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CHALLENGES WELDING DUPLEX AND SUPER DUPLEX STAINLESS STEEL

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ABSTRACT

Welding duplex and super duplex stainless steels is similar to welding austenitic stainless steels; however, critical steps must be taken to maximize both corrosion resistance and mechanical properties. Where maximum results are necessary, such as in corrosive service applications, selecting the proper base material and weld filler metal alone will not guarantee success. Attention to welding process, welder technique, bead shape, preheat/interpass temperatures, heat input on a per bead basis, and corrosion sample preparation are all essential to achieving satisfactory results. All of these factors will be discussed and their importance defined. Target parameters and approaches will also be presented to assist the user in obtaining successful results.

INTRODUCTION

Inherent metallurgical characteristics have at times plagued both Duplex (DSS) and Super Duplex Stainless Steel (SDSS)[1] in applications where welding is involved. Improper welding techniques and procedures can introduce detrimental effects such as unbalanced ferrite (α) to austenite (γ) ratios and the formation of intermetallic phases. This often leads to accelerated corrosion or mechanical failure in the weld zone. Fortunately, these problems can be resolved by implementing welding procedures and techniques that optimize the ferrite and austenite ratios and suppress the undesirable metallurgical phases detrimental to corrosion. Generally all fusion welding processes can be used for welding DSS provided suitable welding procedures and welding filler metals are used. If properly implemented, DSS and welds will provide a reliable level of fitness-for-service.

NOMENCLATURE

α – ferrite
γ – austenite

HISTORY OF DUPLEX STAINLESS STEEL

DSS is not a new material and spans a history of 84 years. The first wrought duplex stainless steels were produced in Sweden in 1930 and were used in the sulfite paper industry. These grades were developed to primarily reduce intergranular corrosion problems in the early high-carbon austenitic stainless steels. That same year duplex castings were produced in Finland; followed by a patent in France in 1936 for the forerunner of what would eventually be known as Uranus 50. Beyond World War II, further alloying developments brought AISI Type 329/3RE60, which was used extensively in the construction of heat exchanger tubing for nitric acid services. 3RE60 was the first DSS alloyed specifically to resist chloride stress corrosion cracking, which DSS is still noted for to date. These alloys served well in specific applications up to the late 1960's; however, they were noted for poor performance in the as-welded condition. This was due to a high ferrite concentration in the heat-affected zone (HAZ) which lowered toughness and corrosion resistance significantly when compared with the base material [1].

During the 1970's, advancements in steel processing and a shortage of raw materials breathed new life into DSS. A cost effective alternative to higher alloyed stainless and nickel alloys was needed. New technology made the control of residual elements tighter and production was more cost effective. This second generation of alloys improved on previous formulations, however there was still something to be desired when it came to applications involving welding. Into the 80's and 90's, research and development showed that nitrogen alloying was an effective

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[1] For the purpose of this paper DSS applies to both DSS and SDSS unless specially noted otherwise.

solution to counter act low toughness and low corrosion resistance that plagued the HAZ. This advancement brought weldability of modern DSS/SDSS to an acceptable and realistic level for most fabricators – when proper care is taken. Due to their higher strength to weight ratio, good toughness strength and greater resistance to corrosion, erosion and stress corrosion cracking (SCC) DSS/SDSS have become the material of choice in many industries. The list within these industries and their applications includes pipelines, pressure vessels, tanks, digesters, manifolds, risers, rotors, impellers and shafts are a few of the applications; certainly, many more haven't been addressed. One example of this is illustrated in Fig. 1.

FIG. 1 ALLOY 2205 DSS ABSORBER TOWER AT COAL FIRED POWER PLANT

CHARACTERISTICS OF DUPLEX STAINLESS

Corrosion performance and cost effectiveness have made the various types of DSS desirable for corrosive service applications in several industries. Having a dual phase microstructure that consist of both austenite and ferrite give this hybrid of stainless steels a unique microstructure which exhibits a high strength and sufficient ductility. Because of the presence of relatively strong ferrite, DSS has greater strength than standard austenitic stainless steel. The increase in strength translates to thinner sections resulting in lighter fabricated components. In addition, ferrite provides a significant resistance to chloride stress corrosion cracking. On the other hand, the austenitic phase content allows DSS to maintain sufficient ductility and toughness. In general, a ~50/50 phase balance of ferrite and austenite, as shown in Fig. 2, is targeted in production of DSS to ensure a good austenite reformation in the HAZ and thereby ensuring good mechanical and corrosion properties of the welded joint. At times, some users will desire slightly more austenite because of higher ductility and formability. However, experience has shown that desirable properties still exist where phases ranges from 30 – 70% ferrite [1].

These qualities combine to make DSS very appealing to designers requiring a strong, yet ductile material when compared to popular 300 series austenitic stainless steels. Other advantages include excellent pitting, corrosion resistance and low thermal expansion. Having a relatively "lean" chemical composition when compared to competitive alloys with higher nickel (Ni) and molybdenum (Mo) content DSS offer additional long term savings.

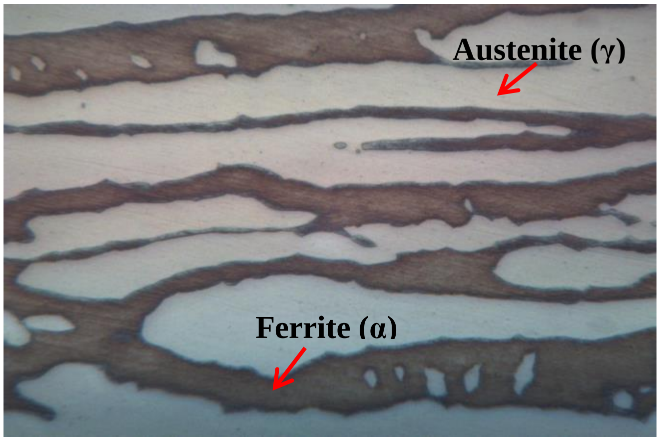


FIG. 2 - DUPLEX STRUCTURE SHOWING THE DUAL PHASE STRUCTURE (LIGHT BANDS AUSTENITE AND DARK BANDS FERRITE)
Source: Maverick Testing Laboratories, Inc.

