) in excess of 0.10%, chromium content range in excess of 1.0%, and molybdenum content range in excess of 0.50%, it is appropriate to further restrict the nitrogen, chromium, and molybdenum to ensure a uniformity of response.
2. The requirements for quenching after heat treatment applicable to S32205 should be specified as applicable to the other grades of duplex stainless steels.
3. The user may wish to specify no weld repair of mill products without specific permission.
4. The material should be tested in accordance with ASTM A 923, Methods A, B, and C, with requirement to report the test values obtained in Methods B and C. Methods A and C, if specified, shall apply at all thicknesses. Method B, if specified, shall apply at all thicknesses, 2.5 mm (0.1 inch) or greater. (Note possible cost savings by using same test to meet ASME requirements when applicable.)
5. The phase balance of the mill product shall be in the range of 35 to 60% ferrite, balance austenite, with testing by automated image analysis being permitted.
6. **For ASME Code construction**, material shall be specified as meeting the appropriate ASME product form specification. For 2205, S31803 should be specified with all specific further restrictions as applicable to S32205 (often achieved by ordering dual certified S31803/S32205).
7. **For ASME Code construction**, Charpy impact tests (three specimens) shall be performed at the minimum material design temperature for the required section thicknesses, meeting the acceptance criteria for lateral expansion, as defined in ASME UHA 51. These tests are permitted to be performed at a lower temperature, such as that in A 923, to reduce cost of redundant testing.

Welding Procedure Qualification Testing

1. Bare wire filler metal shall be selected in accordance with AWS specifications. Flux-shielded filler shall be selected in accordance with AWS specifications and manufacturing source.
2. A tensile test transverse to the weld shall meet the requirements of the base material. Face and root bends of the weld shall be performed in accordance with the requirements for the base material.
3. Charpy impacts tests shall be performed on the weld and on the HAZ for material having thickness of $\geq$ 3/16 inch, or at lesser thicknesses when required by ASME UHA 51. Care should be taken in locating the notch for the HAZ Charpy specimens to encompass the HAZ and the fusion line of the weld.

   For Code applications, the Charpy test shall be performed in accordance with the requirements of UHA 51. It is permitted to perform these tests at a temperature lower than the minimum design metal temperature.

   For non-Code applications, a Charpy test in accordance with ASTM A 923 Method B is permitted. However, A 923 was developed for annealed mill products. The acceptance criterion of 40 ft-lb at –40°C (-40°F) is not applicable to the weld metal and may not be applicable to the HAZ in all cases. Therefore, if an impact energy is used for acceptance of the weld and HAZ, it may be reduced appropriately from the level required of the annealed mill product. The impact energy for flux-shielded welds may have a shelf energy of as little as 20 ft-lb. It may be unreasonable to require that the weld must have the same high impact strength as the annealed base metal, and it is uneconomical to not accept the welding methods that regularly produce a lesser but still acceptable impact energy.

4. The user may elect to perform a corrosion test to confirm the absence of detrimental intermetallic phases or non-metallic phases. The test specimen should encompass weld metal, HAZ, and base metal, but it is not necessary to encompass the entirety of the weldment for larger samples. The acceptance criteria for A 923 were selected as applicable to annealed mill products. The edges of the test specimen shall be ground smooth, but not chemically pickled. It is appropriate to slightly reduce the required temperature of testing when an unannealed

weld is present, e.g., to 22°C for S32205. Corrosion on the edges of the sample shall not be ignored as permitted in ASTM G 48. (See FAQ 8, 9.)

5. Penetrant tests shall be performed on the qualification coupons when required by the ASME procedures.
6. The phase balance shall be determined metallographically for the weld and heat affected zone. For welds, the ferrite shall be at least 25% for the flux covered welds, and at least 30% for gas shielded welds. For the HAZ, it is desired that the ferrite shall be within the range specified for the starting material. However, it is often difficult to measure the phase balance precisely because of the typically small and variable size of HAZ and the variation of ferrite content within the HAZ. In no case shall there be a continuous layer of fully ferritic material surrounding the weld. (See FAQ 17.)

