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Welding of duplex stainless steels

Scope

Duplex stainless steels are finding increasing use in the pulp and paper industry because they offer highly economical combinations of strength and corrosion resistance. Duplex stainless steels have existed for well over seventy years. However, the “first generation” of duplex stainless steels was not readily welded without loss of toughness and corrosion resistance because the desired phase balance was not typically achieved in the as-welded condition. Consequently, their practical use in process applications such as those regularly encountered in a pulp and paper mill was severely limited. In the last twenty-five years a “second generation” of duplex stainless steels has come into commercial production. These grades are characterized by a composition balance, and particularly the use of relatively high contents of nitrogen as an alloying element, that allow practical welding without loss of desirable properties. The higher nitrogen facilitates the rapid formation of austenite after high temperature exposure, enabling a rapid return to the desired balanced phase structure after welding. Reliable weldability makes duplex stainless steels practical as engineering materials.

This Technical Information Paper is intended to assist in identification of duplex stainless steels appropriate to application in the pulp and paper industry and to offer general guidelines for the qualification of welding procedures and for the installation of duplex stainless steels. It is assumed that the reader has a basic familiarity and experience with fabrication and welding of austenitic stainless steels, most typically Type 316L.

Safety precautions

Any welding process requires appropriate safety precautions, techniques, and safety equipment (helmet, shields, gloves, etc). Normal manufacturing safety precautions apply. Some companies require welding permits. Check with the appropriate department at your organization.

These procedures may require the use or disposal of chemicals that may present serious health hazards to humans. Procedures for the handling of such substances are set forth on Material Safety Data Sheets which must be developed by all manufacturers and importers of potentially hazardous chemicals and maintained by all distributors of potentially hazardous chemicals. Prior to the use of this technical information the user should determine whether any of the chemicals to be used or disposed of are potentially hazardous and, if so, the user should follow strictly the procedures specified by both the manufacturer, as well as local, state, and federal authorities for safe use and disposal of these chemicals.

Composition and properties

Table 1 identifies second-generation duplex stainless steels as listed in ASTM specifications covering flat-rolled (plate and sheet) and long-rolled (bar) products. Although few of the duplex grades are patented, some of these grades are closely associated with particular stainless steel producers as proprietary special alloy 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. Since the first edition of TAPPI TIP 0402-23, ASTM has adopted procedures for introducing “common names” in its specifications. Common names are defined as being widely accepted, not associated with any one producer, and not being trademarks. In the case of the duplex stainless steels these common names are most typically based on the combination of the nominal chromium and

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nickel contents, e.g., 2205, with 22% Cr and 5% Ni. ASTM is not permitted to list trademarks or names closely associated with a single producer, but the listing of the widely used common names facilitates the use of the ASTM specifications for ordering the duplex grades. All grades, including those without common names, are listed by their designations in the Unified Numbering System (UNS), as shown in Table 1. It is always prudent to reference all stainless steels by their unique UNS numbers when ordering to the standard specifications to obtain the desired grade.

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

Table 1. Composition of duplex stainless steels^a (with representative austenitic stainless steels)

UNS Number	Type	C	Mn	P	S	Si	Cr	Ni	Mo	N	Cu	Other
Middle Duplex												
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	...	...
S32205	2205 ^b	0.030	2.00	0.030	0.020	1.00	22.0-23.0	4.5-6.5	3.0-3.5	0.14-0.20	...	...
Lean Duplex												
S32001	...	0.030	4.0-6.0	0.040	0.030	1.00	19.5-21.5	1.00-3.00	0.60	0.05-0.17	1.00	...
S32003	...	0.030	2.00	0.030	0.020	1.00	19.5-22.5	3.0-4.0	1.50-2.00	0.14-0.20	...	...
S32101	...	0.040	4.0-6.0	0.040	0.030	1.00	21.0-22.0	1.35-1.70	0.10-0.80	0.20-0.25	0.10-0.80	...
S32304	2304 ^b	0.030	2.00	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	...
Super Duplex												
S32550	255 ^b	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 ^b	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	1.00-2.00	...	...	...
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	...	...
S30403	304L ^d	0.030	2.00	0.045	0.030	0.75	18.0-20.0	8.0-12.0	...	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 ^b	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	0.015	1.00	19.0-23.0	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 Common commercial name not associated with a particular producer.

