THE STATE UNIVERSITY APPLIED SCIENCES IN ELBLAG

INSTITUTE OF TECHNOLOGY

CÉSAR HEVIA LOREDO

WELDING TECHNOLOGY OF DUPLEX STAINLESS STEEL SHEETS USING THE SAW METHOD

FINAL PROYECT

-engineering-

Work supervisor:
prof. dr hab. inż. Jerzy Labanows

Elbalg 2019

INDEX

1. THE STAINLESS STEEL FAMILY

1.1.-Introduction

A short description of the various grades of stainless steel and how they fit into distinct metallurgical families.

Stainless steel is the term used to describe an extremely versatile family of engineering materials, which are selected primarily for their corrosion and heat resistant properties. All stainless steels contain principally iron and a minimum of 10.5% chromium.

Figure 1.1. Stainless steel tubes

At this level, chromium reacts with oxygen and moisture in the environment to form a protective, adherent and coherent, oxide film that envelops the entire surface of the material.

This oxide film (known as the passive or boundary layer) is very thin (2-3 namometres). The passive layer on stainless steels exhibits a truly remarkable property: when damaged (e.g. abraded), it self-repairs as chromium in the steel reacts rapidly with oxygen and moisture in the environment to reform the oxide layer.

Increasing the chromium content beyond the minimum of 10.5% confers still greater corrosion resistance. Corrosion resistance may be further improved, and a wide range of properties provided, by the addition of 8% or more nickel.

The addition of molybdenum further increases corrosion resistance (in particular, resistance to pitting corrosion), while nitrogen increases mechanical strength and enhances resistance to pitting [2].

1.2.-Categories

The stainless steel family tree has several branches, which may be differentiated in a variety of ways e.g. in terms of their areas of application, by the alloying elements used in their production, or, perhaps the most accurate way, by the metallurgical phases present in their microscopic structure :

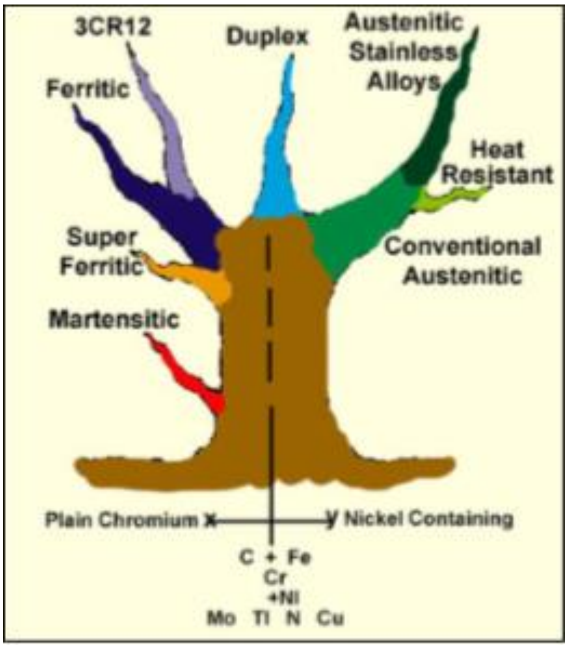

Figure 1.2 The family tree of stainless steel [3]

- Ferritic
- Martensitic (including precipitation hardening steels)
- Austenitic
- Duplex steels, consisting of mixture of ferrite and austenite
- Superduplex steels

Pitting resistance equivalent number (PREN)

It is a predictive measurement of a stainless steel's resistance to localized pitting corrosion based on its chemical composition.

PREN = 1 x %Cr + 3.3 (%Mo + 0.5 x %W) + 16 x %N

In general: the higher PREN-value, the more resistant is the stainless steel to localized pitting corrosion by chloride. PREN is frequently specified when stainless steels will be exposed to seawater or other high chloride solutions. In some instances stainless steels with PREN-values > 32 may provide useful resistance to pitting corrosion in seawater, but is dependent on optimal conditions.

1.2.1.-Ferritic stainless steels:

Consist of chromium (typically 12.5% or 17%) and iron. Ferritic stainless steels are essentially nickel-free. These materials contain very little carbon and are non-heat treatable, but exhibit superior corrosion resistance to martensitic stainless steels and possess good resistance to oxidation.

They are ferromagnetic and, although subject to an impact transition (i.e. become brittle) at low temperatures, possess adequate formability. Their thermal expansion and other thermal properties are similar to conventional steels [2].

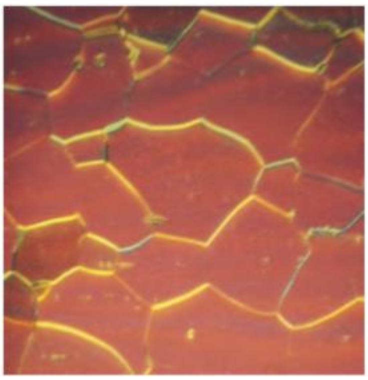

Figure 1.3. Ferritic structure seen from the microscope

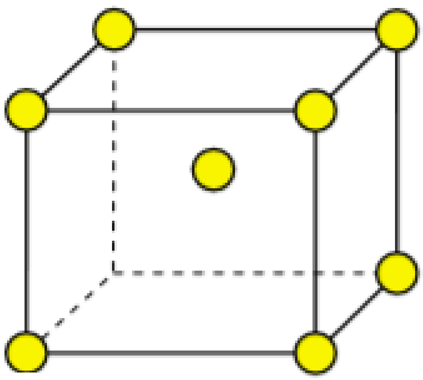

Figure 1.4. Ferritic (Body-CenteredCubic) Structure

Clasification

Ferritic stainless steels are usually ranked into 4 sub-families:

Group 1 grades that contain between 10 to 14%Cr and with a PREN around 10, used in non-severe conditions or when some superficial corrosion is acceptable. Typical grades are AISI 403 (EN 1.4003) and AISI 409Cb (EN A/4601) used in exhaust pipes of cars.

Group 2 grades that contain between 14 to 18%Cr and with a PREN around 16. The best known Grade is AISI 430 (EN 1.4017). This grade is not suitable for welding as grain growth in the Heat-Affected Zone (HAZ) of the weld induces brittleness.

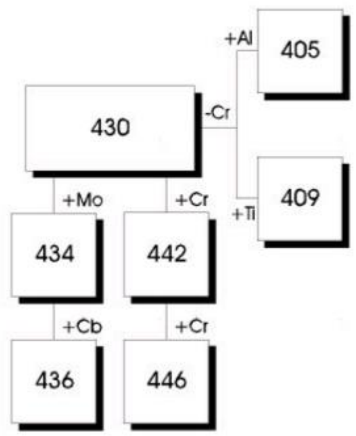

Figure 1.5. Different types of ferritic stainless steel

Group 3 is much similar to group3, but additions of Nb, Ti, and /or Zr in small amounts promote carbide precipitation which in turn avoid the grain growth and brittleness of welds; They are therefore weldable without any particular difficulty.

Group 4 grades can be described as "super ferritics" with higher Mo, and/or Cr mostly. Their PREN lies above 18, making them as good or better as standard austenitic grade AISI 304 (EN 1.4301). The best known grades of this family are AISI 434 and 444 (EN 1.4113 and 4521 respectively).

Electrical resistance ferritic grades Fr-Cr-Al are not included in these groups, as they are designed for oxidation resistance at elevated temperatures [4].

1.2.2.-Martensitic stainless steels

Consist of carbon (0.2-1.0%), chromium (10.5-18%) and iron. These materials may be heat treated, in a similar manner to conventional steels, to provide a range of mechanical properties, but offer higher hardenability and have different heat treatment temperatures.

Their corrosion resistance may be described as moderate. They are ferromagnetic, subject to an impact transition at low temperatures and possess poor formability.

Their thermal expansion and other thermal properties are similar to conventional steels. They may be welded with caution, but cracking can be a feature when matching filler metals are used [2].

Clasification

They fall into 4 categories (with some overlap):

Fe - Cr - C grades: They were the first grades used and they are still widely used in engineering and wear-resistant applications.

Fe-Cr-Ni-C grades: In these grades, some of the Carbon is replaced by Nickel. They offer a higher toughness and a higher corrosion resistance.

Precipitation Hardening grades: Grade EN 1.4542 (a.k.a. 17/4PH), the best known grade, combines martensitic hardening and precipitation hardening. It achieves high strength and good toughness and is used in aerospace among other applications.

Creep-resisiting grades: small additions of Nb, V, B, Co increase the strength and creep resistance up to about 650 °C [4]

Table 1.1 Different types of martensitic stainless steel.

	C	Cr	Mo	Others	Remarks
1.4006	0,08 to 0,15	11,5 to 13,5	—	—	Base grade, used as stainless engineering steel
1.4021	0,16 to 0,25	12,0 to 14,0	—	—	Base grade, used as stainless engineering steel
1.4116	0,45 to 0,55	14,0 to 15,0	0,50 to 0,80	V: 0,10 to 0,20	Used chiefly for professional knives
1.4104	0,10 to 0,17	15,5 to 17,5	0,20 to 0,60	S: 0,15 to 0,35-	Sulphur improves machinability
1.4122	0,33 to 0,45	15,5 to 17,5	0,80 to 1,30	—	Used chiefly for professional knives
1.4125	0,95 to 1,20	16,0 to 18,0	0,40 to 0,80	—	Tool steel grade (440C), high wear resistance
1.4057	0,12 to 0,22	15,0 to 17,0	—	Ni:- 1,50 to 2,50	Ni replaces some C for higher ductility & toughness
1.4418	≤ 0,06	15,0 to 17,0	0,80 to 1,50	Ni: 1,50 to 2,50	Highest corrosion resistance of martensitics
1.4542	≤ 0,07	15,0 to 17,0	≤ 0,60	Ni: 3,0 to 5,0 Cu: 3,0 to 5,0- Nb: 5xC to 0,45	Precipitation hardening grade High strength. Used in aerospace

Heat treatment of martensitic stainless steels:

Martensitic stainless steels form a family of stainless steels that can be heat treated to provide the adequate level of mechanical properties. The heat treatment typically involves three steps:

Austenitizing, in which the steel is heated to a temperature in the range 980 - 1050 °C -depending on the grades.

Quenching(a rapid cooling in air, oil or water). The austenite is transformed into martenisite, a hard a body-centered tetragonal crystal structure. The as-quenched martensite is very hard and too brittle for most applications.

Tempering, i.e. heating around 500 °C, holding at temperature, then air cooling.

1.2.3.-Austenitic stainless steels

Consist of chromium (16-26%), nickel (6-12%) and iron. Other alloying elements (e.g. molybdenum) may be added or modified according to the desired properties to produce derivative grades that are defined in the standards.

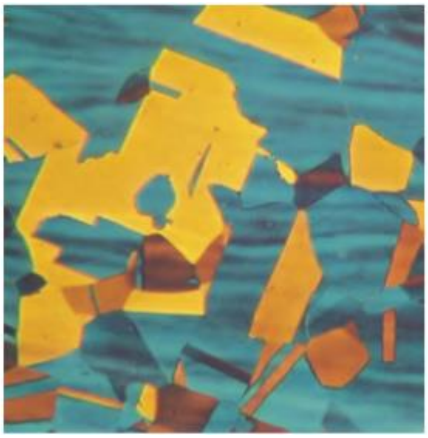

Figure 1.6. Martensitic structure seen from the microscope

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he austenitic group contains more grades, that are used in greater quantities, than any other category of stainless steel. Austenitic stainless steels exhibit superior corrosion resistance to both ferritic and martensitic stainless steels.

Corrosion performance may be varied to suit a wide range of service environments by careful alloy adjustment e.g. by varying the carbon or molybdenum content. These materials cannot be hardened by heat treatment and are strengthened by work-hardening.

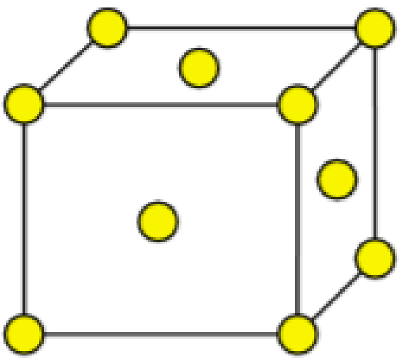


Figure 1.7 Austenitic (Face-Centered Cubic)

Unlike ferritic and martensitic stainless steels, austenitic grades do not exhibit a yield point. They offer excellent formability and their response to deformation can be controlled by chemical composition.

They are not subject to an impact transition at low temperatures and possess high toughness to cryogenic temperatures. They exhibit greater thermal expansion and heat capacity, with lower thermal conductivity than other stainless or conventional steels [2].

Clasification

They can be further subdivided into two sub-groups, 200 series and 300 series:

200 Series: are chromium-manganese-nickel alloys, which maximize the use of manganese and nitrogen to minimize the use of nickel. Due to their nitrogen addition they possess approximately 50% higher yield strength than 300 series stainless steels.

Type 201 is hardenable through cold working; Type 202 is a general purpose stainless steel. Decreasing nickel content and increasing manganese results in weak corrosion resistance.

300 Series: are chromium-nickel alloys, which achieve their austenitic microstructure almost exclusively by nickel alloying, some very highly alloyed grades include some nitrogen to reduce nickel requirements. 300 series is the largest group and the most widely used.

The best known grade is Type 304, also known as 18/8 and 18/10 for its composition of 18% chromium and 8%/10% nickel, respectively. The second most common austenitic stainless steel is Type 316. The addition of 2% molybdenum provides greater resistance to acids and to localized corrosion caused by chloride ions [4].

Table 1.2 Different types of austenitic stainless steel

Type	Name	Number	C	Cr	Mo	Ni	Others
301	X10CrNi18-8	1.4310	0,05 to 0,15	16,0 to 19,0		6,0 to 9,5	—
304	X5CrNi18-10	1.4301	< 0,07	17,5 to 19,5	—	8,0 to 10,5	—
304L	X2CrNi18-9	1.4307	< 0,030	17,5 to 19,5	—	8,0 to 10,5	—
303	X8CrNiS18-9	1.4305	< 0,10	17,0 to 19,0	—	8,0 to 10,0	S: 0,15 to 0,35-
321	X6CrNiTi18-10	1.4541	< 0,08	17,0 to 19,0		9,0 to 12,0	Ti:5xC to 0,70
316	X5CrNiMo17-12-2	1.4401	< 0,07	16,5 to 18,5	2,00 to 2,50	10,0 to 13,0	—
316L	X2CrNiMo17-12-2	1.4404	< 0,030	16,5 to 18,5	2,00 to 2,50	10,0 to 13,0	
316Ti	X6CrNiMoTi17-12-2	1.4571	< 0,08	16,5 to 18,5	2,00 to 2,50	10,5 to 13,5	Ti:5xC to 0,70

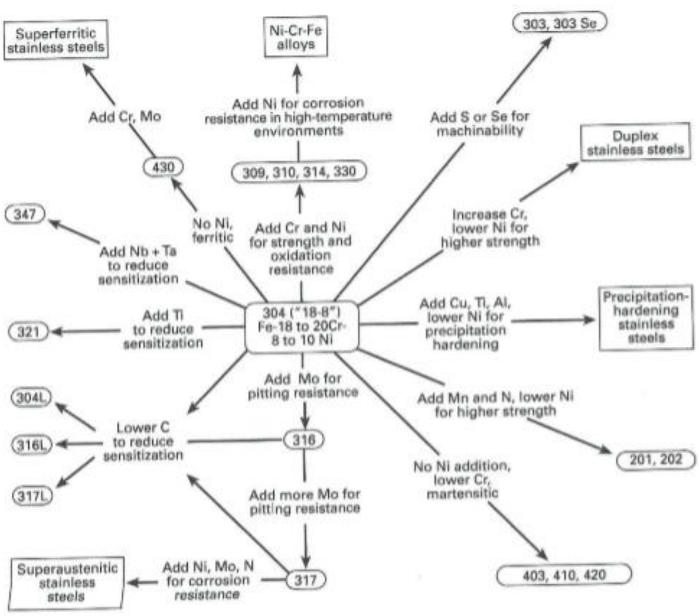


Figure 1.8 The family of stainless steels

1.3.-Applications

Stainless steels are rolled into sheets, plates, bars, wire, and tubing to be used in: cookware, cutlery, surgical instruments, major appliances; construction material in large buildings, such as the Chrysler Building.

Industrial equipment (for example, in paper mills, chemical plants, water treatment); and storage tanks and tankers for chemicals and food products (for example, chemical tankers and road tankers).

Stainless steel's corrosion resistance, the ease with which it can be steam cleaned and sterilized, and no need for surface coatings has also influenced its use in commercial kitchens and food processing plants.[5]

2. DUPLEX STAINLESS STEEL

2.1.-Introduction

Duplex stainless steels are a family of grades combining good corrosion resistance with high strength and ease of fabrication. Their physical properties are between those of the austenitic and ferritic stainless steels but tend to be closer to those of the ferritics and to carbon steel.

The chloride pitting and crevice corrosion resistance of the duplex stainless steels is a function of chromium, molybdenum, and nitrogen content. They all provide significantly greater strength than the austenitic grades while exhibiting good ductility and toughness.

All the duplex stainless steels have chloride stress corrosion cracking resistance significantly greater than that of the 300-series austenitics

Figure 2.1 Chemical Processing Plant of duplex stainless steel

There are many similarities in the fabrication of austenitic and duplex stainless steels but there are important differences. The high alloy content and the high strength of the duplex grades require some changes in fabrication practice [1]

2.2.-History

Duplex stainless steels, meaning those with a mixed microstructure of about equal proportions of austenite and ferrite, have existed for more than 60 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 reduce the intergranular corrosion problems in the early, high-carbon austenitic stainless steels.