As previously noted, weldability of modern DSS is considered to be good. The weld puddle characteristics are similar to austenitic stainless steels, but slightly sluggish. Machining and forming is also considered good, however due to its strength, it can be more difficult to form than other materials.

DSS, like austenitic stainless steel are a family of grades that range in corrosion performance depending on their alloy content. Currently, this family can be divided into five groups:

- Lean Duplex – Contains no deliberate addition of Mo (2304), with assumed PREN 26;
- Standard Duplex (2205), with *PREN 32 - 33;
- 25 Cr Duplex – *PREN <40 - (Alloy 255);
- Super Duplex – addition of Mo and nitrogen (N) - *PREN 40 – 45;
- Hyper Duplex – Highly alloyed DSS - *PREN >45.

***PREN = Pitting Resistance Equivalent Number**
= %Cr + 3.3Mo + 16N
= %Cr + 3.3(Mo + 0.5W) + 16N (for W bearing, e.g., SDSS) [1]

Key 1) Cr – Chromium 2) Mo - Molybdenum
3) N - Nitrogen 4) W - Tungsten

The grade selected for a certain application should be considered on a case by case basis since there is no single grade for a given service environment. The grade should be selected carefully based on PREN, manufacturers' recommendations and experience. Price should always be a consideration, when appropriate; however the selection of material should not be based on cost alone.

Although there are several advantages to using DSS, there are some inherent disadvantages. The unique metallurgical structure of DSS makes it somewhat less stable at elevated temperatures (i.e. welding) compared to other alloys. This instability can lead to the formation of detrimental intermetallic phases, which ultimately reduce corrosion resistance and toughness. In most cases the HAZ adjacent to the weld will be most problematic. It is not uncommon to find DSS applications where improper welding techniques and procedures have caused welds to become severely corroded to the point of through wall leaks, as depicted in Fig. 3, or to find welds that have mechanically failed due to the lack of ductility. It is imperative that the phase balance be controlled as the weld solidifies. The transformation during the cooling phase allows some of the ferrite to transform to austenite; however, the amount of transformation is highly dependent on the chemistry. Relatively small changes in Ni, Cr, Mo and N can have a significant effect on the phase transformation rates and equilibrium.

Fig. 3 CORRODED 2205 WELD DUE TO UNDER-ALLOYED WELD METAL

WELDING DUPLEX STAINLESS STEEL

A necessity of any successful operation is a good plan. The next step is to make sure everyone involved knows the plan. The same is true when working with DSS. Good intentions are often foiled by a lack of communication. When DSS is selected to be used for an application, everyone from the top down must be involved, i.e., upper management, engineering, supervision, quality control and most importantly, the welders/welding operators. There are many DSS fabricated components in service that are literally falling apart because no time or budget was given to properly qualify welding procedures or implement good practices in the field. Simply using the correct filler materials and performing NDE is not enough and will not guarantee a DSS weld joint is fit-for-service. The cost savings and high performance potential of DSS can only be realized when the necessary commitment is given to the effort.

Generally all fusion welding processes can be used for joining DSS provided suitable welding procedures and welding consumables are used. However, the root pass is typically welded with gas tungsten-arc (GTAW), Fig. 4, plasma-arc (PAW) or pulsed gas metal-arc (GMAW-P) welding process with GTAW the most widely used. The fill and cap passes can be accomplished with any of the fusion welding processes or combination of processes since the goal is to fill the weld joint as quickly as possible while maintaining the procedural control necessary to obtain weld metal and HAZ properties that match the corrosion resistance and impact strength properties of the base material.

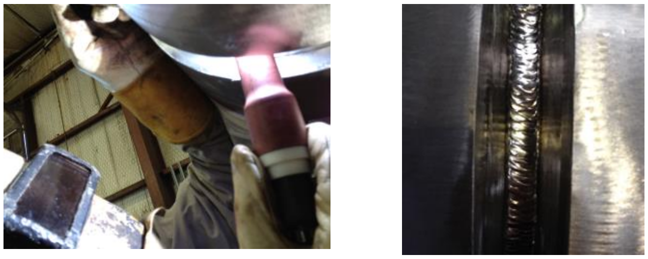


Fig. 4 MANUAL GTAW ROOT PASS IN SDSS
Source: Maverick Testing Laboratories, Inc.

FILLER MATERIAL SELECTION

In general, DSS materials should be welded with a filler metal composition that closely matches the base material composition. In addition, it is recommended that the filler metal meet the chemical composition requirements shown in Table 1. Filler metals commonly used to weld DSS are summarized in Table 2; however, depending on the application other combinations may be more appropriate. In most cases the filler materials are found to be slightly over alloyed, typically with about 3% Ni, to help promote austenite formation in the completed weld.