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

^d AISI designation

Table 2. ASTM specifications covering duplex stainless steels^a

<u>Product Form</u>	<u>ASTM Specification</u>
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 specification.

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, with newer grades being regularly introduced. Users and fabricators should be aware that the ASME has established additional requirements for the qualification of duplex stainless steels and constructions of duplex stainless steels, in comparison with the austenitic stainless steels. Included among these requirements are Charpy tests (with specification of minimum required lateral expansion as acceptance criteria) of the mill products with sections greater than 3/8 inch (9.5 mm) at the Minimum Design Metal Temperature (MDMT), and similar qualification of procedures and fabrications. The qualification of a fabrication may require sample material from the same mill product, something to be considered when ordering material. These requirements are detailed and complex, and the fabricator and user are advised to review these requirements thoroughly 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 required by ASTM A 240, are compared to those of Type 316L in Table 3. The duplex stainless steels typically have yield strengths about twice those of the common austenitic grades, but are somewhat less ductile, typically showing tensile elongations of perhaps 50% of those expected of austenitic stainless steel. The duplex stainless steels also have substantially lower thermal expansion coefficients and substantially higher thermal conductivities than type 316L, with the values for duplex stainless steels more closely resembling those for carbon and alloy steels than that for 316L austenitic stainless steel. Table 4 shows the characterization of duplex stainless steels by several common corrosion test procedures, with comparisons to austenitic stainless steels.

In the first edition of this TIP, the grade now known as 2205 was listed only as UNS S31803 in the specifications. When the common name 2205 was introduced, it was associated with the newer UNS number S32205 having a composition restricted in terms of Cr, Mo, and N, and not the earlier S31803. This grade, 2205 (UNS S32205), is the most readily available duplex stainless steel grade with multiple producers of virtually all product forms and with good availability through common metal distribution channels. This edition now also includes the “super duplex” grades, typically containing about 25% Cr and 3% or more Mo. Also included is the more recently introduced category of “lean duplex” grades having somewhat lower levels of Cr and, in some cases, no intentional Mo addition. The issues regarding selection, qualification, and welding of duplex stainless steels are generally consistent for most grades, although there are issues mostly related with the tendency to form intermetallic compounds associated with the increasing alloy content. The thorough discussion of 2205 and wide experience in its application are a sound basis for modifications to accommodate the other duplex grades, whether of greater or lesser alloy content. The behavior of the lean duplex stainless steels and the super duplex grades will for the most part be discussed by comparison to the behavior of the 2205 duplex stainless steel.

Metallurgical aspects of welding duplex stainless steels

Figure 1 shows typical micrographs of austenitic and duplex stainless steel plates. The appearance of the microstructure of the duplex stainless steels is essentially independent of alloy content. Duplex stainless steels solidify as a fully ferritic structure and then form regions of austenite within the ferritic structure. These regions are typically fairly compact islands of austenite, but they may acquire some distinctive morphology as a result of directional solidification in the cast structure. However, because the duplex grades are typically hot worked under conditions where both phases are present, the austenite tends to acquire a morphology resulting from that hot working process, with a resulting characteristic anisotropy. One of the most important effects of nitrogen as an alloying

element in duplex stainless steels, enabling the second generation of duplex stainless steels, is that it causes the formation of austenite at higher temperatures so that the desired duplex structure is established and progresses toward the equilibrium phase balance quickly at temperatures high enough to enable the movement of all elements closer to their preferred equilibrium positions during initial solidification, as may occur in casting or welding, and during annealing or high temperature exposures as in welding.