These first-generation duplex stainless steels provided good performance characteristics but had limitations in the as-welded condition. The heat-affected zone (HAZ) of welds had low toughness. These limitations confined the use of the first-generation duplex.

The second-generation duplex stainless steels are defined by their nitrogen alloying. This new commercial development, which began in the late 1970s, coincided with the development of offshore gas and oil fields in the North Sea.

2205 became the workhorse of the second-generation duplex grades and was used extensively for gas gathering line pipe and process applications on offshore platforms. The high strength of those steels allowed for reduced wall thickness and reduced weight on the platforms and provided considerable incentive to the use of these stainless steels [1].

2.3.-Clasification

The development of duplex stainless steels has continued, and modern duplex stainless steels can be divided into three groups:

- lean duplex such as 2304, which contains no deliberate Mo addition.
- 2205, the work-horse grade accounting for more than 80% of duplex use.
- 25 Cr duplex such as Alloy 255 and DP-3.

Table 2.1. Different types of duplex stainless steels

Name	UNS No.	EN	C	Cr	Ni	Mo	N	Cu	W
Wrought Duplex Stainless Steels									
First-Generation Duplex Grades									
329	S32900	1.4460	0.08	23.0-28.0	2.5-5.0	1.0-2.0	**	–	–
3RE60 ***	S31500	1.4417	0.030	18.0-19.0	4.3-5.2	2.50-3.00	0.05-0.1	–	–
Uranus 50	S32404		0.04	20.5-22.5	5.5-8.5	2.0-3.0	–	1.00-2.00	–
Second-Generation Duplex Grades									
2304	S32304	1.4362	0.030	21.5-24.5	3.0-5.5	0.05-0.60	0.05-0.20	–	–
2205	S31803	1.4462	0.030	21.0-23.0	4.5-6.5	2.5-3.5	0.08-0.20	–	–
2205	S32205	1.4462	0.030	22.0-23.0	4.5-6.5	3.0-3.5	0.14-0.20	–	–
DP-3	S31260		0.03	24.0-26.0	5.5-7.5	5.5-7.5	0.10-0.30	0.20-0.80	0.10-0.50
UR 52N+	S32520	1.4507	0.030	24.0-26.0	5.5-8.0	3.0-5.0	0.20-0.35	0.50-3.00	–
255	S32550	1.4507	0.04	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.50-2.50	–
DP-3W	S39274		0.03	24.0-26.0	6.8-8.0	2.5-3.5	0.24-0.32	0.20-0.80	1.50-2.50
2507	S32750	1.4410	0.030	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32	0.50	–
Zeron 100	S32760	1.4501	0.030	24.0-26.0	6.0-8.0	3.0-4.0	0.20-0.30	0.50-1.00	0.50-1.00
Wrought Austenitic Stainless Steels									
304L	S30403	1.4307	0.030	18.0-20.0	8.0-12.0	–	0.10	–	–
316L	S31603	1.4404	0.030	16.0-18.0	10.0-14.0	2.0-3.0	0.10	–	–
317L	S31703	1.4438	0.030	18.0-20.0	11.0-15.0	3.0-4.0	0.10	–	–
317LMN	S31726	1.4439	0.030	17.0-20.0	13.5-17.5	4.0-5.0	0.10-0.20	–	–
904L	N08904	1.4539	0.020	19.0-23.0	23.0-28.0	4.0-5.0	0.10	1.0-2.0	–
254 SMO	S31254	1.4547	0.020	19.5-20.5	17.5-18.5	6.0-6.5	0.18-0.22	0.50-1.00	–
6%Mo	Various	Various	0.030	19.5-22.0	17.5-25.5	6.0-7.0	0.18-0.25	1.00	–
Cast Duplex Stainless Steels									
CD4MCuN Grade 1B	J93372		0.04	24.5-26.5	4.4-6.0	1.7-2.3	0.10-0.25	2.7-3.3	–
CD3MN Cast 2205 Grade 4A	J92205		0.03	21.0-23.5	4.5-6.5	2.5-3.5	0.10-0.30	–	–
CE3MN Atlas 958 Cast 2507 Grade 5A	J93404	1.4463	0.03	24.0-26.0	6.0-8.0	4.0-5.0	0.10-0.30	–	–
CD3MWCuN Cast Zeron 100 Grade 6A	J93380		0.03	24.0-26.0	6.5-8.5	3.0-4.0	0.20-0.30	0.5-1.0	0.5-1.0

2.4.-Chemical Composition of Duplex Stainless Steels

Duplex stainless steels are most commonly considered to have roughly equal amounts of ferrite and austenite, with current commercial production just slightly favouring the austenite for best toughness and processing characteristics.

Figure 2.2 Duplex structure seen from the microscope

The interactions of the major alloying elements, particularly the chromium, molybdenum, nitrogen, and nickel, are quite complex. To achieve a stable duplex structure that responds well to processing and fabrication, care must be taken to obtain the correct level of each of these elements.

There is a second major concern with duplex stainless steels and their chemical composition: the formation of detrimental intermetallic phases at elevated temperatures.

Sigma and chi phases form in high chromium, high molybdenum stainless steels and precipitate preferentially in the ferrite. The addition of nitrogen significantly delays formation of these phases. Therefore, it is critical that sufficient nitrogen be present in solid solution. [1]

The effect of the most important alloying elements on the mechanical, physical and corrosion properties of duplex stainless steels:

- Chromium
- Molybdenum
- Nitrogen
- Nickel

Chromium

A minimum of about 10.5% chromium is necessary to form a stable chromium passive film that is sufficient to protect a steel against mild atmospheric corrosion. The corrosion resistance of a stainless steel increases with increasing chromium content.

Chromium is a ferrite former, meaning that the addition of chromium stabilizes the body-centered cubic structure of iron. At higher chromium content, more nickel is necessary to form an austenitic or duplex (austenitic-ferritic) structure.[6]

Molybdenum

Molybdenum acts to support chromium in providing chloride corrosion resistance to stainless steels. When the chromium content of a stainless steel is at least 18%, additions of molybdenum become about three times as effective as chromium additions against pitting and crevice corrosion in chloride-containing environments. It is usually restricted to less than about 7.5% in austenitic stainless steels and 4% in duplex stainless steels.[6]

Nitrogen

Nitrogen increases the pitting and crevice corrosion resistance of austenitic and duplex stainless steels. It also substantially increases their strength and, in fact, it is the most effective solid solution strengthening element. Because of their higher strength, the nitrogen-enhanced austenitic and duplex stainless steels also have increased toughness.

Nitrogen delays the formation of intermetallic phases enough to permit processing and fabrication of the duplex grades. Nitrogen is added to highly corrosion resistant austenitic and duplex stainless steels that contain high chromium and molybdenum contents to offset their tendency to form sigma phase.[6]

Nickel

Nickel is an austenite stabilizer. That means that the addition of nickel to iron-based alloys promotes a change of the crystal structure of stainless steel from body-centered cubic (ferritic) to face-centered cubic (austenitic).

Ferritic stainless steels contain little or no nickel, duplex stainless steels contain an intermediate amount of nickel such as 4 to 7%, and austenitic stainless steels, contain at least 8% nickel. Its presence in about half of the microstructure of duplex grades greatly increases their toughness relative to ferritic stainless steels.[6]

2.5.-Metallurgy of Duplex Stainless Steel

The iron-chromium-nickel ternary phase diagram is a roadmap of the metallurgical behavior of the duplex stainless steels.

A section through the ternary at 68% iron illustrates that these alloys solidify as ferrite, some of which then transforms to austenite as the temperature falls to about 1000°C (1832°F) depending on alloy composition.

There is little further change in the equilibrium ferrite–austenite balance at lower temperatures

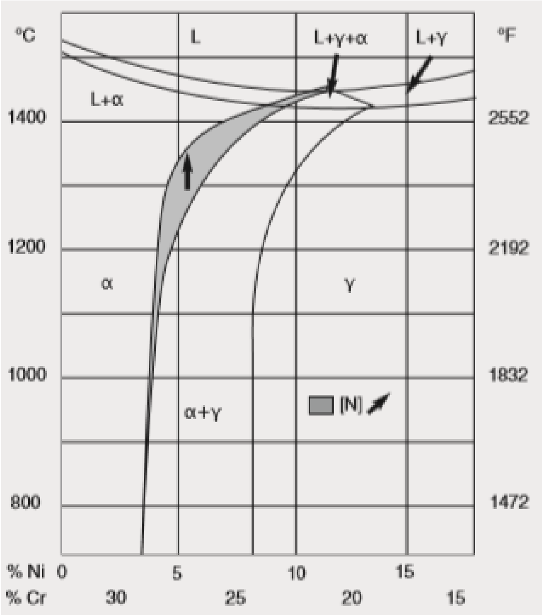


Figure 2.3 Section through the Fe-Cr-Ni Ternary Phase Diagram at 68% Iron

The effect of increasing nitrogen is also shown in the next graphic. Thermodynamically, because the austenite is forming from the ferrite, it is impossible for the alloy to go past the equilibrium level of austenite.

The relative amounts of ferrite and austenite in the material produced or manufactured depend on the composition and thermal history of the steel. The balance of the ferrite/austenite phases in the microstructure can be predicted with mutivariable linear regression in the following way:

$$Cr_{eq} = \%\ Cr + 1{,}73\ \%\ Si + 0{,}88\ \%\ Mo$$

$$Ni_{eq} = \%\ Ni + 24{,}55\ \%\ C + 21{,}75\ \%\ N + 0{,}4\ \%\ Cu$$

$$\%\ Ferrite = -20{,}93 + 4{,}01\ Cr_{eq} - 5{,}6\ Ni_{eq} + 0{,}016\ T$$

An isothermal precipitation diagram for 2304, 2205, and 2507 duplex stainless steels.

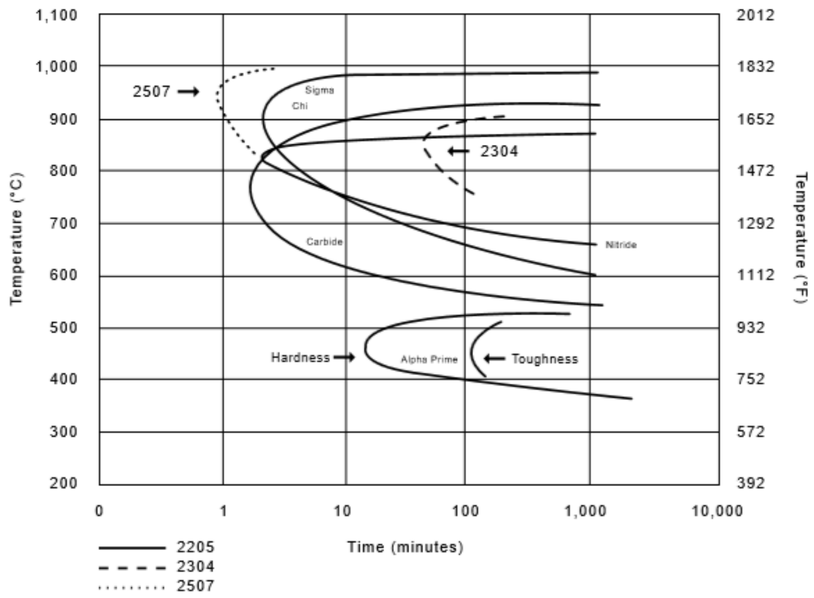


Figure 2.4. Isothermal precipitation diagram

The start of chromium carbide and nitride precipitation begins at the relatively “slow” time of 1-2 minutes at temperature. This is slower than in the ferritic grades or the highly alloyed austenitic grades.

The carbide and nitride formation kinetics are only marginally affected by chromium, molybdenum, and nickel in these grades, so all the nitrogen-alloyed duplex stainless steel grades have kinetics similar to 2205 in regard to these precipitates.

Duplex grades that are more highlyalloyed in chromium, molybdenum, and nickel will have more rapid sigma and chi kinetics than 2205; those with lower alloy content are slower. This is illustrated by the dashed curves in the graphic showing an earlier start of sigma and chi formation in the more highly alloyed 2507 and a slower start for 2304.

Alpha prime precipitates within the ferrite phase, and its effects are to harden and embrittle the ferrite. Fortunately, because duplex stainless steels contain 50% austenite, this hardening and embrittling effect is not nearly as detrimental as it is in fully ferritic steels.

Because long-term, elevated temperature exposure can result in loss of ambient temperature toughness, pressure vessel design codes have established upper temperature limits for the maximum allowable design stresses. [1]

Table 2.2 Upper temperature limits for duplex stainless steel for maximum allowable stress values in pressure vessel

Grade	Condition	ASME		TüV	
		°C	°F	°C	°F
2304	Unwelded	315	600	300	570
2304	Welded, matching filler	315	600	300	570
2304	Welded with 2205/2209	315	600	250	480
2205	Unwelded	315	600	280	535
2205	Welded	315	600	250	480
2507	Seamless tubes	315	600	250	480
Alloy 255	Welded or unwelded	315	600	–	–

2.6.-Corrosion Resistance

Duplex stainless steels exhibit a high level of corrosion resistance in most environments where the standard austenitic grades are useful. However, there are some notable exceptions where they are decidedly superior.

This results from their high chromium content, which is beneficial in oxidizing acids, along with sufficient molybdenum and nickel to provide resistance in mildly reducing acid environments.

The relatively high chromium, molybdenum and nitrogen also give them very good resistance to chloride pitting and crevice corrosion. Their duplex structure is an advantage in potential chloride stress corrosion cracking environments.

If the microstructure contains at least twenty-five or thirty percent ferrite, duplex stainless steels are far more resistant to chloride stress corrosion cracking than Types 304 or 316. Ferrite is, however, susceptible to hydrogen embrittlement. [12] [1]

2.6.1.-Resistance to acids

To illustrate the corrosion resistance of duplex stainless steels in strong acids, the next graphic provides corrosion data for sulfuric acid solutions. This environment ranges from oxidizing at low acidconcentrations, to mildly reducing at high concentrations, with a strongly reducing middle composition range in warm and hot solutions.

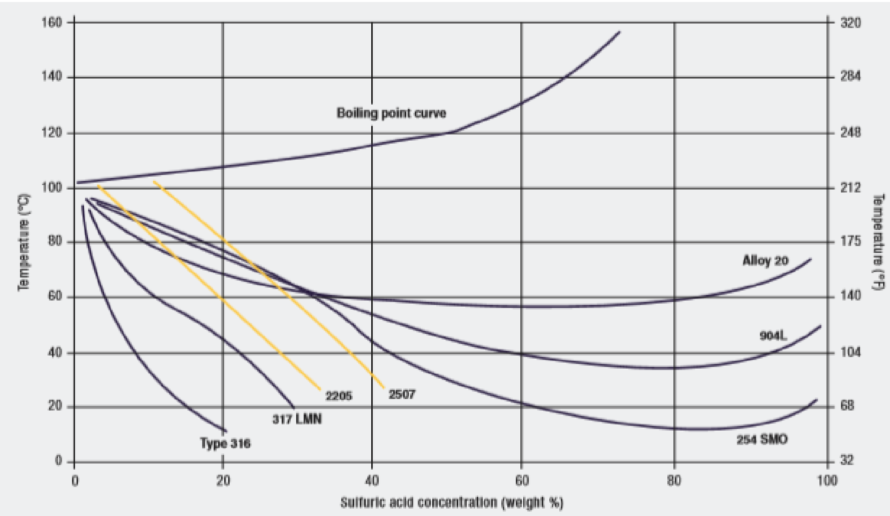


Figure 2.5 Duplex stainless steels in the presence of strong acids

Both 2205 and 2507 duplex stainless steels outperform many high nickel austenitic stainless steels in solutions containing up to about 15% acid. They are better than Types 316 or 317 through at least 40% acid. The duplex grades can also be very useful in acids of this kind containing chlorides or oxidizing constituents.

Their resistance to oxidizing conditions makes duplex stainless steels good candidates for nitric acid service and the strong organic acids for solutions containing 50% acetic acid and varying amounts of formic acid at their boiling temperatures.

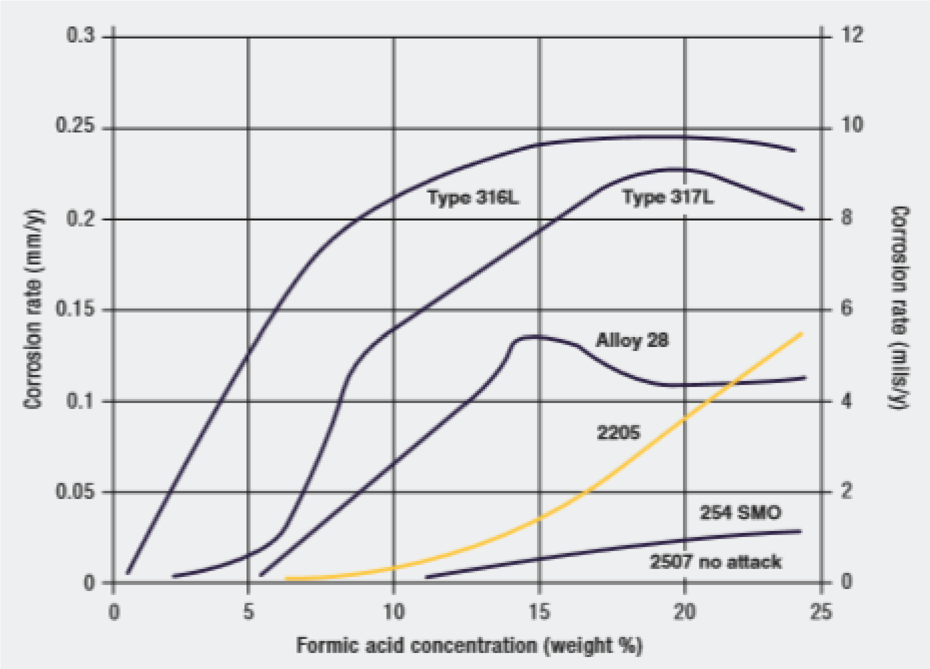


Figure 2.6 Corrosion of duplex and austenitic stainless steels in boiling mixtures of 50%

Although Types 304 and 316 will handle these strong organic acids at ambient and moderate temperatures, 2205 and other duplex grades are superior in many processes involving organic acids at high temperature.[1]

2.6.2.-Resistance to caustics

The high chromium content and presence of ferrite provides for good performance of duplex stainless steels in caustic environments. At moderate temperatures, corrosion rates are lower than those of the standard austenitic grades. [1]

2.6.3.-Pitting and Crevice Corrosion Resistance

For a particular chloride environment, each stainless steel can be characterized by a temperature above which pitting corrosion will initiate and propagate to a visibly detectable extent within about 24 hours.