Testing for Production Weld Test Plates

1. Material used in the fabrication shall conform to the same specification as used for the material used in the weld qualification.
2. Where the welding geometry permits, and with a reasonable frequency for such opportunities, runout tabs of the same heat lot of plate shall be attached to the fabrication plate and the weld continued into the tab without change of procedure. The runout tab shall be evaluated in accordance with the requirements of the ASME, if applicable. In the most conservative approach, a sampling of the runout tabs shall be evaluated using the same tests and acceptance criteria as used in the applicable weld procedure qualification.
3. The runout tab shall be of sufficient size to allow the conditions of welding to be maintained. Sizes of 6 x 6 x t inches to 12 x 12 x t inches are typically used.
4. The heat input shall be measured and reported as a monitoring of the uniformity of procedure. The interpass temperature shall not exceed 150°C (300°F) as measured by a contact thermocouple.
5. Welding that deviates from a qualified procedure shall be reported and documented. The user may require qualification of the actual procedure before accepting the weld.

TRAINING OF WELDERS AND INSPECTORS

Because the thermal expansion and thermal conductivity of duplex stainless steel differs markedly for those of austenitic stainless steel, it is useful for welders to have the opportunity to make a number of trial welds by different geometries and qualified procedures.

It is essential that individual welders and inspectors of the fabricator appreciate the risk to toughness and corrosion resistance of <u>any</u> deviation from the qualified procedures. Simply stated, any deviation from the qualified procedure is more likely to be harmful and is likely to be more harmful than a deviation from procedure for an austenitic stainless steel. While there are some deviations that can be tolerated, it must also be appreciated that seemingly minor deviations can have very large effects. One example is that of a conscientious welder who sought to apply a very small GTAW smoothing pass, not included in the qualified procedure, after the weld had thoroughly cooled. The result was that the solidification of that pass produced nearly 100% ferrite in the weld zone, with significant loss of corrosion resistance.

Other examples of actions that can be more harmful to duplex stainless steels than to austenitic stainless steels include spatter, arc strikes, and small surface repairs. For duplex stainless steels they are likely to produce small regions of highly ferritic structure, with the possibly associated loss of corrosion resistance.

Maintaining dry welding filler materials, and particularly those with flux shielding, is especially important for duplex stainless steels. Practice should begin with oven storage and “hot-box” holding areas. It is also observed that there is greater sensitivity to flux formulation, leading to brand-specific response within a qualified procedure.

It is essential that the welders and inspectors of any subcontractor be adequately trained in the issues discussed above. Similarly, the welders and maintenance engineers of the user/operator of the equipment should be trained in the technology of welding duplex stainless steels. (See TAPPI TIP.) (See FAQ 3, 4, 10, 13, 14.)

SUMMARY

1. The duplex stainless steels are seeing substantial and diverse applications within the pulp and paper industry, as appropriate to their excellent mechanical properties and corrosion resistance, and their economy.
2. A full range of welding practices has been successfully applied to duplex stainless steels.
3. The qualification of welding procedures requires testing of toughness and corrosion resistance to demonstrate the absence of excessive ferrite or the absence of intermetallic phases.
4. The quality of starting material is an important issue in producing welds with consistent and acceptable properties.
5. Total time at temperature for the HAZ is one of the most important control variables for the welding of duplex stainless steel.
6. Repairs during fabrication or future maintenance must be considered and qualified as a complete procedure, extending the originally qualified procedure.
7. Thorough training of welders and inspectors is an essential ingredient leading to the successful application of duplex stainless steels.

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KEYWORDS

Digesters; Stainless Steels; Duplex Stainless Steels; Welding; Welding Procedure Qualification; Specifications

APPENDIX A. FREQUENTLY ASKED QUESTIONS

The following questions reflect the experience of fabricators in the questions most typically asked during fabrication of duplex stainless steel. Answers are suggested but in these practical matters, there is a wide range of possibly “correct” answers. The answer given may not be applicable to all possible situations.

1. Although it is recommended to use plasma torches for back gouging of the root and defect removal, can a conventional carbon arc be used? What is a minimum grinding that should follow arc gouging in order to remove heat-affected layer?