Table 3. ASTM A 240 mechanical test requirements for duplex stainless steels

UNS Designation	Type	Tensile strength, min		Yield strength, min		Elongation in 2 in. or 50 mm, min., %	Hardness, max.		Cold bend
		mPa	ksi	MPa	ksi		Brinell	Rockwell C	
Austenitic									
S31603	316L	485	70	170	25	40	217	95	not required
Middle Duplex									
S31200	...	690	100	450	65	25	293	31	not required
S31260	...	100	690	485	70	20	290	...	...
S31803	2205	620	90	450	65	25	293	31	not required
S32205	2205	620	90	450	65	25	293	31	not required
Lean Duplex									
S32001	..	620	90	450	65	25	293	31	not required
S32003	..								
t ≤ 0.187 in [5 mm]		690	100	485	70	25	293	31	not required
t > 0.187 in [5mm]		655	95	450	65	25	293	31	not required
S32101	...								
t ≤ 0.187 in [5 mm]		700	101	530	77	30	290	...	not required
t > 0.187 in [5mm]		650	94	450	65	30	290	...	not required
S32304	2304	600	87	400	58	25	290	32	not required
Super Duplex									
S32550	255	760	110	550	80	15	302	32	not required
S32750	2507	795	116	550	80	15	310	32	not required
S32760	...	750	108	550	80	25	270	...	not required
S32900	329	620	90	485	70	15	269	28	not required
S32950	...	690	100	485	70	15	293	32	not required

Table 4. Comparison of corrosion resistance of selected austenitic and duplex stainless steels

UNS Designation	Type	ASTM G 48, Practice A Critical Pitting Temperature, °C (°F)	ASTM G 48, Practice B Critical Crevice Temperature, °C (°F)	Critical Pitting Temperature in 1M NaCl °C (°F)
S31603	316L	0-5 (32-41)	-2.5 (27)	7-16° C (45-61° F)
S31703	317L	...	0 (32)	...
N08904	904L	42.5 (109)	12 (54)	59-64° C (138-147° F)
S31254	6% Mo	72.5 (163)	37.5 (99.5)	87-95 (190-203)
S32205	2205	35-42 (95-108)	15 (59)	39-53° C (102-127° F)
S32750	2507	79 (174)	37.5 (99.5)	87->95°C (190->203° F)

The annealed structure shown in Figure 1 has ferrite and austenite in the desired equilibrium condition. Because the steel is processed in the predominantly two-phase condition, the morphology of the phases in a plate is an interlocking “pancake” microstructure as shown in the Figure 1. This structure is substantially anisotropic and is often highly advantageous in practical fabrications, showing the high strength, toughness, and corrosion resistance that recommend the use of the duplex stainless steels. If the structure in the plate were to be heat treated at a temperature above that for which the austenite is stable, the desirable effects of this anisotropy are likely to be lost.

The goal of the welding is to produce an as-welded structure that retains these desirable properties. If there is to be a problem with a duplex stainless steel weld, it can occur in the heat-affected zone (HAZ) or, less frequently, in the weld metal itself. There are two significant problems that must be avoided when welding duplex stainless steels: (1) excessive ferrite in the weld or, more frequently, the high temperature HAZ, sometimes noted as HTHAZ, meaning an area that has gone above the temperature of austenite stability; and (2) the formation of intermetallic phases in the HAZ.

1. Phase balance - avoiding excessive ferrite. Duplex stainless steel solidifies as ferrite and then partially transforms to austenite. After annealing, duplex stainless steel is usually a balance of 40-60% ferrite and 60-40% austenite, most typically with about 45% ferrite in annealed duplex mill products. It is generally accepted that a phase balance with at least 25% of the lesser phase will provide the expected properties for duplex stainless. During welding, the HAZ, and especially the part of the HAZ closest to the fusion line, the HTHAZ, will reach a temperature where much, if not all, of the austenite has transformed into ferrite. After the weld has passed, the weld and HAZ are cooled, mostly by conduction within the workpiece itself. In the first generation of duplex stainless steels, this cooling often had the effect of trapping the HAZ, and possibly the weld, in a highly ferritic condition. The ferrite, especially at a high volume fraction, lacks toughness, and it is also susceptible to precipitation of metallurgical phases and compounds that further reduce corrosion resistance and toughness.