Below this temperature, pitting initiation will not occur in indefinitely long times. This temperature is known as the critical pitting temperature

(CPT). It is a characteristic of the particular piece of stainless steel and the specific environment.

Because pitting initiation is statistically random, and because of the sensitivity of the CPT to minor within-grade variations or withinproduct variations, the CPT is typically expressed for various grades as a range of temperatures.

There is a similar critical temperature for crevice corrosion, called the critical crevice temperature (CCT).The CCT is dependent on the individual sample of stainless steel, the chloride environment, and the nature.

Because of the dependence on the geometry of the crevice and the difficulty of achieving reproducible crevices in practice, there is more scatter for the measurement of CCT than for the CPT. Typically, the CCT will be 15 to 20°C (27 to 36°F) lower than the CPT for the same steel and same corrosion environment. A comparison of pitting and crevice corrosion resistance for a number of stainless steels in the solution annealed condition.[1] [13]

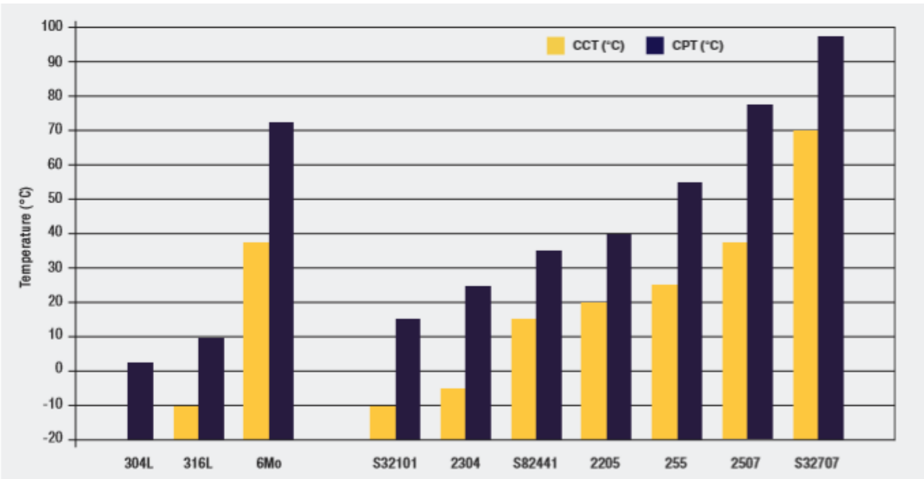


Figure 2.7 Critical pitting and crevice corrosion temperatures for unwelded austenitic stainless steel (left side) and duplex stainless steel (right side) in the solution annealed condition

The result was that only chromium, molybdenum, and nitrogen showed consistent measurable effect on the CPT according to the relationship:

CPT = constant + %Cr + 3.3x%Mo + 16x%N.

2.6.4.-Stress Corrosion Cracking Resistance

Some of the earliest uses of duplex stainless steels were based on their resistance to chloride stress corrosion cracking (SCC). Compared with austenitic stainless steels with similar chloridepitting and crevice corrosion resistance, the duplex stainless steels exhibit significantly better SCC resistance.

However, as with all materials, the duplex stainless steels may be susceptible to stress corrosion cracking under certain conditions. This may occur in high temperature, chloride-containing environments, or when conditions favour hydrogen-induced cracking.

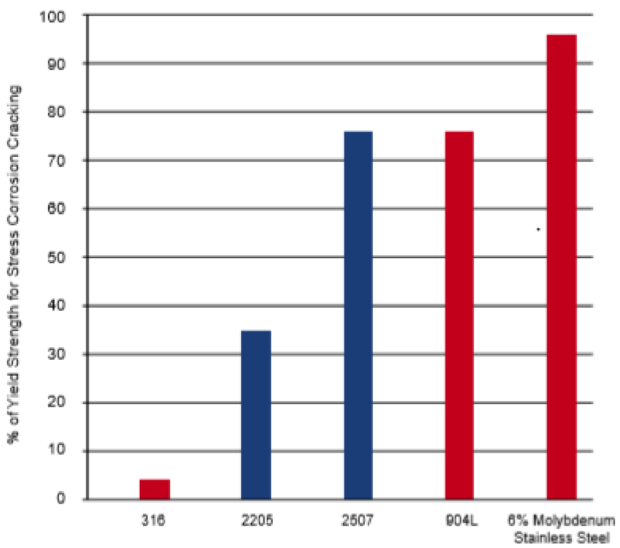


Figure 2.8 Stress Corrosion Cracking Resistance of Mill Annealed Austenitic and Duplex Stainless Steels in the Drop Evaporation Test with Sodium Chloride Solutions at 120°C

The two duplex steels shown, 2205 and 2507, will eventually crack at some fraction of their yield strength in this test, but that fraction is much higher than that of Type 316 stainless steel.

Because of their resistance to SCC in aqueous chloride environments at ambient pressure, for example, under-insulation corrosion, the duplex stainless steels may be considered in chloride cracking environments where Types 304 and 316 have been known to crack. [1]

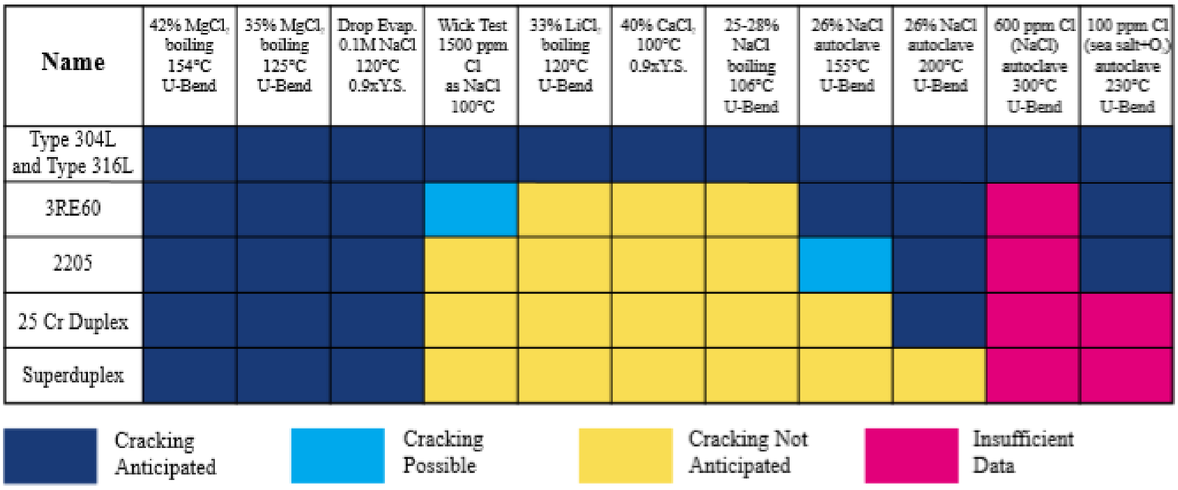


Figure 2.9 Comparative stress corrosion cracking resistance of unwelded duplex and austenitic stainless steels in accelerated laboratory tests

2.7.-Mechanical Properties

Duplex stainless steels have exceptional mechanical properties. Their room temperature yield strength in the solution-annealed condition is more than double that of standard austenitic stainless steels not alloyed with nitrogen. This may allow the design engineer to decrease the wall thickness in some applications.

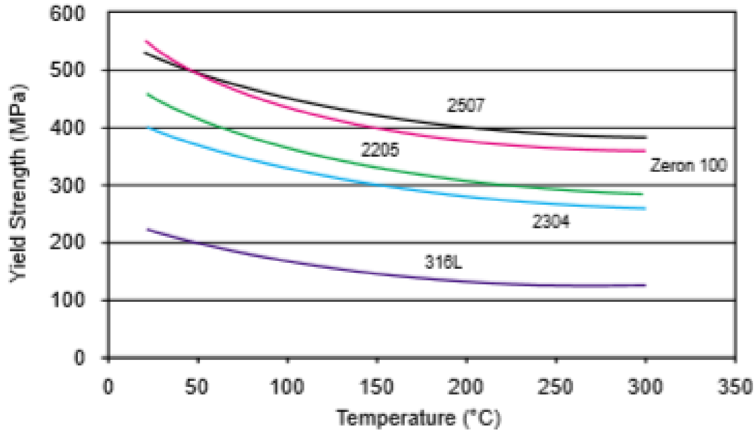


Figure 2.10. Comparison of Typical Yield Strength of Duplex Stainless Steels and Type 316L (austenitic stainless steel)

Duplex stainless steels should not be used in service at temperatures above those allowed. The mechanical properties of wrought duplex stainless steels are highly anisotropic, that is, they may vary depending on the orientation. This anisotropy is caused by the elongated grains and the crystallographic texture that results from hot or cold rolling.

The strength is higher perpendicular to the rolling direction than in the rolling direction. The impact toughness is higher when the crack propagates perpendicularly to the rolling direction than in the rolling direction.

The measured toughness will be higher for a "longitudinal" (L-T) Charpy test specimen than for other test directions. The Charpy pendulum is a pendulum devised by Georges Charpy which is used in tests to determine the tenacity of a material. They are impact tests of a notched specimen and tested to flexion in 3 points. The pendulum falls on the back of the specimen and the part.

The difference between the initial height of the pendulum (h) and the final height after impact (h') makes it possible to measure the energy absorbed in the process of fracturing the specimen. Strictly speaking, the energy absorbed in the area below the load curve is measured, a displacement known as resilience.

The impact energy of a transverse specimen from a duplex stainless steel plate will typically be 1/2 to 2/3 that of a longitudinal specimen.

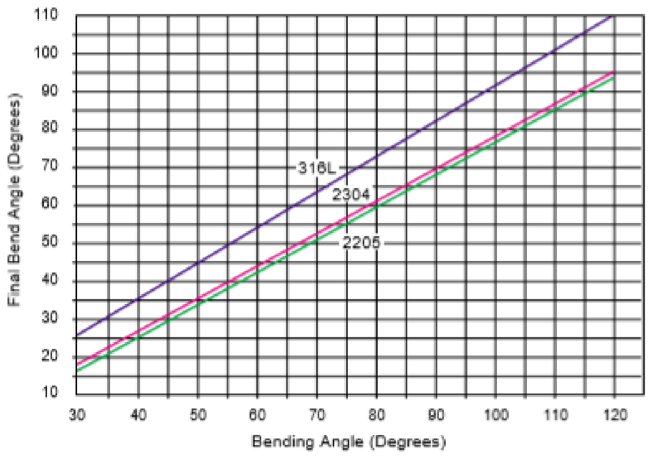


Figure 2.11 Comparison of Springback of Duplex Stainless Steels and Type 316L

Despite the high strength of duplex stainless steels, they exhibit good ductility and toughness. Compared with carbon steel or ferritic stainless steels, the ductile-to-brittle transition is more gradual.

Duplex stainless steels retain good toughness even to low ambient temperatures, for example, -40°C/F; however, ductility and toughness of duplex stainless steels are lower than those ofaustenitic stainless steels.

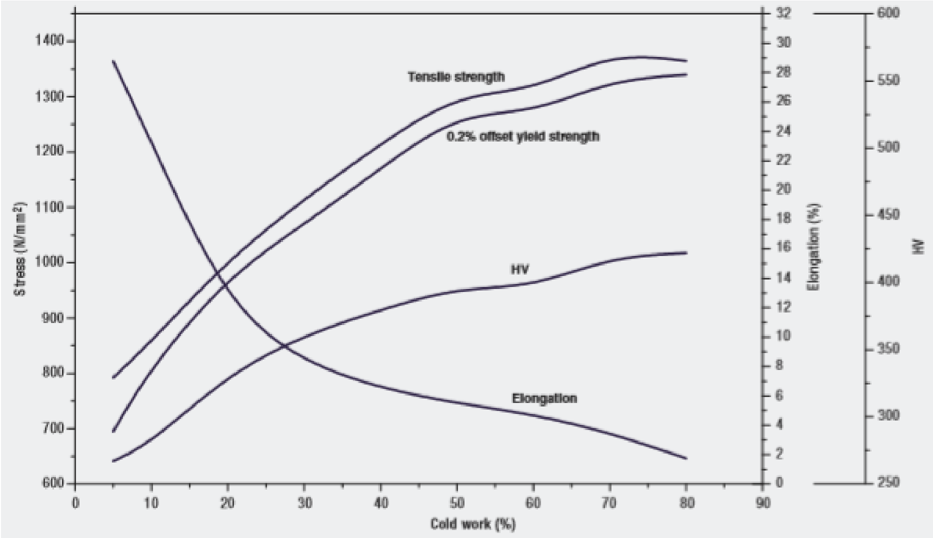


Figure 2.12 Effect of cold work in a duplex stainless steel

It can be clearly seen that at lower temperatures the elongation of the material is reduced and both the hardness and the yield strength are increased.

Because of their higher hardness and the high work hardening rate, duplex stainless steels reduce the tool life in machining operations or require increased machining times compared with standard austenitic grades.

Annealing cycles may be needed between forming or bending operations because the ductility of duplex stainless steels is more quickly exhausted than that of austenitic stainless steels. [1] [14]

2.8.-Physical Properties

Table 2.3 Properties of duplex 2205 on different temperatures

Density/Electrical resistance/Electrical conductivity/Thermal capacity/Electrical resistance

	Densidad lb_m/in^3	Resistencia Eléctrica mW·in	Conductividad Eléctrica (BTU/hr·ft·°F)	Capacidad Térmica BTU/lb_m·°F	Resistencia Eléctrica (in x 10^{-6})
at 68°F	0.278	27.6	**8.7**	**0.112**	33.5
at 212°F		**26.1**	9.2	0.119	35.4
at 392°F		25.4	9.8	0.127	37.4
at 572°F		24.9	**10.4**	**0.134**	39.4

In all cases, differences in physical property values among the duplex grades are very slight and probably reflect differences in test procedures.

The physical properties of the duplex grades all fall between those of the austenitic stainless steels and carbon steels, but tend to be closer to those of the stainless steels. [15]

Table 2.4 The physical properties of the duplex grades.

Name	UNS No.	Density		Specific Heat		Electrical Resistivity		Young's Modulus	
		g/cm³	lb./in³	J/kg°K	Btu/lb./°F	micro ohm-m	micro ohm-in.	GPa	x10⁶ psi
Carbon Steel	G10200	7.64	0.278	447	0.107	0.10	3.9	207	30.0
Type 304	S30400	7.98	0.290	502	0.120	0.73	28.7	193	28.0
Type 316	S31600	7.98	0.290	502	0.120	0.75	29.5	193	28.0
Type 329	S32900	7.70	0.280	460	0.110	0.80	31.5	200	29.0
3RE60	S31500	7.75	0.280	482	0.115	–	–	200	29.0
2304	S32304	7.75	0.280	482	0.115	0.80	31.5	200	29.0
2205	S31803	7.85	0.285	482	0.115	0.80	31.5	200	29.0
DP-3	S31260	7.80	0.281	502	0.120	–	–	200	29.0
UR 47N	S32750	7.85	0.285	480	0.114	0.80	31.5	205	29.7
Ferralium 255	S32550	7.81	0.282	488	0.116	0.84	33.1	210	30.5
DP-3W	S39274	7.80	0.281	502	0.120	–	–	200	29.0
Zeron 100	S32760	7.84	0.281	–	–	0.85	33.5	190	27.6
52N+	S32520	7.85	0.280	450	0.108	0.85	33.5	205	29.7
2507	S32750	7.79	0.280	485	0.115	0.80	31.5	200	29.0

2.9.-Application

Duplex Stainless Steel serves many different applications in these industry categories:

Chemical Process	Water Desalination
Petrochemical	LNG(Liquefied Natural Gas)
Oil & Gas	Biomass
Pharmaceutical	Mining
Geothermal	Utilities
Sea Water	Nuclear and solar power

S31803 - (2205) - The corrosion resistance of 2205 duplex stainless steel is superior to 316L stainless steel used in heat exchangers, gas scrubbers, fans, chemical tanks, marine and refinery applications.

S32304 - (2304) - The corrosion resistance of 2305 duplex stainless steel is similar to 316L stainless steel, with high yield strength, used in the marine, mining, construction, food and energy industries.

S32750 - (2507) - Corrosion resistance is extremely high in harsh marine environments, chloride and acid. [16]

Figure 2.13 Oil installation in a harsh marine environment

2.10.- Superduplex Stainless Steel

Super Duplex stainless like S32750, is a mixed microstructure of austenite and ferrite (50/50) which has improved strength over ferritic and austenitic steel grades.

The main difference is that Super Duplex has a higher molybdenum and chromium content which gives the material greater corrosion resistance than standard duplex grades. The balanced duel phase microstructure combines high strength with cost effective corrosion resistance particularly in high chloride environments.