Carbon arc back gouging has been successfully used in the construction of 2205 duplex stainless steel vessels, but care must be taken to minimize the heating and the potential for carbon contamination. When care is taken in the back gouging procedure, the minimum grinding is not burdensome. It would be appropriate to perform a weld procedure qualification in which the typically applied back gouging has been included as it will be used in the practical construction.

2. What is the maximum allowed thickness reduction resulting from cold forming before solution anneal/ water quenching treatment would be required?

A precise answer to this question has not been developed. However, it has been common in construction of 2205 duplex stainless steel vessels to apply the same limits that are applied to carbon steels by the ASME Code. This limitation, while possibly overly conservative, has not led to any problems in service. For vessels not being constructed to ASME Code, significantly more aggressive deformation has been permitted, with no reports of problems attributed to this cold worked condition.

3. What is a proper method of repairing small defects and metal tears on the process side (for example, caused by knocking off of the pre-cut ladder supports and lifting lugs – usual method of removal)?

The repair procedure most typically satisfactory is to open the defect by grinding, if necessary, and then to repair by GTAW with the typical matching filler. Because of the size of the weld involved, it is unlikely that small defects or tears will lead to excessive time at temperature for these repair welds. However, care must be taken to avoid too rapid cooling of the weld (with resulting excessive ferrite). Slight warming of the metal under shielded conditions using the weld torch before the filler is introduced will typically prevent too rapid cooling. Autogenous repairs are not recommended because of the likelihood of forming excessive ferrite in the weld.

4. Excessive heat input may result from weld repair of the defect discovered by post-weld NDT. Should such procedure be pre-qualified, and how?

It is appropriate to demonstrate that the weld repair has not damaged the material, i.e., to qualify the repair in much the same way as the procedure was qualified. So fabricators have qualified reasonably anticipated repair procedures in advance. Alternatively, the repair practice can be documented and simulated on a production runout tab, with the usual production test plate procedures then being applied to the repaired weld.

5. What is in fact the upper limit for weld heat input, provided base metal fully passed A-923 criteria?

Because the goal is to limit total time at temperature, it is generally better to complete a weld in fewer passes with relatively high heat input than many passes of lower heat input. The duplex stainless steels can tolerate relatively high heat inputs. It is not impossible to hot crack a duplex stainless steel during welding, but it is rare. The duplex stainless steels have relatively low thermal expansion and high thermal conductivity. The solidification of the duplex filler metals is not prone to hot cracking as is a fully austenitic solidification. Maximum heat input values as high as 65-100 kJ/mm have been found to be satisfactory, depending on the welding process.

6. Can heat input be allowed below the mentioned bottom value of 0.5 kJ/mm as long as the ferrite content does not exceed 70% (for example, due to the over-alloying of the base and electrodes)?

Exceedingly low heat input is permitted, provided that the result is demonstrated to meet the usual requirements for phase balance and corrosion resistance.

7. Does soda lime glass bead blasting provide an adequate finish for corrosive service, as an alternative to pickling and what is the recommended surface profile range?

Whether or not a glass blasting will be sufficient for corrosive service will depend on the degree and nature of the oxidized surface and the corrosivity of the service, including the tendency of the medium to adhere to the surface of the steel. While a pickled surface provides corrosion resistance to the maximum capability of the grade, a thoroughly blasted surface may be sufficient and economical. Scale and heat tint for the duplex stainless steels are especially adherent and resistant to both mechanical and chemical removal.

8. What is the best way to prepare weld/HAZ specimens for A 923 Method C testing?

The specimen should be removed by the method least disruptive of the metal condition. Cold cutting is recommended if possible. If a hot cutting method is applied, then there should be further cold cutting or grinding to remove all material that was affected by the hot cutting. In order to avoid weight loss during the test that could be associated with heat tint, it is a good practice to pickle the whole specimen before final grinding of the specimen surfaces. However, the surfaces that are actually tested should be as-ground without any subsequent pickling or other chemical treatment that might clear the surface of detrimental phases. It is permitted to leave the weld faces of the specimen in the as-pickled condition as long as the cross-sectional edges are tested in the ground condition. A slight chamfering of the specimen is helpful, but the should not be substantial rounding off of the edges. The presence of burrs on the edges will cause weight losses not related to the presence of intermetallic phases. Corrosion attack on the edges must be included in the limiting acceptance criterion. "Modified G 48" procedures that permit disregarding of edge corrosion are not correctly testing for the presence of detrimental intermetallic phases. If intermetallic phases are present, they are much more likely to occur within the metal, and therefore be exposed on the specimen edges, than on the faces of the product.