TABLE 1

RECOMMENDED ADDITIONAL CHEMICAL COMPOSITION REQUIREMENTS

Element	Duplex Percent (%) (minimum)	Super Duplex Percent (%) (minimum)
Nitrogen	0.14	0.2
Nickel	8.0	9.0
Molybdenum	3.0	3.5

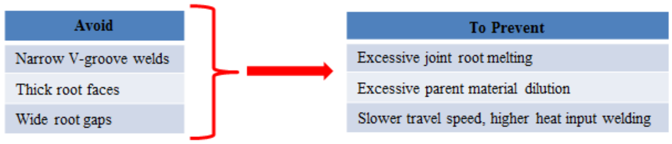
Often times during fabrication there is a need for welded joints between DSS and other alloys, e.g., carbon steel, austenitic stainless steel, etc. these “dissimilar” welds always require careful attention to achieve acceptable mechanical and corrosion properties. Common practice is to use either an over or under matching filler metal based on the composition of the base material and service requirements. A summarization of the most common dissimilar combinations filler metals/base materials is listed in Table 3; however, as previously noted depending on application other combinations may be more appropriate. Just as with matching welds, a filler material with a slight increase in nickel content relative to the DSS base material should be considered.

Caution should be used when selecting filler metals containing columbium / niobium (Nb), such as NiCrMo-3 classification should not be used. The Nb has an affinity for nitrogen; therefore, depleting the nitrogen from the DSS. This depletion of nitrogen can potentially lead to accelerated formation of harmful intermetallic inclusions in the HAZ.

JOINT DESIGN

Joints should be designed based on the thickness of the materials, access and the welding process. As with most welding applications, the joint should be designed so that it will have the smallest cross section possible but still allow for full penetration and manipulation of the weld puddle for good side wall fusion. Joints that are too narrow, have a thick root face or wide root gaps must be avoided. These conditions will cause excessive root melting, high dilution, and slower travel speeds resulting in longer exposure time in the harmful temperature range, is illustrated in Fig. 5.

Groove welds may be prepared by grinding, machining or plasma arc cutting/beveling; however, if plasma arc is used the HAZ should be removed prior to fitting and welding. To achieve better consistency in fit-ups and ensure balanced heat input around the circumference of the weld joint machining is highly recommended. Joint preparations for DSS are basically the same as those used for austenitic stainless steel. However, for one-sided groove welds a slightly wider gap, thinner root face and a more open groove angle are preferred, as shown in Fig. 6.



Avoid	To Prevent
Narrow V-groove welds	Excessive joint root melting
Thick root faces	Excessive parent material dilution
Wide root gaps	Slower travel speed, higher heat input welding

Fig. 5 PITFALLS TO AVOID [2]

Prior to any welding, the joint shall be thoroughly cleaned. Heavy oxides and rough grinding burs shall be removed by grinding with dedicated grinding wheel, flapper disc and when required brushed with stainless steel wire brushes. All paint, oil, grease, dirt or other foreign materials shall be removed from the inside diameter/surface (I.D.) and outside diameter/surface (O.D.) at least a minimum of two (2) inches beyond the edge of the groove opening. Isopropyl alcohol or other solvents approved for use on stainless steel, i.e., controlled fluorides, chlorides and sulphides, which will not leave a residue, may be used. Implement good austenitic stainless practices such as:

- Segregation of materials
- Careful storage and handling e.g. cover steel racks, forks on fork truck, chains, roller, fabrication tables, etc.
- Avoid using contaminated tools
- Avoid carbon contamination e.g. oil, grease, shop dirt, grinding sparks, etc.
- Use clean air
- Filler metal control
- Follow qualified welding procedure specification requirements
- Training of “all personnel”

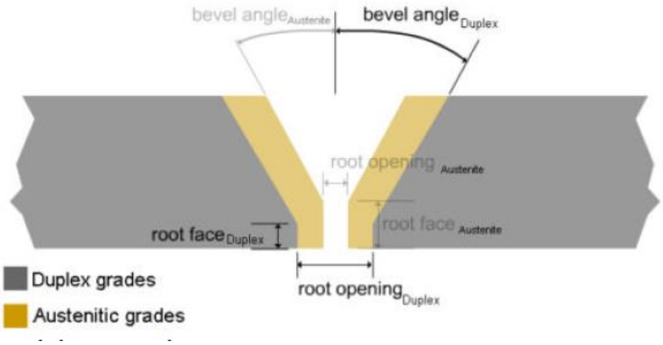


Fig. 6 DSS VERSUS AUSTENITIC STAINLESS STEEL JOINT PREP FOR SINGLE-SIDED GROOVE WELD

PREHEAT AND INTERPASS TEMPERATURE

An elevated preheat is generally unnecessary and usually not recommended. In some cases depending on temperature and humidity, a light preheat, < 100°F (38°C), may be used to remove moisture or condensation that may be on the surface of the weld joint. If preheat is used it should be applied after the weld joint is cleaned with an approved solvent and be applied uniformly around the weld joint. Also, be aware that preheat with an oxy-fuel torch or air-fuel torch to a peak temperature lower than 212°F (100°C) can allow the combustion products (water vapor) from the flame to condense on the base metal, and may actually do more harm than good by promoting porosity. So if preheating is required it should be performed using either infrared heaters or electrical resistance strip heaters [3]. On the other hand, the interpass temperature must be monitored closely; since it has a significant effect on time at transition temperatures where phase transformations and intergranular migrations take place. Too high of an interpass temperature will increase the cooling rate which has a key effect on the phase balance in the HAZ and weld. It also significantly affects the formation of intermetallic phases and corrosion resistance. Table 4 shows maximum interpass temperatures based on base material at the weld joint base on the current consensus of the welding industry. Preheat, when required and interpass temperatures can be checked using thermocouples, temperature indicating crayons, pyrometers or other suitable means. However, if temperature crayons are used they should be approved for use on stainless steel, i.e., controlled fluorides, chlorides and sulphides. For critical applications the use of either contact thermocouples or pyrometers is recommended and the temperature should be checked precisely at the point of the arc start-up just prior to welding.