Super Duplex has the same benefits as its counterpart – it has lower alloying costs when compared with similar ferritic and austenitic grades with equipment corrosion resistance in chloride containing environments due to the material's increased tensile and yield strength. [17] [18]

Table 2.5 MechanicalProperties

Temper	Annealed	
Tensile Rm	115	ksi (min)
Tensile Rm	800	MPa (min)
R.p. 0.2% Yield	80	ksi (min)
R.p. 0.2% Yield	550	MPa (min)
Elongation (2" or 4D gl)	15	% (min)

Table 2.6 Chemical Composition (% by weight)

Element	Min	Max
C	-	0.03
Cr	24	26
Cu	0.5	1
Mn	-	2
Mo	3	5
N	0.24	0.35
Ni	6	8
P	-	0.35
S	-	0.015
Si	-	1

Table 2.7 Physical Properties (Room Temperature)

Specific Heat (0-100°C)	500	J.kg-1.°K-1
Thermal Conductivity	15	W.m -1.°K-1
Thermal Expansion	11	µm/µm/°C
Modulus Elasticity	200	GPa
Electrical Resistivity	8.12	µohm/cm
Density	7.8	g/cm3

Typical Applications:

Subsea control lines
Offshore platforms
Fire-fighting systems
Injection & ballast water systems
Heat exchangers

Industries predominantly using this Grade

Chemical processing
Oil and gas

3. WELDING DUPLEX STAINLESS STEEL

3.1.-Differences Between Duplex and Austenitic Stainless Steel

When there are problems with welding of austenitic stainless steels, the problems are most frequently associated with the weld metal itself, especially the tendency for hot cracking in a fully or predominantly austenitic solidification.

For the more common austenitic stainless steels, adjusting the composition of the filler metal to provide a significant ferrite content minimizes these problems. For the more highly alloyed austenitic stainless steels where the use of a nickel-base filler metal is necessary and austenitic solidification is unavoidable, the problem is managed by low heat input, often requiring many passes to build up the weld.

Because duplex stainless steels have very good hot cracking resistance, hot cracking is rarely a consideration when welding these steels. The problems of most concern in duplex stainless steels are associated with the HAZ, not with the weld metal. The HAZ problems are loss of corrosion resistance, toughness, or post-weld cracking.

To avoid these problems, the welding procedure should focus on minimizing total time at temperature in the “red hot” range 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.

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. [1]

3.1.1.-What is the HAZ?

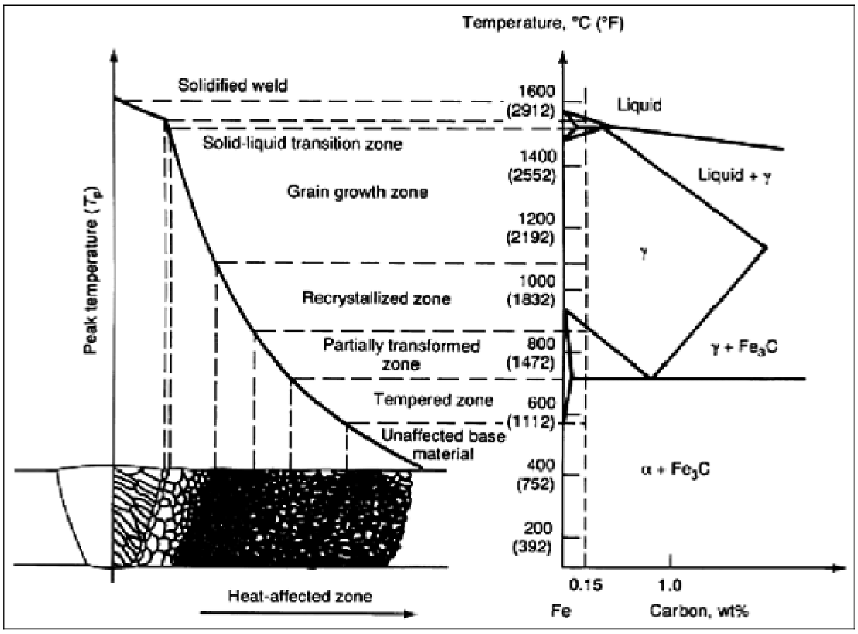


Figure 3.1 The example of HAZ structure for carbon steel containing 0.15% C

The heat-affected zone (HAZ) is the area of base material, either a metal or a thermoplastic, which is not melted but has had its microstructure and properties altered by welding or heat intensive cutting operations.

The heat from the welding process and subsequent re-cooling causes this change from the weld interface to the termination of the sensitizing temperature in the base metal. The extent and magnitude of property change depends primarily on the base material, the weld filler metal, and the amount and concentration of heat input by the welding process. [7] [8]

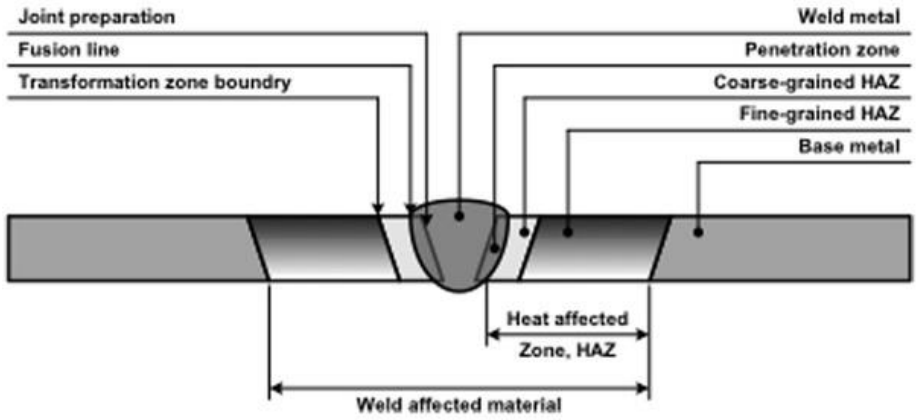


Figure 3.2 The different areas of the welding structure

To calculate the heat input for arc welding procedures, the following formula is used:

$$Q = \left(\frac{V \times I \times 60}{S \times 1000}\right) \times \text{Efficiency}$$

3.2.-Selection of Starting Material

The response of duplex stainless steels to welding may be substantially changed by variations in chemistry or processing. The importance of the base metal containing sufficient nitrogen has been repeatedly emphasized.

If the starting material is cooled slowly through the 705 to 980°C (1300 to 1800°F) range, or if it is allowed to air cool into this range for a minute or so prior to water quenching, then those actions have used up some of the “time on the clock” for the welder to complete the weld without any detrimental precipitation reactions occurring.

It is important that the metallurgical condition of the material used in actual fabrication is the same quality, with regard to composition and production practice, as the material used to qualify the welding procedure.[1][27]

3.3.-Cleaning Before Welding

The key to any good weld is clean metal, but the best way to clean metal before you start welding depends the tools that you have and the overall goal of the project there are a few ways to prep your metal to get a nice clean weld every time.

The best welds come from pure clean metal to metal contact, any foreign materials in the welding area can cause welding imperfections. Even brand new metal must be prepped before it can be welded because there is usually a coating put on new metal so it does not rust or oxidize during the shipping process.

This is a factor that is often overlooked and will always result in a weak and ugly weld. Be mindful, once you remove this coating the metal is exposed to the elements, if left out unprotected steel will begin to rust, even indoors.

To start, the type of welding you are doing will determine how you prep the metal. Inherently MIG welding steel does not need the metal to be perfectly clean.[1][27]

3.4.-Joint Design

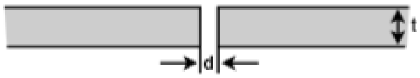
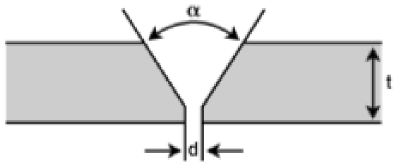
GROOVE	Process	Thickn. th(mm)	GAP d (mm)	ROOT K (mm)	BEVEL α(°)
	GTAW	3 - 5	1 - 3	-	-
	GMAW	3 - 6	1 - 3	-	-
	SMAW	3 - 4	1 - 3	-	-
	SMAW	4 - 15	1 - 3	1 - 2	55 - 65
	GTAW	3 - 8	1 - 3	1 - 2	60 - 70
	GMAW	5 - 12	1 - 3	1 - 2	60 - 70
	SAW	9 - 12	0	5	80

Figure 3.3 Different types of joint design with their properties

For duplex stainless steels, a weld joint design must facilitate full penetration and avoid undiluted base metal in the solidifying weld metal. It is best to machine rather than grind the weld edge preparation to provide uniformity of the land thickness or gap.

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, some of these techniques may cause a longer than expected exposure in the harmful temperature range, leading to results outside of those of the qualified procedure.[1]

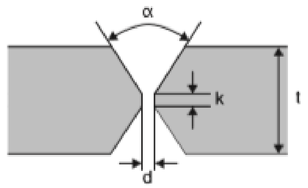
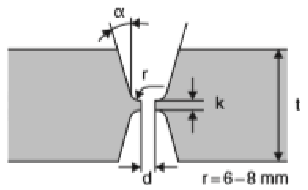
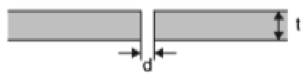
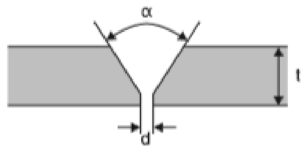
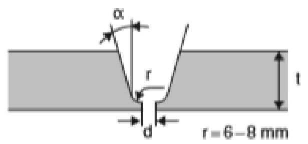
	SMAW	>10	1,5–3	1–3	55–65
	GMAW	>10	1,5–3	1–3	60–70
	SAW	>10	0	3–5	90
	SMAW	>25	1–3	1–3	10–15
	GMAW	>25	1–3	1–3	10–15
	SAW	>25	0	3–5	10–15
	GTAW	>3	0–2	–	–
	GMAW	>3	0–2	–	–
	SMAW	>3	0–2	–	–
	SMAW	3–15	2–3	1–2	60–70
	GTAW	2,5–8	2–3	1–2	60–70
	GMAW	3–12	2–3	1–2	60–70
	SAW	4–12	2–3	1–2	70–80
	SMAW	12–60	1–2	2–3	10–15
	GTAW	>8	1–2	1–2	10–15
	GMAW	>12	1–2	2–3	10–15
	SAW	>10	1–2	1–3	10–15

Figure 3.4 Different types of joint design with their properties

3.5.-Preheating

As a general rule, preheating is not recommended because it may be detrimental. It 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 deal with 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 if the weld is one of those exceptional cases where there is a risk for forming a highly ferritic HAZ because of very rapid quenching. These cases are relatively rare but may involve heavy section plate. [1]

3.6.-Heat Input and Interpass Temperature

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 austenitic weld metals.

Duplex stainless steels, with higher thermal conductivity and lower coefficient of thermal expansion, do not have the same high intensity of local thermal stresses at the welds as austenitic stainless steels.

- Thermal conductivityk= Q * L / A(T2-T1)
- Coefficient of thermal expansion: is a material property that is indicative of the extent to which a material expands upon heating.

While it is necessary to limit the severity of restraint on the weld, hot cracking is not a common problem.Exceedingly low heat input may result in fusion zones and HAZ which are excessively ferritic with a corresponding loss of toughness and corrosion resistance.

Exceedingly high heat input increases the danger of forming intermetallic phases.
To avoid problems in the HAZ, the weld procedure should allow rapid cooling of this region after welding. The temperature of the work piece is important because it provides the largest effect on cooling of the HAZ. As a general guideline, the maximum interpass temperature is limited to 150°C (300°F).

When a large amount of welding is to be performed, planning the welding so there is enough time for cooling between passes is good, economical practice.[1]

3.7.-Postweld Heat Treatment

Postweld stress relief is not needed for duplex stainless steels and is likely to be harmful because the heat treatment may precipitate intermetallic phases or alpha prime (475°C/885°F) embrittlement causing a loss of toughness and corrosion resistance.

Any postweld heat treatment should be a full solution anneal followed by water quenching.[28]

Table 3.1 Annealing temperatures after welding of different types of steels.

Grade	Minimum Annealing Temperature	
	°C	°F
Lean Duplex (2304)	980	1800
2205	1040	1900
25 Cr Duplex	1040	1900
Superduplex (depending on grade)	1050 to 1100	1925 to 2010

3.8.-Desired Phase Balance

The phase balance of duplex stainless steels is often said to be "50-50", equal amounts of austenite and ferrite. However, that is not strictly true because modern duplex stainless steels are balanced to have 40-50% ferrite with the balance being austenite.

It is generally agreed thatchacteristic benefits of duplex stainless steels are achieved when there is at least 25% ferrite with the balance austenite. In some of the welding methods, particularly those relying upon flux shielding, the phase balance has been adjusted toward more austenite to provide improved toughness, offsetting the loss of toughness associated with oxygen pickup from the flux.[1]

3.9.-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.

Table 3.2 The (AWS) electrode designation (E) for different steels.

	2304	2205	25 Cr	Superduplex
2304	2304 E2209 E309L	E2209	E2209	E2209
2205	E2209	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
25 Cr	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
Superduplex	E2209	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N	25Cr-10Ni-4Mo-N
304	E309L E309MoL E2209	E309MoL, E2209	E309MoL, E2209	E309MoL
316	E309MoL E2209	E309MoL, E2209	E309MoL, E2209	E309MoL, E2209
Carbon steel **Low alloy steel**	E309L E309MoL	E309L, E309MoL	E309L, E309MoL	E309L, E309MoL

These examples show the AWS electrode designation (E), but depending on the process, joint geometry and other considerations, bare wire (AWS designation ER) and flux cored wire may be considered.

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.[28]

4. WELDING METHODS

The second-generation duplex stainless steels saw significant commercial development beginning in the early 1980s.

With only limited understanding of the role of nitrogen in delaying the formation of intermetallic phases, the early views of welding focused on limiting heat input.

However, the properties of the duplex stainless steels are so desirable that much effort was directed to learning how to use the more economical processes.

4.1.-Gas Tungsten Arc Welding (GTAW/TIG)

TIG welding or GTAW welding is characterized by the use of a permanent tungsten electrode, sometimes alloyed with thorium or zirconium in percentages not exceeding 2%. Thorium is currently banned as it is highly harmful to health.

Due to the high temperature resistance of tungsten (melts at 3410 °C), accompanied by gas protection, the electrode tip hardly wears out after prolonged use. The most commonly used gases for arc protection in this welding are argon and helium, or mixtures of both. [19]

- EQUIPMENT

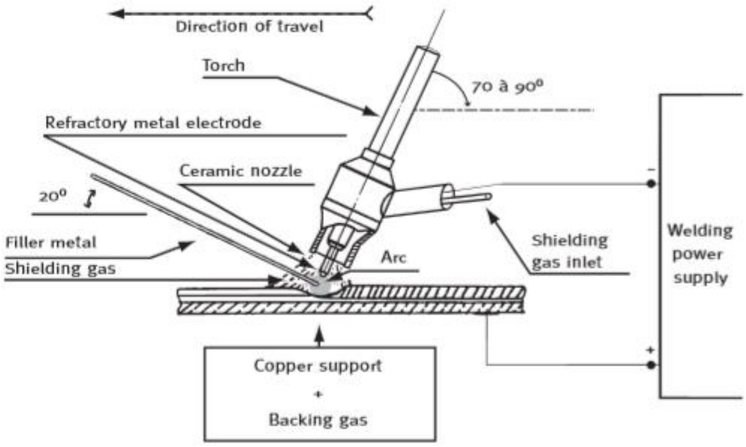


Figure 4.1 Principle of manual gas tungsten-arc welding

-

Power source.

-Mask.

-High frequency unit.

-Torch.

-Protective gas supply.

-Cooling water supply.

- ADVANTAGES

The great advantage of this welding method is, basically, the obtaining of more resistant, more ductile and less sensitive beads to corrosion than in the rest of the procedures, since the protective gas prevents contact between the oxygen in the atmosphere and the melting bath.

Another advantage of arc welding in an inert atmosphere is that it allows clean and uniform welds to be obtained due to the scarcity of fumes and projections; the mobility of the gas surrounding the transparent arc allows the welder to see clearly what he is doing at all times, which has a favourable effect on the quality of the weld.

- DISADVANTAGES

As drawbacks is the need to provide a continuous flow of gas, with the subsequent installation of pipes, cylinders, etc., and the increase in price that this entails.

In addition, this method of welding requires highly skilled labour, which also increases costs.

- APPLICATIONS

First pass welding of alloy steels, stainless steels and nickel alloys.
Welding of aluminium, titanium and nickel alloy equipment.
Welding of tubes to the plate of heat exchangers. [20]

4.2.-Gas Metal Arc Welding (GMAW/MIG-MAG)

MIG/MAG (Metal Inert Gas or Metal Active Gas, depending on the gas to be injected) also called GMAW (Gas Metal Arc Welding) is an arc welding process under protective gas with consumable electrode.

The arc is produced by means of an electrode formed by a continuous wire and the parts to be joined, this being protected from the surrounding atmosphere by an inert gas (MIG welding) or by an active gas (MAG welding).The use of solid and tubular wires has increased the efficiency of this type of welding up to 80%-95%.

MIG/MAG welding is a versatile process, being able to deposit metal at high speed and in all positions. This procedure is widely used in small and medium thicknesses in steel structures and aluminum alloys, especially where a lot of manual work is required.