9. Is “modified G 48” testing the same thing as A 923 Method C?

ASTM G 48 Practice A and A 923 Method C are similar to the extent that they use similar equipment and laboratory procedures. However, they are substantially different in their application. ASTM G 48 is a description of laboratory procedure, but it does not specify the temperature of testing, the time of exposure, the technique of assessing corrosion, and an acceptance criterion. The “modified G 48” test indicated that the individual ordering specification was attempting to address these deficiencies, but few specifications addressed all of them. ASTM A 923 Method C specifically addresses each of these issues, and provides a basis for acceptance of the duplex stainless steels with regard to the absence of detrimental intermetallic phases.

One important difference is that G 48 permits the tester to disregard corrosion on the edges of the specimen. This permission is totally inappropriate for use of the test to demonstrate the absence of intermetallic phases in duplex stainless steels. It is unlikely that the intermetallic phases will occur in the faces of the plate or the faces of the weld, but rather will occur in the interior of the metal. Therefore, incidents of pitting on the edges of the sample should be considered indicative of a problem, and not ignored.

G 48 is usually a procedure performed at a series of temperatures, with the goal of identifying the critical pitting temperature. Accordingly, the time of exposure and the inspection for pitting on the surface are designed to detect subtle pitting initiation. The single test temperature for each grade in A 923 is chosen to be below the critical pitting temperature for material without intermetallic phases, and above the critical pitting temperature for material with intermetallic phases. The pitting, when it does occur, is readily visible. However, the weight loss is what is measured in order to remove the potential for debate over visual interpretation. That weight loss is converted to a corrosion rate in order to permit different sizes and geometries of specimens to respond to a single acceptance criterion.

An important issue is the surface preparation of the sample. The goal of the test is to detect intermetallic phases if present. Chemical treatment of the specimen surface (passivation or pickling) may reduce the exposure of intermetallic phases in the surface and thereby cause the test not to detect the presence of intermetallic phases. The specimen edges should be fine ground but not chemically treated for most effective use of the A 923 test. If there is concern that the faces of the specimen may contribute to the weight loss, the appropriate specimen preparation is to pickle the specimen before final grinding of the edges.

10. When you encounter a need to weld repair a structure of duplex stainless steel and you do not have a detailed history of the welding during construction, how do you decide how much welding is safe? What filler metal do you use?

The correct answer will depend on the nature of the weld, the conditions of application, and on the application itself, particularly whether or not the structure was built to ASME Code, or is being used in a situation of significant safety risk. The safest approach is to sample the fabrication weld and perform a qualification of the proposed repair. However, this approach imposes extra costs and opens the necessity to repair also the position of sampling. The value of good records in welding fabrication is amply demonstrated by this situation. It is appropriate to consult metallurgical engineers before making the weld repair.

The problem, it there will be one, will most likely occur in the HAZ of the original fabrication welds. The selection of the filler metal is unlikely to have any favorable effect on dealing with this part of the problem. The is no reason that the filler metal should not be the same filler metal that would be used with the duplex stainless steel in the original fabrication welds.

11. Are there any special problems in cleaning the heat tint of a duplex stainless steel?

Because of the relatively high chromium content and the relatively low thermal expansion of a duplex stainless steel, the oxide scale is typically thin and highly resistant to removal. It is desirable to remove any heat tint in order to get maximum corrosion resistance, but there are some applications where the process itself will remove the heat tint. Grinding to clean bright metal is effective. Blasting can also be effective but, depending on the scale and the blasting medium, may not be as effective as grinding for removing the oxide. Pickling, by solution or by paste, is effective, but longer times or more aggressive pickling chemistries are required for duplex grades than are typically required for austenitic grades.

Passivation, in the sense of removing free iron (from tooling contact, etc.), is no different than for austenitic stainless steels. It is appropriate to confirm the effectiveness of a passivation treatment by testing such as that listed in ASTM A 967.