TABLE 4

MAXIMUM RECOMMENDED INTERPASS TEMPERATURE FOR DSS & SDSS

Thickness inches (mm)	Maximum Interpass Temperature	
	Duplex Stainless Steel (e.g. UNS S32205) °F (°C)	Super Duplex Stainless Steel (e.g. UNS S32750) °F (°C)
< 1/8 (3)	120 (50)	120 (50)
< 1/4 (6)	160 (70)	160 (70)
< 3/8 (10)	210 (100)	210 (100)
≥ 3/8 (10)	300 (150)	250 (120)

WELDING PROCESSES

As previously noted DSS is capable of being welded with all the common fusion welding processes including GTAW, GMAW, SMAW, FCAW and Submerged-Arc Welding (SAW). Mechanization of those suitable processes is advantageous because of consistent heat input and precise control of parameters offered, as illustrated in Fig. 7.

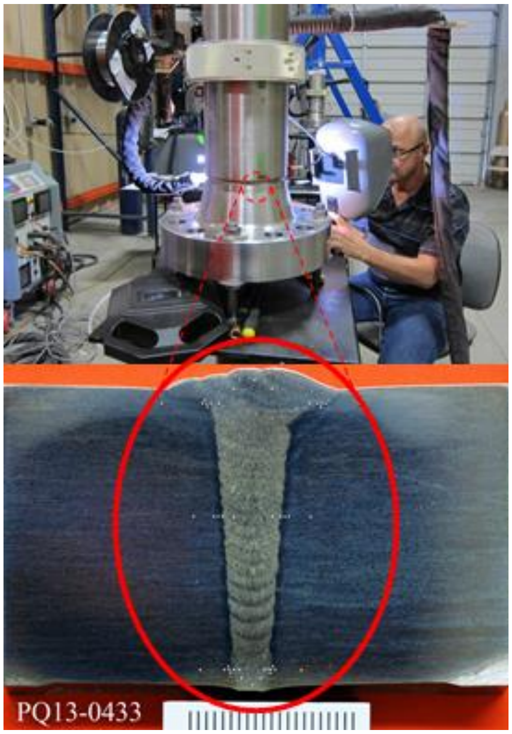


FIG. 7 MACHINE HOT WIRE GTAW WELDING OF HEAVY WALL DSS USING NARROW GROOVE JOINT DESIGN

Sources: Liburdi Dimetrics, Corporation and Maverick Testing Laboratories, Inc.

GAS SHIELDING AND PURGE

Recommendations for shielding and purging gas compositions for those welding processes requiring these gases are shown in Table 5. To ensure acceptable corrosion properties are met nitrogen (N_2) is typically added to slow progression of sigma phase. The flow rates for shielding gas should be checked at the cup or gas nozzle to ensure adequate flow. Purging gas should be checked with a calibrated oxygen analyzer and should not have an oxygen content exceeding 0.25% oxygen (O_2), (2500 ppm). To ensure adequate protection the purge should be maintained until a minimum of 1/4 inch (6mm) weld metal has been deposited or until the joint is complete, whichever comes first.

TABLE 5

RECOMMENDED GASES FOR SHEILDING AND PURGING DUPLEX STAINLESS STEEL

Process		Shielding Gas^1	Purging Gas
GTAW		Ar + 2-2.5%N_2 max. (Note 1) or 100%Ar	100%N_2 or 90%N_2 + 10%He or Ar + N_2 (not less than 5% N_2)
GMAW	Short Circuit	Ar + 20-30%He + 1-2%O_2	
	Spray Transfer	Ar + 20-30%He + 1-2%O_2 (DSS) Ar + 2-3%CO_2 (SDSS)	
	Pulse Transfer	Ar + 20-30%He + 1-2%O_2 (DSS) 100%Ar (SDSS)	
FCAW		Ar + 18-25%CO_2 or 100% CO_2	

Key

1) Ar - Argon
2) N_2 - Nitrogen
3) He - Helium
4) O_2 - Oxygen
5) CO_2 – Carbon Dioxide

Note

1) Strongly recommended that Ar/N_2 mix be replaced with 100%Ar after 2nd pass because excessive use of Ar/N_2 shielding gas may lead to micro-porosity defects in multipass welds [4].

HEAT INPUT

Heat input is critical to the performance of DSS welds for the same reasons interpass temperature is. When the weld, HAZ and adjacent base material stay at elevated temperatures, they also spend more time passing through temperatures range where the detrimental sigma phase, chi phase and carbide formation occur. Heat input is the most critical when depositing the root pass in pipe and/or vessel welds made from one side. To help control this and enhance control of root bead quality it is advisable to deposit weld beads as a series of balanced segments, as illustrated in Fig. 8, yields the following advantages:

- Controlling joint gap closure.
- Reducing overall joint distortion.
- Maximizing production while helping to maintain interpass temperature controls.

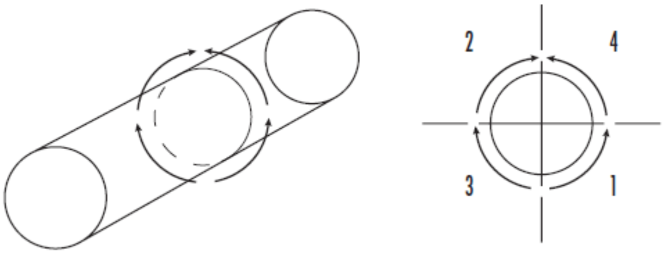


FIG. 8 BALANCED WELD JOINT SEGEMENTS

When welding DSS, the extreme re-heating of the root pass by the deposit of the "hot pass" will often degrade the corrosion resistance of the root, especially the HAZ, to an unsatisfactory level. Since the root pass is a relatively small deposit (volumetrically) with a substantial amount of base metal dilution welding back over it with a very hot and relatively heavy "hot pass" is simply too much to maintain a stable metallurgical state, as pointed out in Figs. 9-11.