Metal inert gas welding (MIG) uses a metal electrode that serves as a filler material for welding and is consumed during welding. [19]

- EQUIPMENT

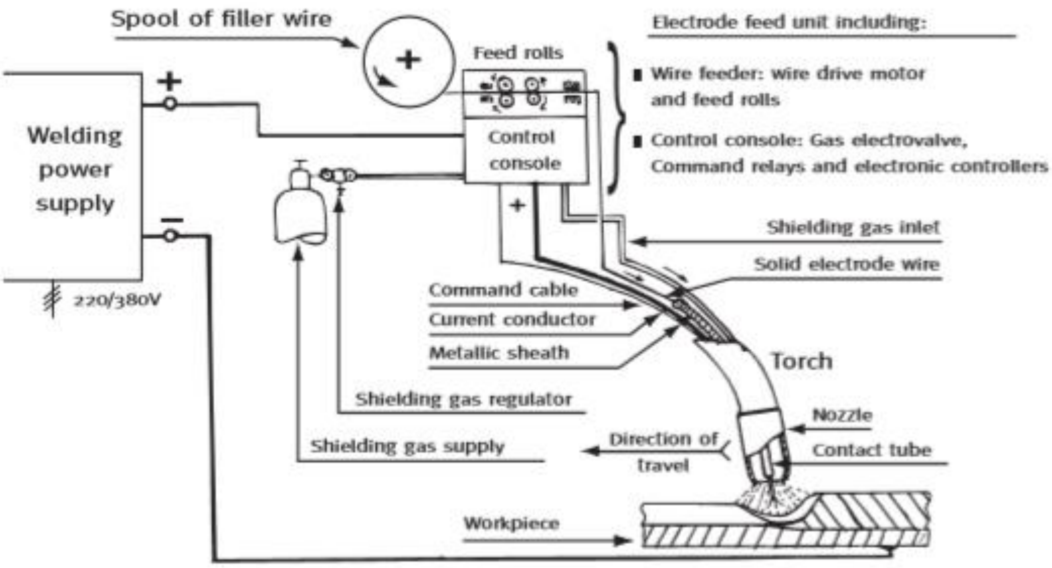


Figure 4.2 Principle of gas metal arc welding

-Transformer
-Rectifier
-Inductance
-Wire feeder unit
-Protective gas circuit
-Welding torch
-Trigger factor

- ADVANTAGES

It can be welded in all positions. Good appearance or finish (few splashes). Low formation of contaminating and toxic gases.

Welding thicknesses from 0.7 to 6 mm without edge preparation.Semi-automatic or automatic process (less dependent on operator skill). High productivity or high rate of added metal.

The main benefits of this process are high productivity and excellent quality; in other words, large amounts of metal can be deposited (three times more than with the coated electrode process) with good quality.

- DISADVANTAGES

Equipment for GMAW is more complex and expensive and less portable than that used in SMAW.

It is difficult to use in hard-to-reach joints. The arc must be protected from air currents. It has an arc of greater radiation and intensity, generates discomfort in the welders.

Between the torch and the power supply there can be no more than 10 m. Limited variety of wires available.

- APPLICATIONS

Employed in industry, manufacture engineering assemblies in overlapping joints of carbon steel, aluminum, magnesium, stainless steel and alloys containing copper. Widely used in the automotive and transport industry.[21]

4.3.-Flux Core Wire Arc Welding (FCW)

Flux-cored arc welding (FCAW or FCA) is a semi-automatic or automatic arc welding process. FCAW requires a continuously-fed consumable tubular electrode containing a flux and a constant-voltage or, less commonly, a constant-current welding power supply.

An externally supplied shielding gas is sometimes used, but often the flux itself is relied upon to generate the necessary protection from the atmosphere, producing both gaseous protection and liquid slag protecting the weld. The process is widely used in construction because of its high welding speed and portability.

FCAW was first developed in the early 1950s as an alternative to shielded metal arc welding (SMAW). The advantage of FCAW over SMAW is that the use of the stick electrodes used in SMAW is unnecessary.[19]

- EQUIPMENT

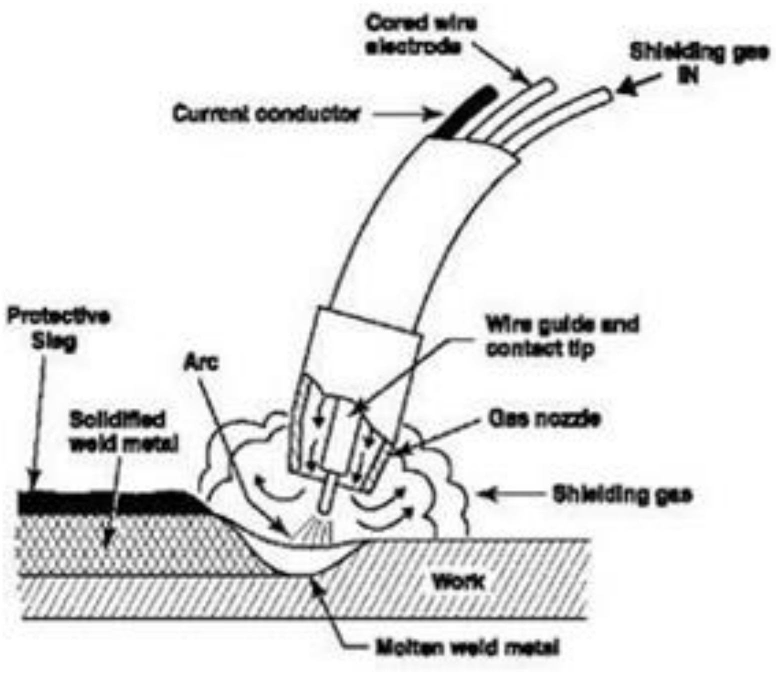


Figure 4.3 Principle of flux core wire arc welding

- ADVANTAGES

FCAW may be an "all-position" process with the right filler metals (the consumable electrode). No shielding gas needed with some wires making it suitable for outdoor welding and/or windy conditions

A high-deposition rate process (speed at which the filler metal is applied). As compared to SMAW and GTAW, there is less skill required for operators.Less precleaning of metal required

Metallurgical benefits from the flux such as the weld metal being protected initially from external factors until the slag is chipped away.

Porosity chances very low. Less equipment required, easier to move around (no gas bottle)

- DISADVANTAGES

Melted contact tip – when the contact tip actually contacts the base metal, fusing the two and melting the hole on the end.Irregular wire feed – typically a mechanical problem.

Porosity – the gases (specifically those from the flux-core) don't escape the welded area before the metal hardens, leaving holes in the welded metal. More costly filler material/wire as compared to GMAW.The amount of smoke generated can far exceed that of SMAW, GMAW, or GTAW.

Changing filler metals requires changing an entire spool. Creates more fumes than SMAW.

- APPLICATIONS

Mild and low alloy steels.
Stainless steels
Some high nickel alloys
Some wearfacing/surfacing alloys
Some "high-speed" (e.g., automotive) applications.[22] [23]

4.4.-Shielded Metal Arc Welding (SMAW/stick electrode)

Shielded metal arc welding (SMAW), also known as manual metal arc welding (MMA or MMAW), is a manual arc welding process that uses a consumable electrode covered with a flux to lay the weld.

An electric current, in the form of either alternating current or direct current from a welding power supply, is used to form an electric arc between the electrode and the metals to be joined. The workpiece and the electrode melts forming a pool of molten metal (weld pool) that cools to form a joint.

As the weld is laid, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielding gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination.

Because of the versatility of the process and the simplicity of its equipment and operation, shielded metal arc welding is one of the world's first and most popular welding processes.[19]

- EQUIPMENT

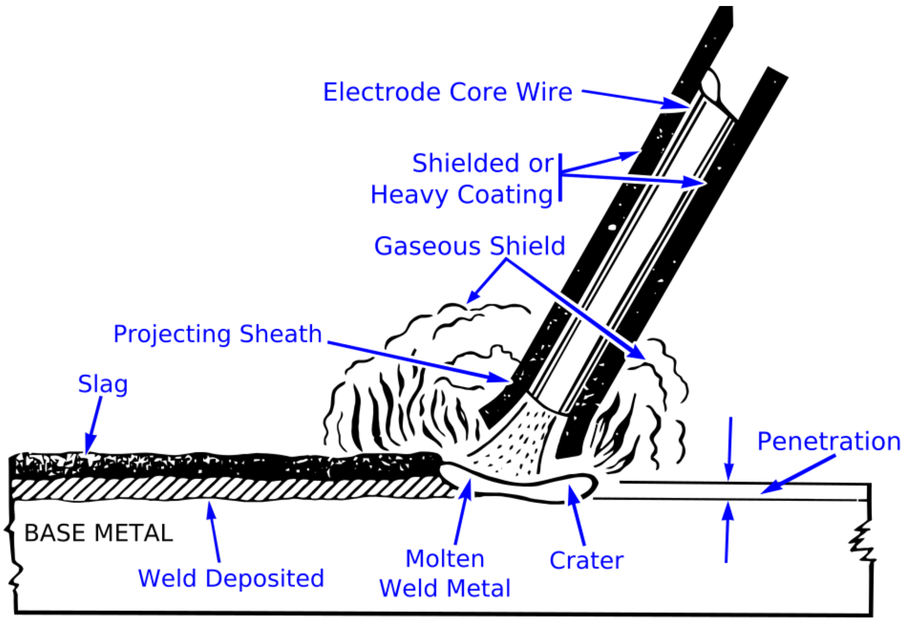


Figure 4.4 Principle of the shielded metal arc welding

-Power supply

-Electrode holder

-Electrode cable and ground cable

-Earth clamp

- ADVANTAGES

Simple, portable and low-cost equipment.

Applicable to a wide variety of metals, welding positions and electrodes.

Has relatively high metal deposition rates.

Suitable for outdoor applications.

- DISADVANTAGES

The process is discontinuous due to the limited length of the electrodes. As it is a manual welding, it requires great expertise on the part of the welder.

The weld may contain slag inclusions.

The fumes make it difficult to control the process.

- APPLICATIONS

Heavy construction, such as in the shipbuilding industry, and field sodadura are largely based on the SMAW process. And although the SMAW process is widely used to weld virtually all steels and many of the non-ferrous alloys, it is mainly used to join steels such as low carbon soft steels, low alloy steels, high strength steels, hardened and tempered steels, high alloy steels, stainless steels and various castings. [24]

The SMAW process is also used to bond nickel and its alloys and, to a lesser extent, copper and its alloys, although it is rarely used to weld aluminium.

4.5.-Submerged Arc Welding (SAW)

Submerged arc welding (SAW) is a common arc welding process. The first patent on the submerged-arc welding (SAW) process was taken out in 1935 and covered an electric arc beneath a bed of granulated flux. Originally developed and patented by Jones, Kennedy and Rothermund, the process requires a continuously fed consumable solid or tubular (metal cored) electrode.

The molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds. When molten, the flux becomes conductive, and provides a current path between the electrode and the work. This thick layer of flux completely covers the molten metal thus preventing spatter and sparks as well as suppressing the intense ultraviolet radiation and fumes that are a part of the shielded metal arc welding (SMAW) process.

SAW is normally operated in the automatic or mechanized mode, however, semi-automatic (hand-held) SAW guns with pressurized or gravity flux feed delivery are available. The process is normally limited to the flat or horizontal-fillet welding positions (although horizontal groove position welds have been done with a special arrangement to support the flux).

Single or multiple (2 to 5) electrode wire variations of the process exist. SAW strip-cladding utilizes a flat strip electrode. DC or AC power can be used, and combinations of DC and AC are common on multiple electrode systems. Constant voltage welding power supplies are most. [19]

- EQUIPMENT

Essential equipment components for SAW are:

-Power source -Flux handling

-SAW head -Protective equipment

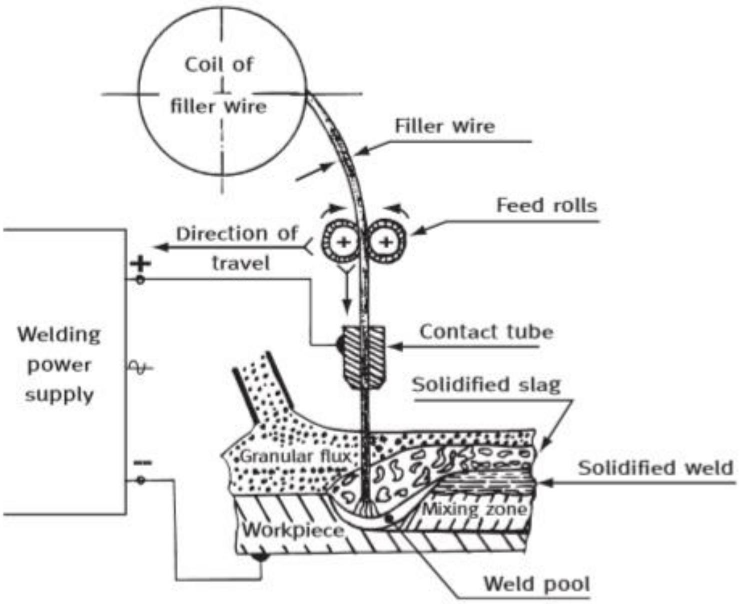


Figure 4.5 Principle of the submerged arc welding process

- ADVANTAGES

High deposition rates. High operating factors in mechanized applications.Deep weld penetration.Sound welds are readily made (with good process design and control).

High speed welding of thin sheet steels up to 5 m/min (16 ft/min) is possible. Minimal welding fume or arc light is emitted.Practically no edge preparation is necessary depending on joint configuration and required penetration.

The process is suitable for both indoor and outdoor works. Welds produced are sound, uniform, ductile, corrosion resistant and have good impact value.Single pass welds can be made in thick plates with normal equipment.

The arc is always covered under a blanket of flux, thus there is no chance of spatter of weld. 50% to 90% of the flux is recoverable, recycled and reused

- DISADVANTAGES

Limited to ferrous (steel or stainless steels) and some nickel-based alloys. Normally limited to long straight seams or rotated pipes or vessels.Requires relatively troublesome flux handling systems.

Flux and slag residue can present a health and safety concern. Requires inter-pass and post weld slag removal.Requires backing strips for proper root penetration.Limited to high thickness materials.

- APPLICATIONS

The automatic submerged arc welding system allows the maximum metal deposition speed, among the systems used in industry, for the production of medium and high thickness pieces (from 5 mm. approx.) that can be positioned to weld in a flat or horizontal position: beams and structural profiles, ponds, gas cylinders, machine bases, shipbuilding, etc.

Chemical industry, boiler, heat exchanger, pressure vessel, pharmacy, construction machinery, military, nuclear power industries. [25]

4.6.-Resistance Welding

Resistance welding is considered a manufacturing process, thermoelectric, is performed by the heating experienced by metals, to forging or melting temperature due to its resistance to the flow of an electric current, is an autogenous type welding that does not involve input material.

The electrodes are applied to the ends of the parts to be welded, they are placed together under pressure and an intense electric current is passed through them for an instant. The union zone of the two pieces, as it is the one that offers greater electrical resistance, is heated and melts the metals, carrying out the welding. The amount of heat required, therefore the intensity applied and time of pressure exerted will depend on the type of metal to be welded. [19]

The main types of resistance welding are as follows:

- Spot welding.
- Welding projections or projections.
- Welding seam.
- Butt welding
- Spark welding
- Isolated thread welding

- EQUIPMENT

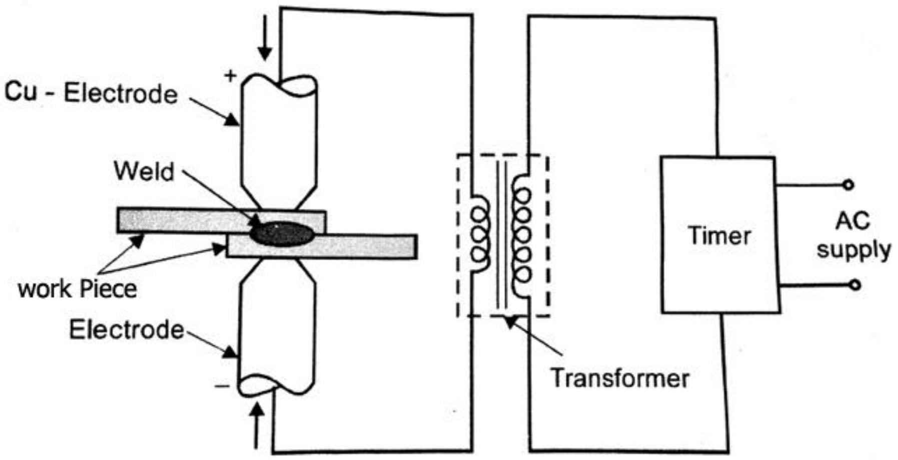


Figure 4.6 Principle of the resistance welding

- ADVANTAGES

It can weld thin (0.1 mm) as well as thick (20mm) metals.

High welding speed.

Easily automated.

Both similar and dissimilar metals can be weld.

The process is simple and fully automated so does not required high skilled labor.

High production rate.

- DISADVANTAGES

High equipmentcost.

The thickness of work piece is limited due to current requirement.

It is less efficient for high conductive materials.

High electric power required.

Weld joints have low tensile and fatigue strength.

- APPLICATIONS

Resistance welding is widely used in automotive industries.

Projection welding is widely used in production of nut and bolt.

Seam welding is used to produce leak prove joint required in small tanks, boilers etc.

Flash welding is used to welding pipes and tubes.[26]

5. EXPERIMENTAL

5.1.-Aim of Experimental work

The aim of this project was to work up butt welding technology of ferritic-austenitic duplex 2205 steel plate using submerged arc welding method (SAW).

The following works and tests have been carried out, which we will see throughout the chapter. The preliminary welding procedure specification (pWPS) as a basis for the practical implementation of the joint.Assessment of the welding technology was verified in tests; macroscopic and microscopic metallographic examinations, hardness tests, assessment of the amount of delta ferrite in the weldmetal and heat affected zone (HAZ) microstructure.