It should be noted that the complete removal of heat tint may not always be necessary, depending on the application. For example, removal of all heat tint is not required for exposure to kraft liquor, but is desirable for service in acid sulfite liquors.

12. When is post weld heat treatment beneficial, and what treatments should be used?

There are no heat treatments in the 315-980°C (600-1800°F) range that are beneficial to duplex stainless steels. Postweld stress relief heat treatments are used with steels that are capable of forming martensite, but duplex stainless steels do not form martensite. The metallurgical condition of a duplex stainless steel will be severely damaged if it is exposed to the stress relief treatment applied to a carbon or alloy steel (a consideration in dissimilar welds).

If the duplex stainless steel for whatever reason is exposed to conditions that lead to the formation of intermetallic phases, then the appropriate remedy is to heat treat the whole structure. The only heat treatment that works for duplex stainless steel is a full anneal above the minimum temperature listed in ASTM A 240, (1040°C (1900°F) in the case of 2205) and quench. When the construction cannot be annealed and quenched, the only remaining alternatives are to scrap the whole construction, or to cut out and replace the affected parts of the metal.

13. When is preheating useful or required?

Preheating the duplex stainless steel before welding is useful in two situations. If the part is damp, as from condensation, heating uniformly to a maximum of about 95°C (200°F) will avoid the problems associated with moisture in the weld. Preheating is one alternative for avoiding welds that are excessively ferritic as a result of too rapid quenching. Examples include spot resistance welds, superficial surface repair, and welding of thin material to heavy sections (sheet liners, tube-to-tubesheet welds). As with the suggested interpass temperature, 150°C (300°F) is an appropriate maximum temperature for preheating.

14. What is the correct design for a runout tab?

The fact that the purpose of the runout tab is produce a sample of weld that is identical to the production weld dictates the design of the tab. Ideally, the plate of the tab is from the same heat and thickness as the workpiece. It should be of a size that will produce neither unusual heating or unusual cooling. It should be large enough to readily supply the samples necessary for the qualification tests selected. Experience indicates that tabs from 6x6xt to 12x12xt inches finished size have been satisfactory.

Sample material can be obtained from the plate itself when there are manways or nozzles to be cut, but this source of samples may not always be available. When a bill-of-materials order is made for a large project construction, with special sizes of plate being rolled, there may not always be off-cuts from the plates for the sample material. It is a good idea to obtain the sample material with the purchase of the plate in order to assure the availability of matching sample material.

15. How significant is the selection of the temperature for Charpy tests, comparing the –40°C (-40°F) of A 923 and the ASME minimum design metal temperature?

ASTM A 923 and ASME UHA 51 have in common only that they both use Charpy tests. However, the purpose on the tests for the two procedures are quite different. The purpose of A 923 was to demonstrate that the heat treatment applied to a duplex stainless steel mill product had eliminated the intermetallic phases. The Charpy test was chosen because it was familiar to producer and user. As shown in the appendix of ASTM A 923, an acceptance criterion of 40 ft-lb at –40°C (-40°F) was found to correlate with the appearance of the intermetallic phase in a metallographic examination and a loss of corrosion resistance. Impact energy was selected as the acceptance criterion because of its intuitive meaning and the fact that it is so readily measured in an impact test. A 923 was not intended to demonstrate suitability for use at this temperature. The test was chosen to demonstrate the absence of the intermetallic phase. The high impact energy and low test temperature were necessary in order to get a meaningful indicator for the extremely tough annealed mill product. A 923 states that it is not applicable to a welded structure.

In comparison, ASME UHA 51 is designed to demonstrate suitability for use. The temperature is minimum design metal temperature, a factor of design specific to each installation. The standard test of three specimens is performed using the lateral expansion measurement to confirm results. Impact strength well below 40 ft-lb is accepted as suitable for use. It is applicable to the whole construction, whether base metal, weld metal, or HAZ. Where appropriate, it is permitted to use the more demanding test conditions of ASTM A 923, but with the number of specimens and measurements of both impact energy and lateral expansion, to qualify for ASME UHA 51, and so reduce testing costs.

16. Why is 20 ft-lb impact energy sufficient for a weld when the specification for the plate requires 40 ft-lb at –40°C (-40°F)?