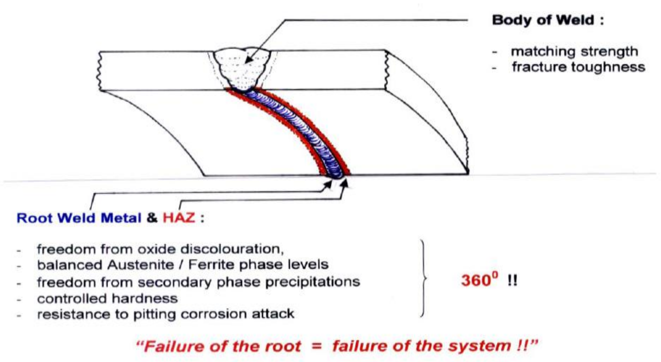


FIG. 9 CROSS SECTION DIAGRAM OF WELD AND ROLES OF EACH REGION [2]

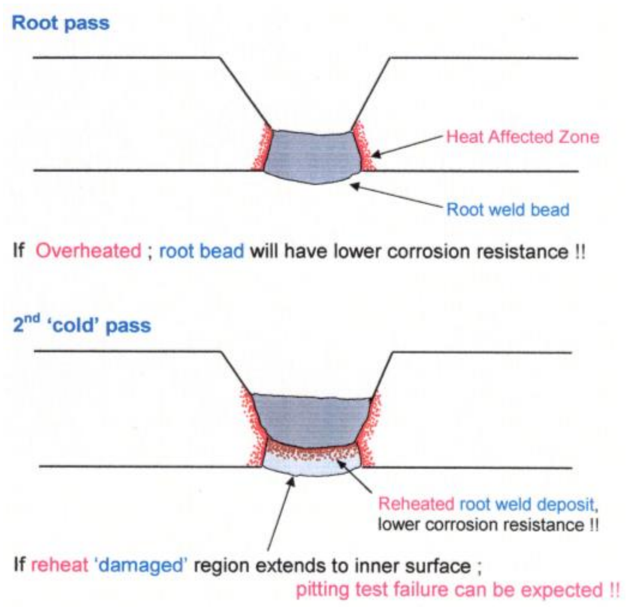


FIG. 10 DAMAGE RESULTING FROM OVERHEATING AND REHEATING ROOT PASS [2]

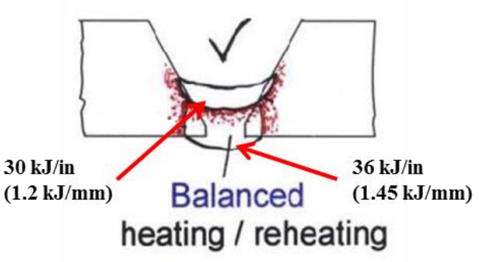


FIG. 11 BALANCE HEATING AND REHEATING IS ESSENTIAL FOR SUCCESS [2]

To overcome this extreme reheating of the root, parameters and procedures must be adjusted accordingly. The "hot pass" must become a "cold pass"; meaning the heat input should be ~75% of the root pass [4].

Heat input must also be observed in fill and cap passes. Even heating and bead placement is essential for full performance benefits. Table 6 contains recommended heat inputs for different grades of DSS. Applications where thinner or thicker sections or alternative welding process are used may require adjustments to heat input.

When determining heat input, careful consideration should be given to the process being used. The traditional heat input formula will not be accurate if using waveform controlled power sources. It is recommended the rules of QW-409.1 of ASME Section IX be used to determine heat input accurately [6].

TABLE 6
RECOMMENDED HEAT INPUT [7]

DSS Grades	Heat Input (imperial)	Heat Input (metric)
2304 Lean DSS	15-50 kj/in.	0.5 – 2.0 kj/mm
2205 Standard DSS	15-65 kj/in.	0.5 – 2.5 kj/mm
2507 Super DSS	8-38 kj/in.	0.3 – 1.5 kj/mm

Note

1) Heat input shown are only recommendations

POST WELD CLEANING

Post weld cleaning for DSS is the same as for austenitic stainless steel. The removal of surface discontinuities is just as important as following the welding procedure specification (WPS); the goal of both is to ensure that the fabricated component will adequately perform in-service. The discontinuities such as undercut, weld spatter, arc strikes, coarse grinding marks, scratches, grease, oil, or paint should be removed. Figure 12 shows typical surface discontinuities and surfaces conditions encountered during fabrication. All iron contamination should be removed; however, removal by mechanical methods is not recommended due to the tendency of smearing and spreading the contamination further.

Like other stainless steels, DSS forms a tenacious chromium rich oxide layer to provide resistance to corrosion. The heat tint oxides formed during thermal cycles block this formation resulting in accelerated corrosion; therefore, it is recommended that heat tint be removed. A number of methods may be employed to achieve this including blasting, grinding, pickling and electro-polishing.