5.2.-Material and Consumables

The plate 15 mm in thickness made of 2205 duplex stainless steel X2CrNiMoCuN22-5-3 acc. to EN 10088-2 (1.4462) steel was used.

Duplex 2205 stainless steel has high properties of general, localized and stress corrosion resistance, as well as high mechanical strength and excellent impact toughness.

Alloy 2205 offers superior pitting and crack corrosion resistance to austenitic 316L or 317L stainless steels in almost all corrosive media. In addition, it has good corrosion and erosion fatigue properties as well as lower thermal expansion and higher thermal conductivity than austenitic stainless steels.

It offers approximately twice the mechanical strength performance of austenitic stainless steels. This allows the designer to save weight and makes the alloy more cost competitive.

The plate was delivered after solution heat treatment from temperature 1100ºC, water cooled.Chemical composition and mechanical properties of the steel plate are presented in Tables 5.1 and 5.2.

Table 5.1 Chemical composition of steel used for welding trials, wt.%

	C	Si	Mn	P	S	Cr	Mo	Ni	N
X2CrNiMoCuN22-5-3 acc. to EN 10088-2	max 0,03	max 1,00	max 2,00	max 0,035	max 0,015	21,0 23,0	2,50 - 3,50	4,50 6,50	0,10 0,22

Acc. To control analysis	0,027	0,41	0,80	0,013	0,001	22,8	3,11	5,33	

In the first row of the table 5.1 shows requirements for the chemical composition of steel, while the second row shows the results of the control analysis of the used plate.

Table 5.2 Mechanical properties of duplex stainless steel plate (producer data)

Stal	TS [MPa]	YP [MPa]	Amin [%]	HBW	KV(T) min [J]
Duplex 2205 (1.4462)	640-840	460	25	290	40

Duplex stainless steel filler metal with increased nickel content relative to the base material was used. The chemical composition of the ϕ3,2 mm ESAB OK. Autrod 16.86 (22Cr9Ni3Mo) wg EN 10204 wire is presented in Table 5.3.

ESAB OK. Flux 10.93 SAW wg EN 760 was used.

Table 5.3 Typical chemistry of weld metal

Material (wire)	C	Si	Mn	Cr	Ni	Mo	Cu	N
ESAB OK. Autrod 16.86	0,02	0,46	1,6	23,0	8,6	3,10	-	0,16

Table 5.4 Typical mechanical properties of weld metal Autrod 16.86

$R_{p0,2}$ (MPa)	R_m (MPa)	Elogation (%)	Impact value, KV [J]		
			-60ºC	-20ºC	20ºC
600	765	28	60	85	100

5.3.-Preparation of Welding Procedure Specification

Two sections of sheets 15 × 150 × 500 mm have been prepared for making one welded joint. The sections were located along the long edge parallel to the rolling direction of the sheets. Welded joint was prepared in accordance with PN-EN ISO 15614-1.

Butt joint was performed using “2Y” edge preparation without any gap. The height of the threshold was 3,0 mm in order to obtain correct dilutions between base and welded metals. The method of preparing the edges for welding is shown in Figure 5.1. The edges of the sheets were milled and cleaned before welding by grinding using an angle grinder. The runway plates panels of 100 mm long were welded to both sides of welded sections (Fig. 5.2, 5.3).

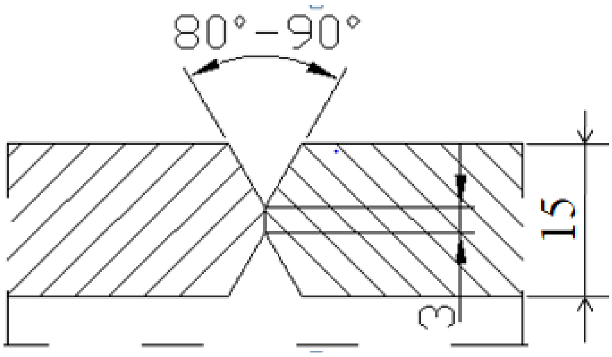


Fig. 5.1. The edge preparation for welded joint

Fig. 5.2.Side view of edge preparation for welded joint

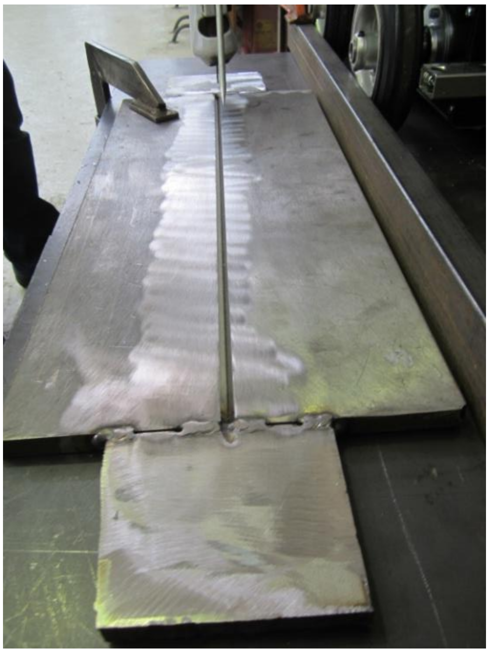


Fig. 5.3. Steel plates before being welded with extra material

121 (SAW) Welding process

This is probably the most widely used process for welding bridge web-to-flange fillet welds and in-line butt welds in thick plate to make up flange and web lengths. The process feeds a continuous wire via a contact tip, where it makes electrical contact with the power from the rectifier, into the weld area, where it arcs and forms a molten pool.

The weld pool is submerged by flux fed from a hopper. The flux immediately covering the molten weld pool melts, forming a slag and protecting the weld during solidification; surplus flux is collected and re-cycled. As the weld cools, the slag freezes and peels away, leaving high quality, good profile welds.

The process is inherently safer than other processes, as the arc is completely covered during welding, hence the term submerged arc. This also means that personal protection requirements are less.

5.4.-Preliminary Welding Procedure Specification

The preliminary welding procedure specification was elaborated before weld preparation. This specification indicates all technical requirements for welding process.

Before welding, technological WPS welding instructions was developed, Fig. 5.4.
The amount of heat input Q is calculated from the relation given in the PN EN 1011 standard:

$$Q = \frac{U \times I}{v_s} \times k$$

k- coefficient of thermal efficiency of the process; k=1,0 for SAW.

The welding parameters and the amount of heat input to the joint in welded joints are summarized in Table 5.5.

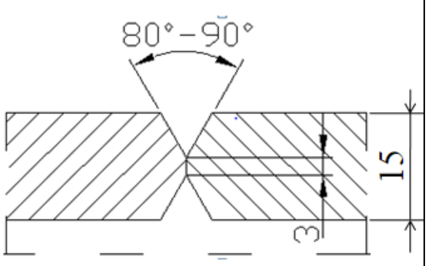
Table 5.5. Applied welding parameters of joints

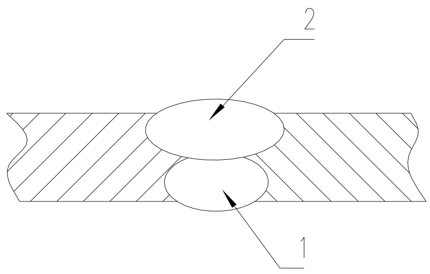
Thickness (mm)	Preparation	Number of passes	Heat input kJ/mm	Side/ pass
15	2Y	2	2,4 3,48	1/1 2/1

PWSZ Elbląg	PRELIMINARY WELDING PROCEDURE PRELIMINARY WELDING PROCEDURE SPECIFICATION pWPS	WPS 121_01

Place: Manual welding technology: **pWPS Nr: 121_01** Manufacture: PWSZ **Elbląg** Welding process: **121 (SAW)** Model of metal transfer: **spray** Joint type: **BW** Joint preparations details	Examiner or examining body: Method of preparation and cleaning*:* **Mechanical cutting or plasma cutting, grind.** Parent material specification**: Material group CR ISO 15608: 10; Materiał wg PN EN 10088-2 X2CrNiMoN22-5-3 (1.4462)** Material thickness[mm]: **15** Outside diameter [mm]: Welding position: **PA**

Joint desing	**Welding sequences**





Detailed welding parameters

Run	Process	Size of fillet metal (mm)	Current (A)	Voltage (V)	Type of current/polarity	Wire feed speed (m/min)	Travel speed vs (cm/min)	Heat input, Q (Kj/mm)
1	121	3,2	460÷500	32	DC (+)	-	38-40	2,4
2	121	3,2	560÷580	33	DC (+)	-	30	3,4

Filler metal, classification, trade name: **121: 3,2 ESAB OK. Autrod 16.86**
Any special baking or drying:
- Gas/flux: **Esab OK. Flux 10.93**
- Shielding*:*
- Penetatios protection: **ceramic, flat**

Gas flow rate:
Shielding gas (protective):
Forming gas:
Tungsten electrode type/size:
Nozzlediameter:
Back gouging/ backing:
Minimum ambient temperature: **5ºC**
Preheat temperature:
Interpass temperature: **100ºC**
Post weld heat treatment:: -
Time, temperature, method: -
*Heating and cooling rate**: -

Other information:
- lay stitches

Oscillation: amplitude, frequency:
Pulse welding details:
Stand-off distance: **15-20 mm**
Plasma welding details:
Torch angle:

Track welding:- track per meter/circum:
- lenght of weld:

Remarks: 1 Clean the edges of thesteel components using extraction naphtha. 2 Keep a constantarc length.

Fig.5.4. Welding procedure specification for test joint

Fig.5.5. ESAB SAW unit used for welding test joint

Fig.5.6.Welding process of test joint

The final dimensions of the welded plate can be seen in figure 5.7 and in figure 5.8 an overview of how the weld looks with the naked eye once the process is finished.

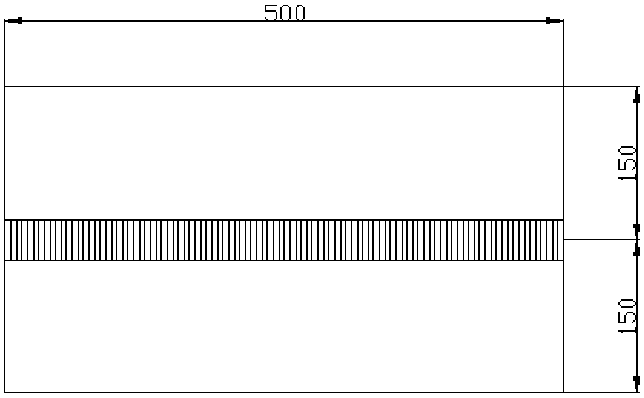


Fig. 5.7 Dimensions of welded plate

Fig. 5.8.General view of welded plate

Each weld was X-rayed and crack tested, and found to be satisfactory with B quality class according to EN 25817.

5.5.-Metallographic Examinations

Welded plates were cut for specimens for metallographic examinations. Preparation of metallographic samples consisted of grinding with sandpaper grit, respectively, 80, 120, 300, 600, 800 and 1.000.

Fig. 5.9.Sandpaper grit 80

Samples for macroscopic examinations were etched in Marble 'a reagent (4g $CuSO_4$, 20 ml HCl, 20 ml H_2O). Macroscopic view of cross section of test plate is presented in figure 5.10.

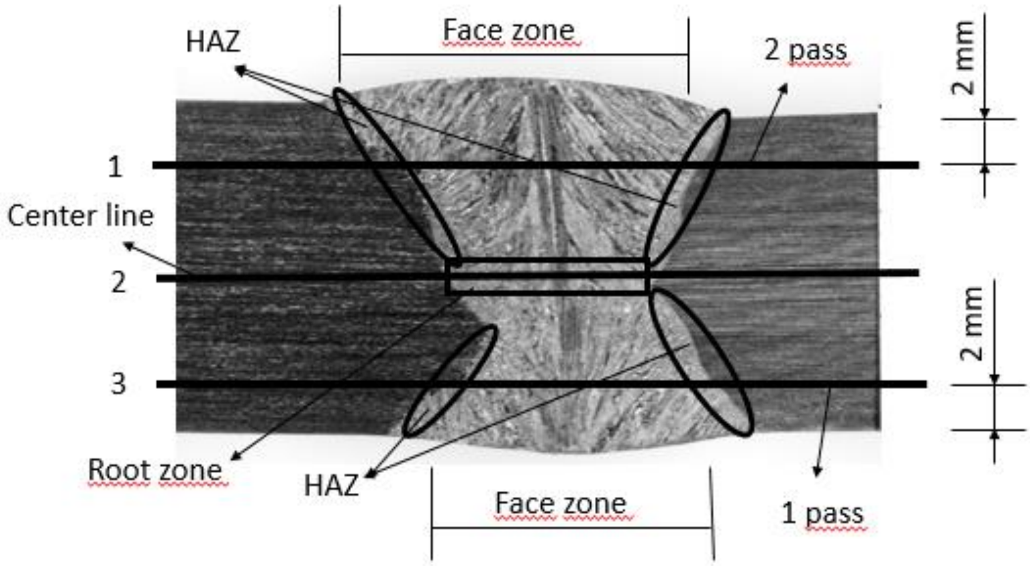


Fig. 5.10 Macroscopic view of cross section with the different parts

The geometry of the weld, the width of the weld in face (both sides) zone is 17 mm. No cracks or other defects have been detected.

For microscopic examinations samples were etched with the use of Berah'a reagent ($HCl + K_2S_2O_4$). Examinations were performed on light microscope Neophot 2.

Fig. 5.11 Neophot 2 light microscope

In the microscopic metallographic examinations three aspects were considered:

- the general microstructure and in particular the presence of secondary austenite presence.
- the width and structure of heat affected zones,
- solidification pattern of weld with special attention to any solidification cracking.

Places of microscope observations of welded joints are shown in Fig 5.12.

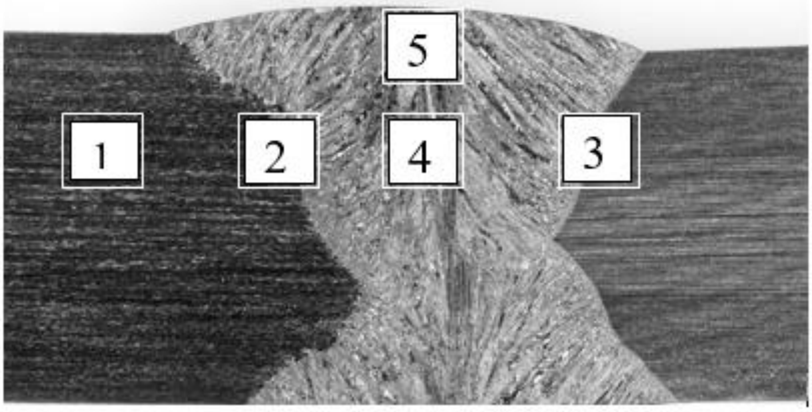


Fig. 5.12 Places of microscope observations of the welded joint

1. Base material
2. HAZ-1 zone
3. HAZ-2 zone
4. Weld metal
5. Weld metal - Face zone
6. Weld metal - Root zone

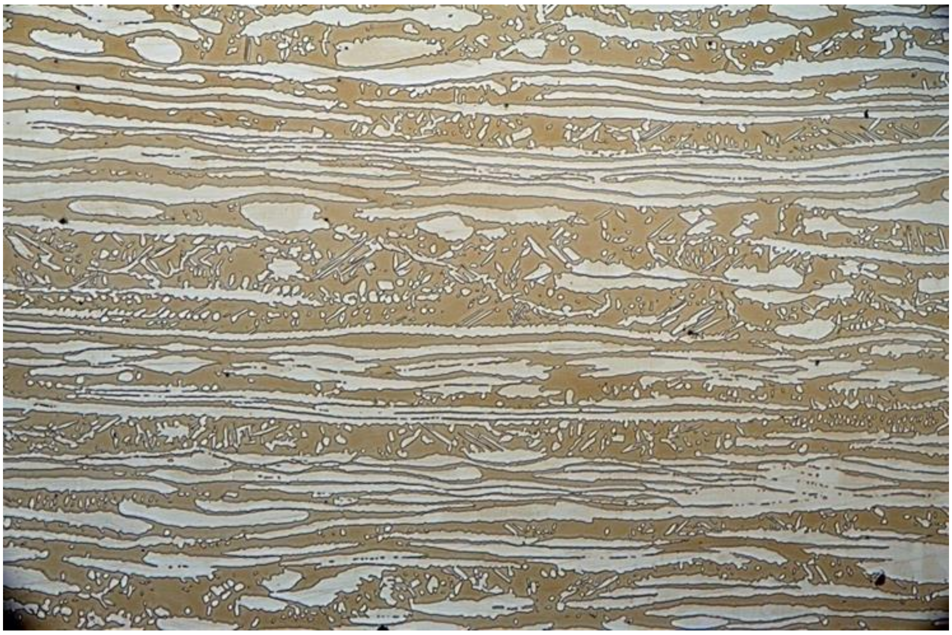
Below are a series of photos taken with the microscope at different magnifications of the welded joint. Hot cracks were not observed in weld metal deposits.

Liquation cracking is in most cases associated with a combination of high restraint and weld structure.Weld metals solidifying partly as ferrite shows high resistance to hot cracks formation.