The ASME has determined that 20 ft-lb is an adequate toughness for service in a particular class of applications. This level of toughness is not high enough to correlate well with the observance of intermetallic phase in the microstructure and the associated loss of corrosion resistance in a duplex stainless steel mill plate. The duplex stainless steel plate structure is tough enough that it may still show significant impact energy even after significant intermetallic phase formation. On the other hand, a weld metal may occasionally have toughness less than 40 ft-lb even when no intermetallic phase is present. For example, weld toughness is particularly affected by the presence of oxygen in the weld, as may occur with flux-shielded welds.

17. Why is 25% ferrite enough for a weld, when higher ferrite content is specified for the base metal?

The base metal is specified with a composition that, for a fully annealed and quenched structure, will lead to about 40 to 50% ferrite, essentially the equilibrium structure. This chemistry is found to return rapidly to almost that balance after the thermal cycle that occurs in the HAZ during welding, retaining corrosion resistance and toughness. It is known that the oxygen associated with flux shielding reduces the toughness of the weld metal. Therefore, the compositions of the filler metal for flux-shielded welds have been adjusted to produce the highest austenite that can be accepted while still retaining the benefits of the duplex structure. If there is significant dilution from the base metal, then the weldment will have slightly more ferrite. The 25% ferrite represents the minimum that will be achieved in there is essentially no dilution, as in a capping pass.

18. Is it necessary to water quench after every heat treatment of a duplex stainless steel?

It is necessary to water quench after the final anneal of a mill product or of a constructed and heat-treated component such as a head, fitting, or forging. However, it may be convenient to air cool the piece during intermediate processing and then perform the final anneal and quench as a separate operation. The air-cooled piece will not have optimal toughness and corrosion resistance in that condition, but it is sufficient for further processing. The part will be brought to maximum toughness and corrosion resistance by the final heat treatment with its water quench.

19. Are there temperature limits, low and high, on the use of duplex stainless steels?

The toughness of the duplex stainless steel mill plate does not undergo an abrupt ductile-brittle transition. Rather it decreases gradually from its high shelf energy to a very low impact energy as temperature decreases from about ambient to temperatures in the range of –45 to –75°C (–50 to –100°F). So the minimum application temperature is determined in accordance with the tough of the duplex stainless steel. To date, there have been few applications with minimum design metal temperature below –40°C (-40°F).

The maximum temperature for ASME Code applications is 315°C (600°F). The temperature was chosen because it represents the lowest temperature for the transformation curve for 475°C (885°F) embrittlement. Below that temperature, the steel will not be embrittled by this reaction in many years of exposure. In non-Code applications, it would be possible to consider use of 2205 in applications where there are limited excursions in the range just slightly above the limiting temperature. However, the embrittling reaction is real and exceptions to the 315°C (600°F) limit should not be undertaken without full knowledge and evaluation.

20. How do the properties of duplex stainless steels affect wall thickness, thermal expansion, and heat transfer in comparison to austenitic stainless steels?

Although it is generally correct to say that the yield strengths of the duplex stainless steels are twice that of the common austenitic stainless steels, that relationship does not imply that the thickness of the duplex stainless steel will be simply half that of the austenitic stainless steel in the same design. The higher strength of the duplex grades is reflected in higher allowable design stresses in the ASME Code. Depending on the shape of the construction, it is possible to reduce significantly the thickness of the material required when using duplex stainless steel, an opportunity for cost savings.

The thermal expansion of a duplex stainless steel is intermediate to that of carbon steel and austenitic stainless steels. This difference can be an advantage in structure with cyclic heating because there is less necessity to accommodate the large expansions associated with the austenitic materials. On the other hand, using duplex stainless steel within a construction of austenitic stainless steel may create problems when the duplex steel does not expand to the same extent. The combination of high strength and lower expansion may mean that the duplex stainless steel will impose high stresses at the point where it is joined to the austenitic structure.

Because the duplex stainless steel has a ferritic matrix, it is more efficient in heat transfer than the austenitic stainless steels. This property, combined with the thinner material that results from economical use of the higher strength of the duplex grades, can be used to significant advantage in heat transfer applications.

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