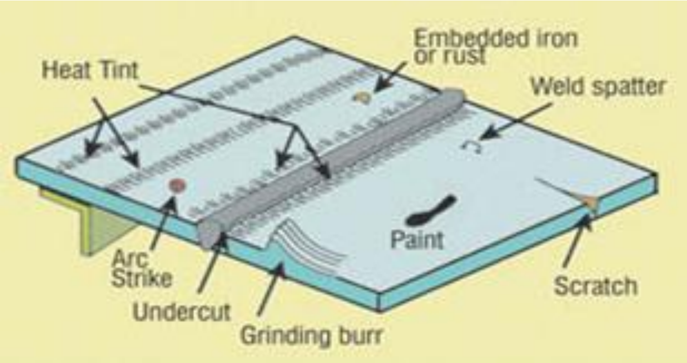


FIG. 12 TYPICAL SURFACE DISCONTINUITIES AND SURFACE CONDITIONS [8]

WELDING PROCEDURE QUALIFICATION

In many cases, following good austenitic stainless steel welding practices with the addition of monitoring heat input and observing stricter interpass temperatures will serve well. Prior to qualifying a procedure, it is worthwhile to experiment with parameters, travel speed, techniques, joint design and heat input in order to find a combination that will work for the welding process and application.

While welding a procedure qualification test specimen extra care should be taken to record all parameters including travel speed, voltage, amperage and heat input for each welding pass deposited. This data is critical in completing the supporting procedure qualification record (PQR) and WPS. In addition, this information may be crucial when determining the cause of undesired test results if the test specimen fails to meet the acceptance criteria.

Section thickness must also be considered since it plays a critical role in the heating and cooling characteristics encountered during welding. Thin sections typically heat and cool relatively quickly, while a thicker section tends to hold heat, but at the same time acting as a heat sink to the HAZ. Therefore it stands to reason that parameters providing acceptable results when used on a thick section will likely not work with a thinner section and vice versa. Recommendations on production section thickness versus test coupon thickness used for PQR qualification has historically varied greatly. A rule of thumb used by many is that production section thickness should not be more than 20% thicker or thinner than the coupon thickness used for PQR qualification. Without specific directions from governing Codes regarding thickness requirements for DSS many experts within the welding/fabrication industry feel the following thickness guidelines shown in Table 7 should be implemented.

TABLE 7

RECOMMENDED THICKNESS GUIDELINESS FOR PRODUCTION THICKNESS VERSUS PROCEDURE QUALIFICATION TEST COUPON RANGE

Production Thickness (t) in. (mm)	Minimum and Maximum Qualification Thickness Base on Test Coupon Thickness (T)	
	Minimum	Maximum
≤ 5/8 (16)	T	2T up to 5/8 in. (16mm)
> 5/8 to < 1-1/8 (16 to 29)	Min. & Max may be qualified by qualification test coupons in this range	
≥ 1-1/8 (29)	T	1.2T

Many welding procedures are based on simple mechanical tests. For many materials, this is sufficient; however, in the case of DSS simple bend testing and tensile testing are not sufficient. Additional testing is required in order to ensure corrosion, toughness and hardness properties have not been degraded by an improper welding procedure and techniques. The most popular test is ASTM A923 [9]. This test was designed specifically for testing DSS and is divided into three parts or “methods” A, B and C. Each one of these methods targets specific criteria that are critical to the performance of DSS.

Test Method A - rapid screening test. The idea being that if the test specimen passes this test, it is likely the specimen will pass method B and C tests as well. This test consists of sodium hydroxide etch from which a photomicrograph will be produced. This will be analyzed and compared to other photomicrographs to determine if any intermetallic phases are present within the ferrite grain boundaries. Depending on results, the user may or may not choose to perform the additional tests to verify results. While performing this test, it would also be worthwhile to perform a ferrite count in accordance with ASTM E562 guidelines and at a magnification of 400X or greater. The number of fields and points per sampled area shall be in agreement with the guidance displayed in the 10% relative accuracy column in Table 3 of ASTM E562, as portrayed in Fig. 13 [10]. As a guideline, magnification should be based on the initial determination of the sample areas to be tested to ensure that the microstructure can be clearly resolved without having an adjacent grid point fall over the same constituent feature. A 100 point grid map over 10 fields in a target (weld/HAZ) may be considered sufficient for material with 30% or greater ferrite content.

The acceptable ferrite to austenite ratio and locations y should be taken in areas that have been the subject of many studies and debates. To this date, the governing Codes have not provided any specific direction. Again many of the experts feel the locations should be evaluated and the ferrite content shown in Table 8 be reported on the PQR.

TABLE 8

RECOMMENDED: AREAS TO BE EVALUATED FOR α/γ RATIO AND ACCEPTANCE CRITERIA

Location ↓→	Weld Metal[1, 2] (% α)	HAZ (% α)	Base Metal (% α)
Root	30 - 65	40 - 65	
Mid-thickness	30 - 65	40 - 65	
Cover Pass	30 - 65[3]	40 - 65	
Base Metal			40 - 60

Notes

1) Ferrite count down to 25% may be acceptable for the weld metal if corrosion or other tests are satisfactory to the client/purchaser.
2) When a nickel alloy consumable is used the ferrite content of the weld metal may be zero.
3) In addition to point count evaluation, a minimum of five readings should be taken with a Feritscope and the readings averaged and recorded on the PQR. This information will be used as a reference point for acceptance of production welds.