In the area of the base material (1), a ferritic-austenitic structure with a characteristic band-like structure is visible during the plastic working (rolling) of the sheet,

Fig. 5.13 a), b). The etching reagent used does not fully reveal grain boundaries in ferritic and austenitic areas. The share of both phases is approx. 50%.

a)



b)

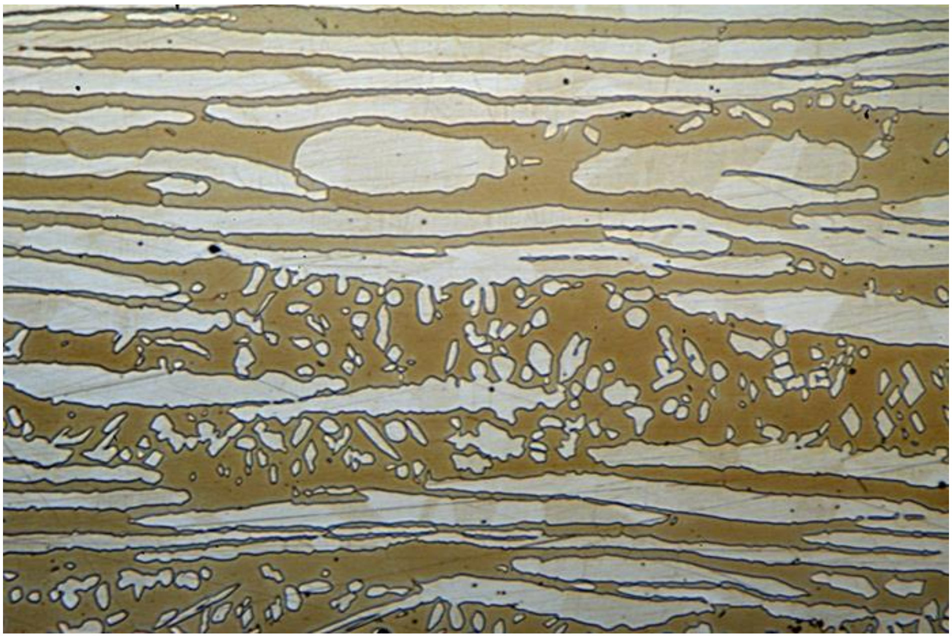
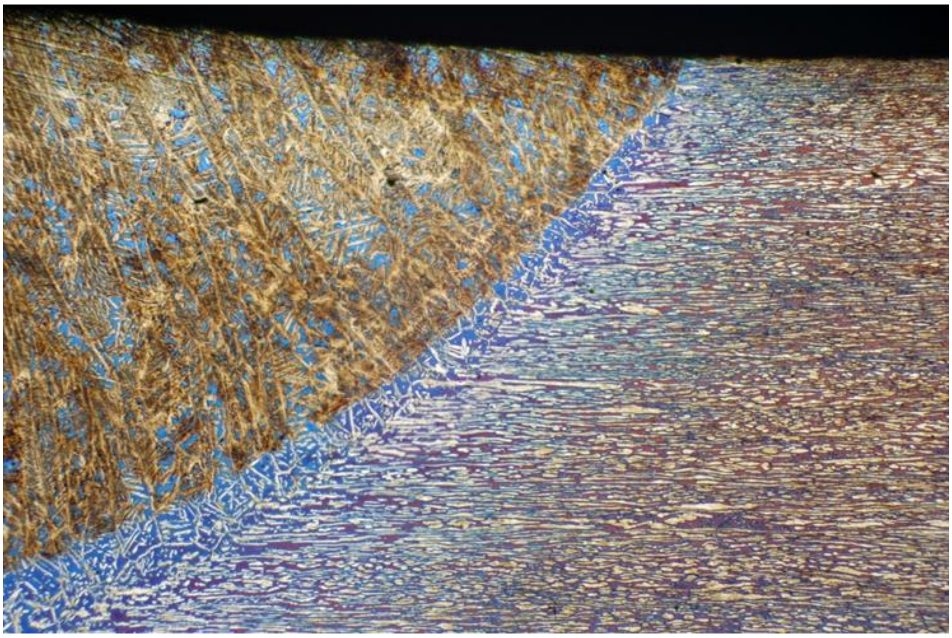


*Fig. 5.13. The structure of the base material of 2205 duplex stainless steel
Magn. a) 100 ×, b) 250 ×*

a)



b)

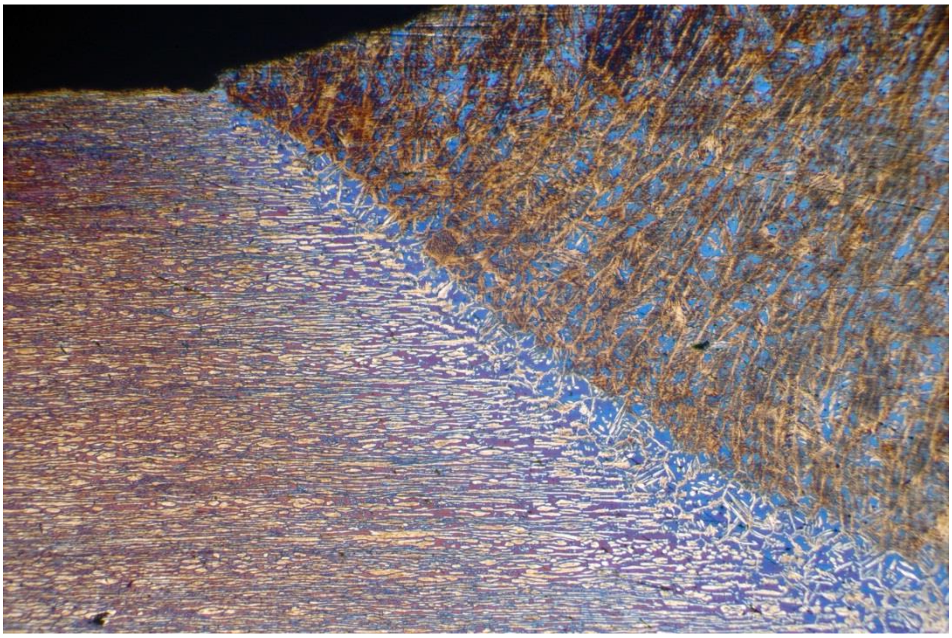
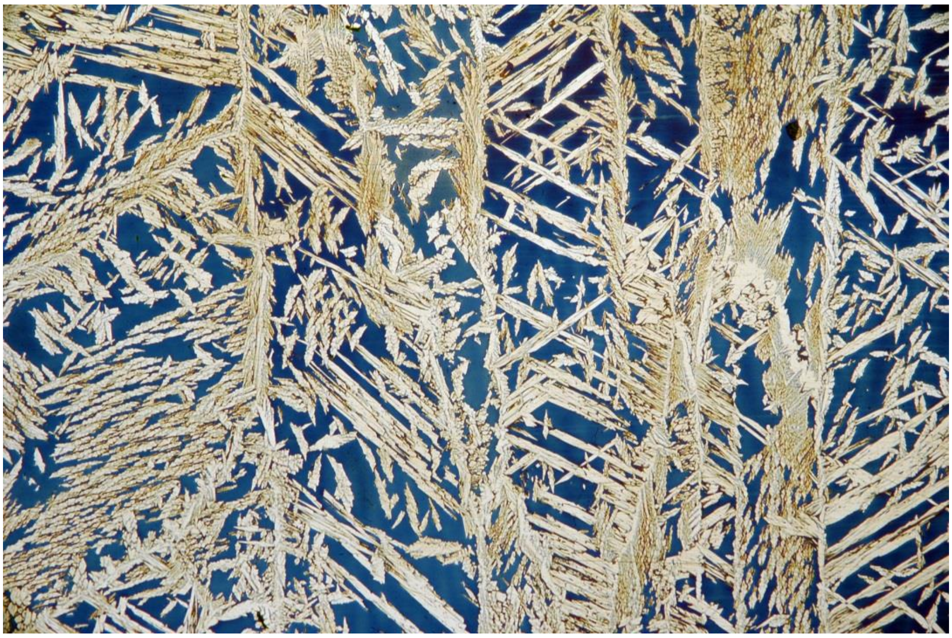


Fig. 5.14. The structure of 1-st pass of welded joint (points 2 and 3) 2205 duplex stainless steel
a) Magn.32 × b) Magn.32 ×

a)

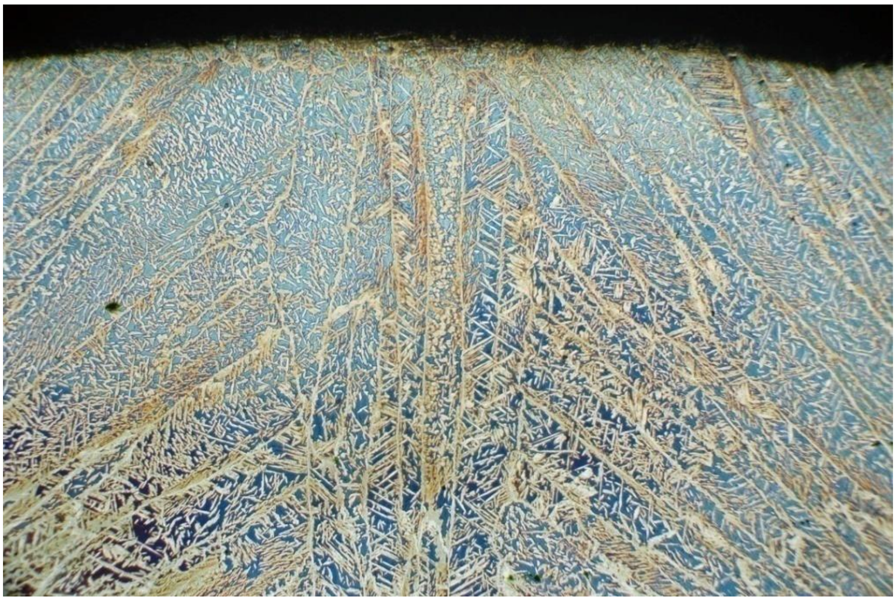


b)

Fig. 5.15.The structure of weld metal (point 4). 2205 duplex stainless steel welded joint. Magn. a) 100 ×, b) 250 ×

Structure of weld metal consists of ferrite (blue) and austenite (bright). During solidification of duplex weld metal an almost completely ferrite structure is formed. Further cooling initiates the formation of the austenite phase nucleating at the ferrite grain boundaries. Dendrite structure of ferrite is visable.

a)



b)

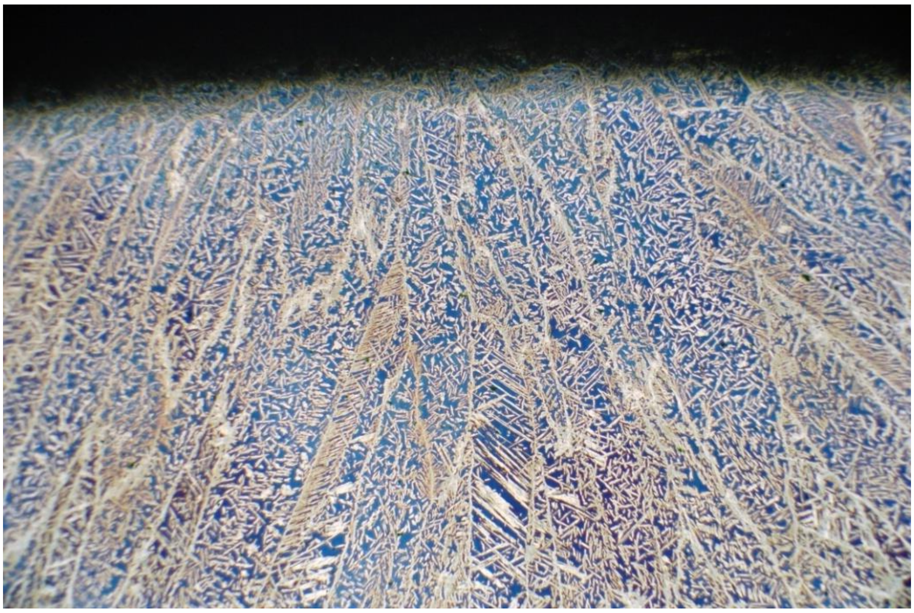
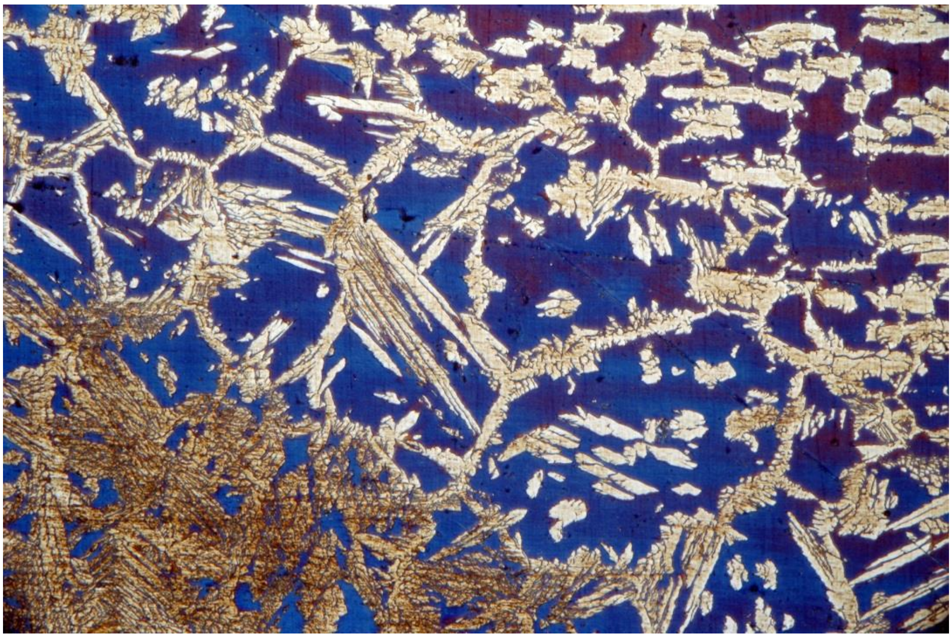


Fig. 5.16.The structure of weld metal (point 5). 2205 duplex stainless steel welded joint. Magn.a) 25 × , b) 25 ×

a)



b)

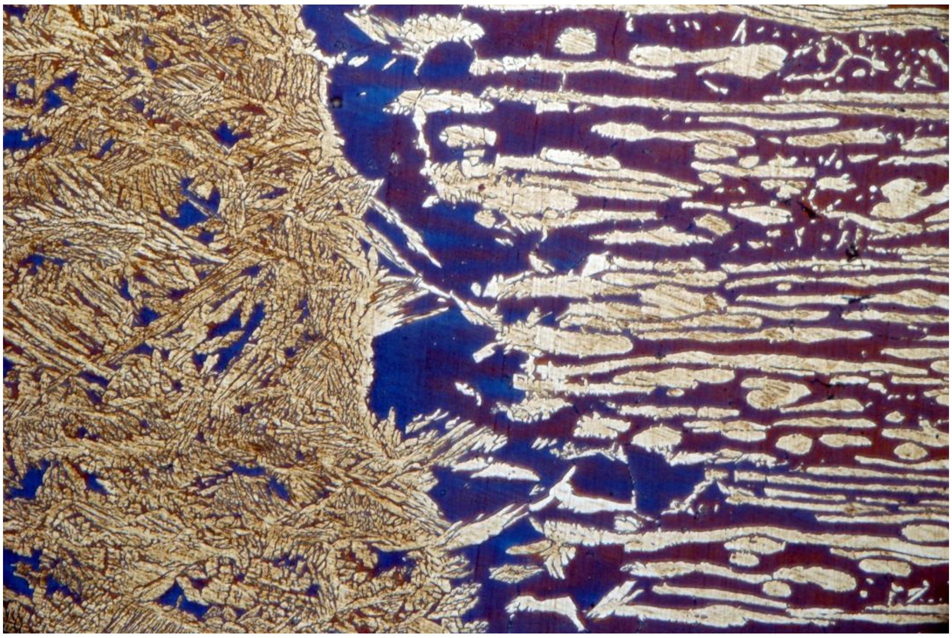


Fig. 5.17.The structure of HAZ (points 2, 3). 2205 duplex stainless steel welded joint. Magn.a) 200 × , b) 100 ×

In the heat affected zone of welded joint, large ferrite grains are visible with a limited number of acicular austenite precipitations. Austenite separations are mainly located on the boundaries of ferrite grains and to a lesser extent inside the ferrite grains. The ferrite grains have grown considerably.

This construction of the HAZ is characteristic of welded duplex steel joints. When the HAZ is heated to a temperature of about 1400ºC, this area obtains an almost completely ferritic structure. During cooling, austenite is evolved, but the process is limited by a short thermal cycle.

As a result, large quantities of ferrite can remain in the couplings in the HAZ, which is undesirable due to the lowering of the mechanical properties and the corrosion resistance of the joints. Heat affected zones are very narrow, and their width varies depending on the position in the joint.

5.6.-HAZ Width Measurements

The width of HAZ (ζ) was measured by drawing a line perpendicular to the melt line and then reading the width of HAZ along this line, fig.

The measurements were made on joint cross-sections in 3 lines: line 1, at a distance of more or less 2 mm from the joint face, line 2, in the middle of the joint thickness, line 3 at a distance of more or less 2 mm from the joint ridge.