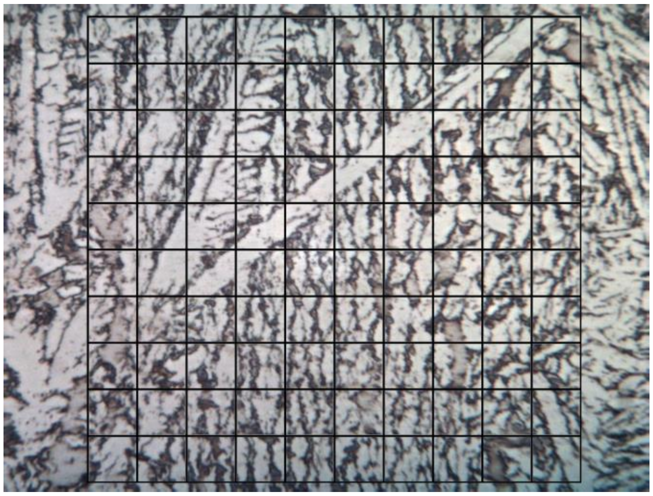


Fig. 13 POLISHED AND ETCHED HAZ SPECIMEN (800x) WITH 100 POINT GRID IN PREPARATION OF PERFOMING FERRITE POINT COUNT
Source: Maverick Testing Laboratories, Inc.

Test Method B - Charpy impact tests. Specimens are taken from the base metal, weld metal, HAZ or all three, as represented in Figs. 14, 15. Low impact values are typically an indication of intermetallic phases being present.

Currently there are no acceptance criteria in ASTM A923 for lean, super or hyper duplex stainless steels; therefore, the acceptance values have to be agreed upon prior to testing.

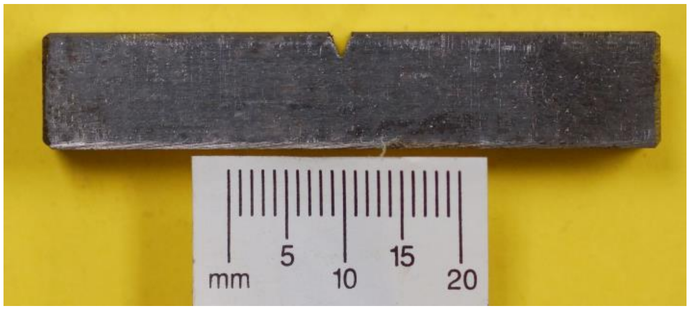


FIG. 14 MACHINED CHARPY IMPACT TEST SPECIMEN
Source: Maverick Testing Laboratories, Inc.

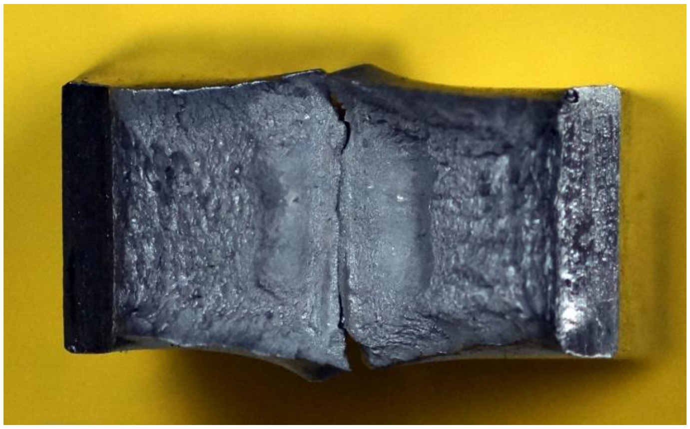


FIG. 15 BROKEN CHARP IMPACT TEST SPECIMEN FOR EVALUATION
Source: Maverick Testing Laboratories, Inc.

Test Method C - Ferric chloride corrosion test. The specimen is prepared and weighed, then immersed in the ferric chloride solution. This solution is designed to cause pitting in DSS materials that contain detrimental phases and low corrosion resistance, as illustrated in Fig. 16. The specimen is removed after a specified time and weighed. Weight loss is calculated and corrosion rate is expressed in mdd (milligrams per square decimeter per day). Variations of the ASTM G48 [11] test (another immersion corrosion test) are also used to determine corrosion rates.

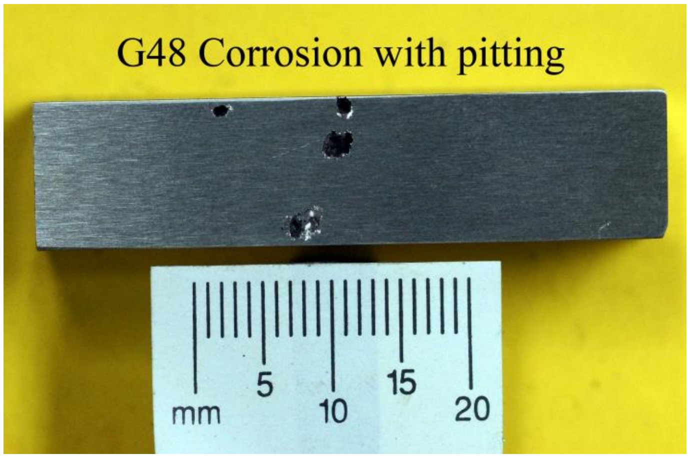


FIG. 16 G48 TEST SPECIMEN WITH PITTING
Source: Maverick Testing Laboratories, Inc.

Hardness testing, as depicted in Fig. 17, is yet another test that is typically imposed to determine the extent of the weld quality. High hardness readings are normally encountered in root region of the weld joint. This is primarily a problem in multipass welds in thick material, > 3/4 in. (19mm). The higher hardness reading in the root is the result of strain hardening caused by the thermal cycle of subsequent passes. Recommended maximum hardness values are listed in Table 9:

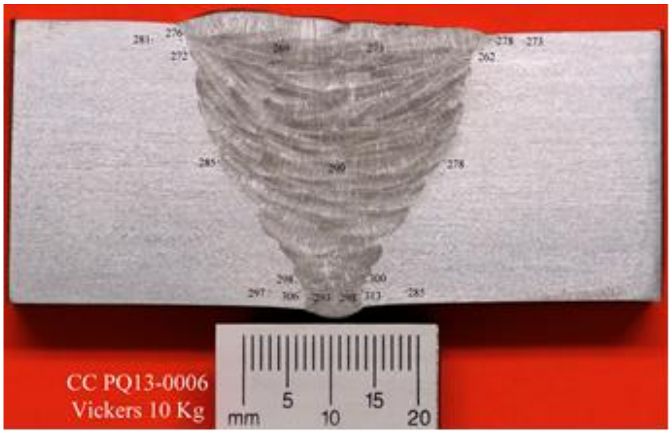


FIG. 17 VICKERS HARDNESS TEST
Source: Maverick Testing Laboratories, Inc.

TABLE 9

RECOMMENDED MAXIMUM HARDNESS VALUES

DSS Grades	Maximum Vickers Hardness (HV) (10 kilogram-force load)
Standard (2205)	320
Super (2507)	350

Only with these additional tests can an objective determination be made regarding the effectiveness of the WPS; to successfully produce welds that will maintain toughness and corrosion resistance properties throughout its life. However, a successfully qualified WPS is only part the cost savings and high performance potential of DSS can only be realized when the necessary commitment is given to the effort.

CONCLUSION

Applications for duplex stainless steel continue to grow and the production has increased steadily over the past decade meeting the demands of numerous industries. This growth has been accentuated by current higher cost of raw materials which allows DSS to be very cost competitive when compared to austenitic stainless steels. Therefore, both fabricators and constructors will continue to see an increased scope of work utilizing duplex.

Welding duplex and super duplex stainless steels is similar to welding austenitic stainless steels; however, critical steps must be taken to maximize corrosion resistance and mechanical properties. When the ultimate goal is to achieve maximum corrosion resistance, strength and toughness, as shown in Fig. 18, selecting the proper base material and weld filler metal alone will not guarantee success. Attention to welding process, welder technique, bead shape, preheat/interpass temperatures, heat input on a per bead basis, and corrosion sample preparation are all essential to achieving satisfactory results.

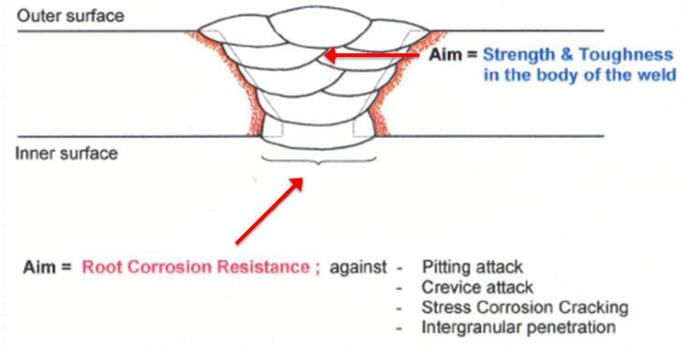


FIG. 18 GOAL - ACHIVING MAXIMUM CORROSION RESISTANCE, STRENGTH AND TOUGHNESS [2]

Everyone from the top down must be educated and committed, i.e., upper management, engineering, supervision, quality control and most importantly, the welders/welding operators. It is imperative for those closely associated with fabrication/welding of DSS to not only have an understanding of the practical issues of DSS but also an appreciation of the technical requirements. Management, at all levels, must also understand the basics for the technical requirements and support the fact that greater attention to details is necessary. With education and commitment, at all levels, DSS can be fabricated and welded successfully and will provide satisfactory throughout its design lifecycle.

ACKNOWLEDGMENTS

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TABLE 2

FILLER METALS FOR WELDING DUPLEX STAINLESS STEELS [12]

Base Materials ↓→	**Duplex Base Materials**					
Unified Numbering System (UNS) No.	**S32304**	**S31803** **S32205**	**S32550**	**S32760**	**S32750**	**S39274**
S32304	2209 DP3W 309LMo	2209 DP3W 309LMo	2209 DP3W 309LMo	2209 DP3W 309LMo	2209 DP3W 309LMo	2209 DP3W 309LMo
S31803 **S32205**		2209 DP3W	2209 DP3W	2209 DP3W	2209 DP3W	2209 DP3W
S32550			2553 DP3W	2553 DP3W	2553 DP3W	2553 DP3W
S32760				2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14	2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14	2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14
S32750					2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14	2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14
S39274						2594 DP3W NiCrMo-10 NiCrMo-13 NiCrMo-14

Note

1) DP3W is currently unclassified by the American Welding Society (AWS)

TABLE 3

FILLER METALS FOR WELDING DISSIMILAR (UNDER/OVER MATCHED) WELDS [12]

Base Materials ↓→	**Under Matched Alloys**			**Over Matched Alloys**		
Unified Numbering System (UNS) No.	**P-No. 1 through P-No. 5**	**P-No. 8 Type 304**	**P-No. 8 Type 316**	**P-No. 8 Type 254 SMO**	**P-No. 43 Alloy 625**	**P-No. 43 Alloy 825**
S32304	2209 309L 309LMo	2209 309L 309LMo	2209 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14
S31803 **S32205**	2209 309L 309LMo	2209 309L 309LMo	2209 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14
S32550	2209 2553 309L 309LMo	2209 2553 309L 309LMo	2209 2553 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14
S32760	2209 DP3W 309L 309LMo	2209 DP3W 309L 309LMo	2209 DP3W 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14
S32750	2209 DP3W 309L 309LMo	2209 DP3W 309L 309LMo	2209 DP3W 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14
S39274	2209 DP3W 309L 309LMo	2209 DP3W 309L 309LMo	2209 DP3W 309LMo	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14	NiCrMo-10 NiCrMo-13 NiCrMo-14

Note

1) DP3W is currently unclassified by the American Welding Society (AWS)