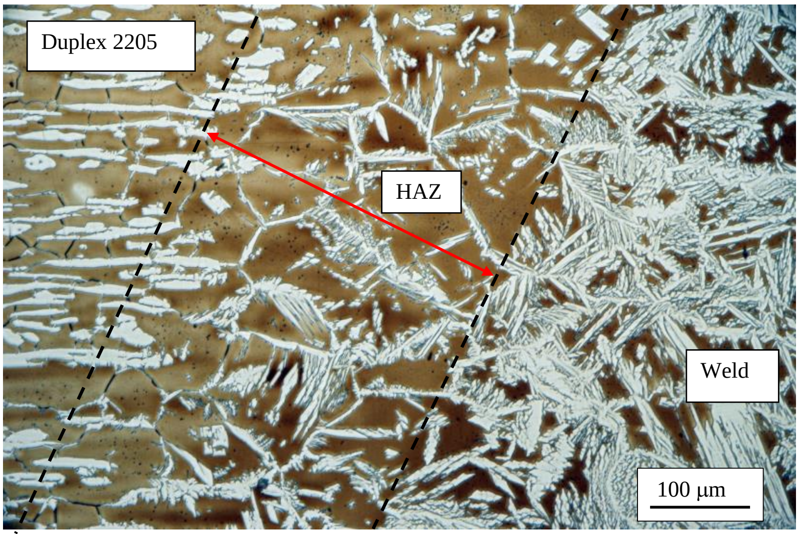


Fig 5.18. HAZ width of the joint

On each of the lines n = 9 measurements were taken, for which an average, standard deviation (s) was determined.

The HAZ width of the tested joint oscillated between 0.105 mm and 0.488 mm, Table 5.6. A larger width of HAZ was found at the face and ridge in relation to the centre of the joint thickness.

Table.5.6 Results of HAZ width measurements of welded duplex steel joints

No line	HAZ width , mm			
	n	$\overline{\zeta}$	s	
Weld1				
1	9	0,210	0,010	
2	9	0,152	0,008	
3	9	0,374	0,012	

5.7.-Ferrite Content Measurements in the Structures of Joint

Measurements of ferrite content were made with the use of metallographic method and magnetic method using a ferritometer manufactured by Fisher MP30 company.

Fig. 5.19 .Ferritometer manufactured by Fisher MP30 company

Portable ferritoscope is used to measure ferrite content in welds, plate layers in austenitic steel and duplex as well as to determine the amount of martensite in austenitic steels. The apparatus uses a method based on the measurement of magnetic induction.

Ferrite content is calculated from the magnetic permeability of the tested material. The results can be given in percent or in ferritic numbers/numbers (FerriteNumber - FN). After calibrating the instrument, the ferrite content on the polished surface of the connector cross-sections was measured using a measuring head.

Table 5.7 shows the percentage share (mean value from 6 measurements) of ferrite volume determined by metallographic method and ferritometer.

Table 5.7 Volumetric share of ferrite in individual areas of welded joints.

Connection area	**Ferrite content (%)**	
	n	**α**
Duplex steel 2205	6	52,2
	Connector 3	
HAZ duplex face	6	67,5
HAZ dúplex measure	6	72,8
HAZ dúplex ridge	6	70,8
Weld face	6	51,2
Weld measure	6	45,9
Weld ridge	6	39,7

In the base material of stainless steel duplex the average amount of ferrite was 52.2%. The SAW welded joints showed an increase in ferrite content in HAZ even above 70%.

Ferrite content in different areas of the welded joint is in the range given by the standard. The largest percentage of the amount of ferrite present in the HAZ is a result of the high cooling rates after heating of this zone to a temperature 1400ºC, where almost same ferrite exists.

Areas of joint, in which there is an excessive amount of ferrite, have low plastic properties and reduced corrosion resistance, so it is important that the ferrite content should not exceed 70% in the steel structure.

5.8.-Hardness Tests

Hardness measurements of welded joints were carried out on samples taken transversely to the weld, on which metallographic inspections were prepared, containing the centrally located cross-section of the weld.

The specimens were etched with Marble's reagent to reveal the melt lines and boundaries of the welding heat affected zone, necessary for the proper distribution of hardness measurement points in the joints.

Hardness measurements of welded joints were performed in accordance with EN ISO 9015-1 standard with HPO-250 hardness tester. The tests were performed by Vickers method according to EN 6507: 2007 at 49 N (HV5) load. The load action time was 15 s.

In the Vickers method penetrator is a diamond pyramid with a base angle of 136°. The following formula is used to determine the number of roughness:

$$HV \approx 0.1891 \frac{F}{d^2} \quad [\mathrm{N/mm^2}]$$

The imprints were taken in three measurement lines passing through the parent material, HAZ and the weld of each specimen. The first line and the third line were 2 mm from the sheet metal surface, the second line was in the middle of the joints.

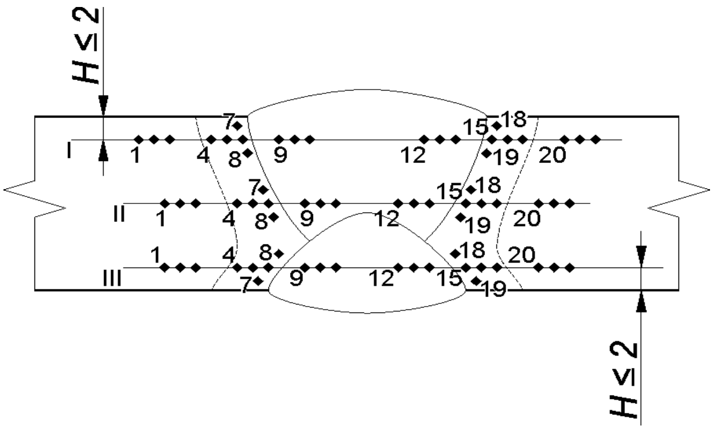


Fig. 5.20 .Positioning of prints in welded join. Measurement line diagram

Due to the very narrow area of the heat affected zone, hardness measurements in this zone were taken on the measuring line and additionally above and below the measuring line.

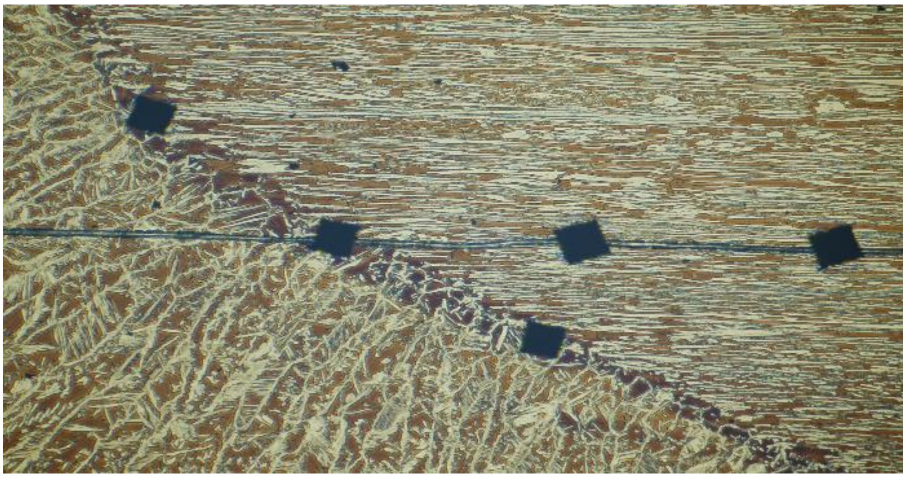
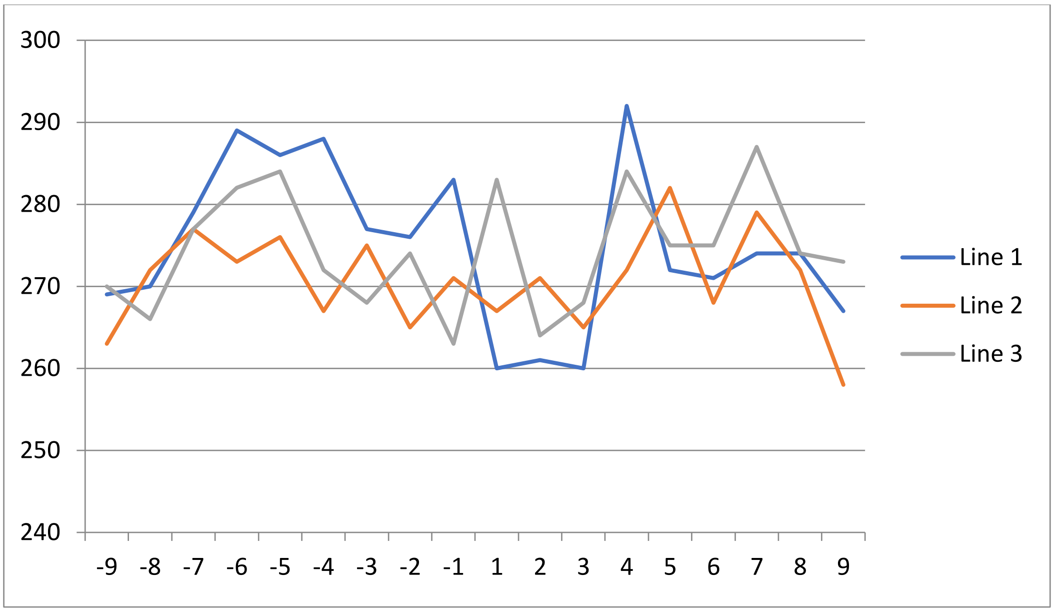


Fig. 5.21 .Positioning of prints in welded joint. The distribution of fingerprints in the SWC

The results of measurements are presented in the table 5.8. The measurements taken along the melt line (in HAZ) have been averaged.

Table 5.8. Results of hardness measurements

Distance from the weld centreline	Joint area	HV5 Line 1 (face)	HV5 Line 2 (root)	HV5 Line 3 (face)
-9	BASE	269	263	270
-8		270	272	266
-7		279	277	277
-6	HAZ	289	273	282
-5		286	276	284
-4		288	267	272
-3	WELD	277	275	268
-2		276	265	274
-1		283	271	263
1		260	267	283
2		261	271	264
3		260	265	268
4	HAZ	292	272	284
5		272	282	275
6		271	268	275
7	BASE	274	279	287
8		274	272	274
9		267	258	273



Base HAZ Weld HAZ Base

Fig. 5.22. Hardness distribution across the welded joint

In a SAW-welded joint, the hardness of the joint does not vary significantly in cross-section - it ranges from 260 to 283HV5 throughout the joint. Only slightly higher hardness was found in HAZ of the joint, which is related to increased ferrite content in this zone.

6. CONCLUSIONS

1. Duplex 2205 stainless steel is an innovative material and is used for gas gathering line pipe and process applications on offshore platforms.

2. The high strength of those steels allow to reduce wall thickness and reduce weight on the platforms. The corrosion resistance of 2205 duplex stainless steel is superior to 316L stainless steel.

3. In duplex stainless steels there is a clear increase in the percentage of ferrite in both HAZ and weld, together with the tendency to precipitation of intermetallic phases make their weldability restricted.

4. Two sections of sheets 15 × 150 × 500 mm have been prepared for making one welded joint. Butt joint was performed using "2Y" edge preparation without any gap. The height of the threshold was 3,0 mm in order to obtain correct dilutions between base and welded metals.

5. The preliminary welding procedure specification (pWPS) was prepared for butt welded joint of 15 mm thick duplex stainless plates steel grade X2CrNiMoN22-5-3 (1.4462).

6. The submerged arc welding method (121 SAW) with the use of 3,2 mm wire ESAB OK. Autrod 16.86 (22Cr9Ni3Mo) was applied. This method has a very high efficiency and the material in the HAZ reaches temperatures of 1400 degrees.

7. The joint was made with relatively high heat input welding energy of 3,4 kJ/mm. Two passes were made.

8. Weld was X-rayed and crack tested, and found to be satisfactory with B quality class according to PN-EN 25817.

9. Structure of weld metal consists of ferrite (blue) and austenite (bright). Further cooling initiates the formation of the austenite phase nucleating at the ferrite grain boundaries. Dendrite structure of ferrite is visable.

10. The HAZ width of the tested joint oscillated between 0.105 mm and 0.488 mm. A larger width of HAZ was found at the face and ridge in relation to the centre of the joint thickness.

11. The ferrite content in the weld metal do not exceed 52% and 73% in HAZ. Such result is acceptable for duplex welded joints. In the welded structure there is no evidence of intermetallic precipitates.

12. In general the hardness of the joint does not vary much, it is in a range between 260 and 283HV. Only in zone 3 of Fig 5.12 a higher hardness was found due to the increase of ferrite in that zone.

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TECNOLOGÍA DE SOLDADURA DE PLACAS DE ACERO INOXIDABLE DUPLEX USANDO EL MÉTODO DE ARCO SUMERGIDO

The State University of Applied Sciences in Elblag

César Hevia Loredo

Introducción

El trabajo consta de dos partes, una primera en la cual se hace una explicación teórica sobre los temas de los cuales habla el trabajo, y una segunda parte y experimental que es la más importante.

En la primera parte se cuenta un poco de que familia procede el acero dúplex utilizado en el proyecto así como alguna de las características generales de esta familia. También se cuenta más a fondo las características principales de el tipo de acero en concreto, el dúplex 2205.

A continuación se informa sobre el tratamiento que debe tener este acero previa soldadura, para encontrarse en las condiciones ideales para realizarla.

Y para finalizar esta primera parte se añade los principales métodos de soldadura con sus características, ventajas y desventajas, focalizando en el método SAW 121, que es el utilizado en este proyecto.

La segunda parte puede ser la más importante y la cual va tener más peso en este resumen, ya que es la parte que yo he realizado de investigación en el laboratorio estos meses.

Se divide a su vez en dos partes, una que realizo antes de la soldadura de preparación y otra después de la soldadura de observación de los resultados obtenidos.

He trabajado junto con la ayuda de un mecánico para realizar las soldaduras a mano y para las observaciones a posteriori he estado tanto en el laboratorio de mi facultad Elblag, como en el de una facultad contigua la de Gdansk, ya que en Elblag no se disponía de todo el material necesario.

PARTE TEÓRICA

Tecnología de soldadura

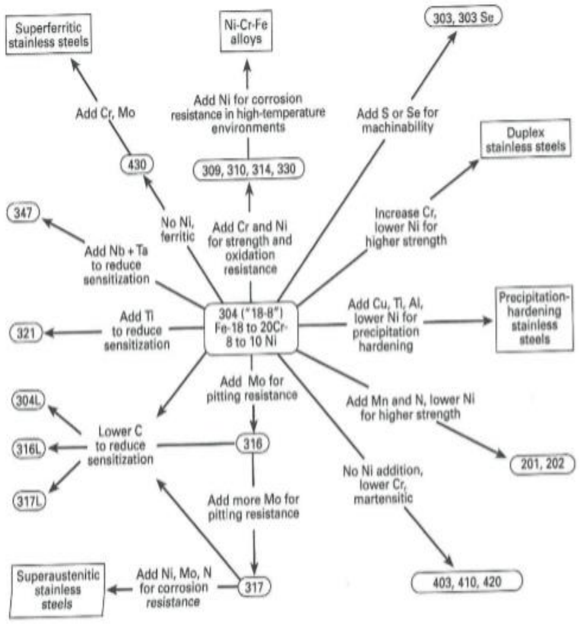
Se puede decir que la soldadura es de suma importancia en la industria en general, ya que es el proceso más económico, rápido y factible para generar uniones entre piezas de forma permanente y que, a pesar de ser más económico, ofrece una alta calidad.

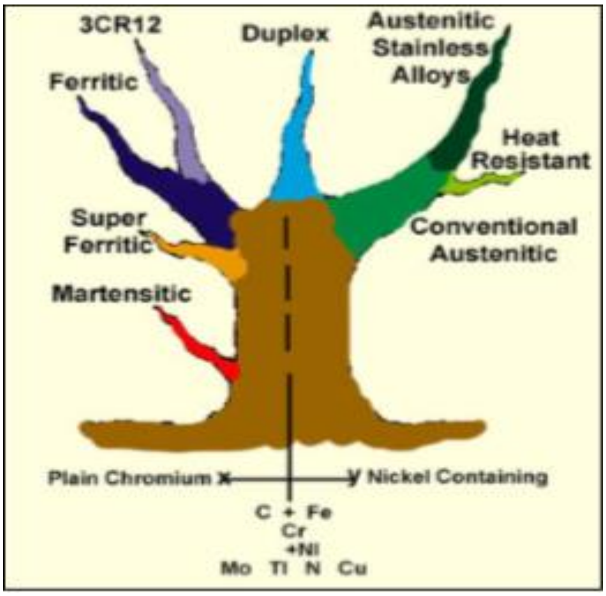
El problema del ensamblaje de la chapa se solucionó mediante soldadura por fusión, en la que se desplaza a lo largo de la junta una fuente de calor lo suficientemente intensa como para fundir los bordes de las dos chapas a ensamblar.

Acero inoxidable Duplex 2205

Acero inoxidable es el término utilizado para describir una familia extremadamente versátil de materiales de ingeniería, que se seleccionan principalmente por sus propiedades resistentes a la corrosión y al calor. Todos los aceros inoxidables contienen principalmente hierro y un mínimo de 10,5% de cromo.

El árbol genealógico del acero inoxidable tiene varias ramas, que pueden diferenciarse de diversas maneras, por ejemplo, en términos de sus áreas de aplicación, por los elementos de aleación utilizados en su producción o, quizás de la manera más precisa, por las fases metalúrgicas presentes en su estructura microscópica.

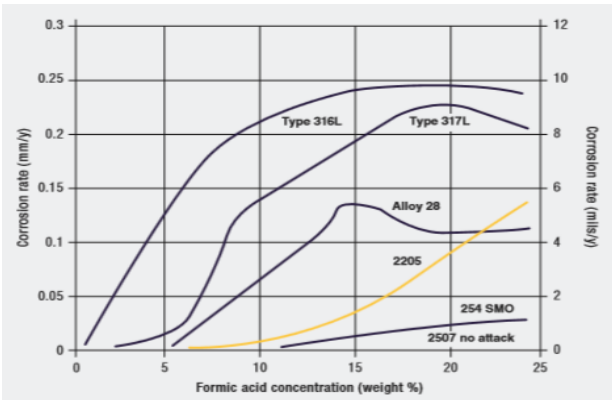


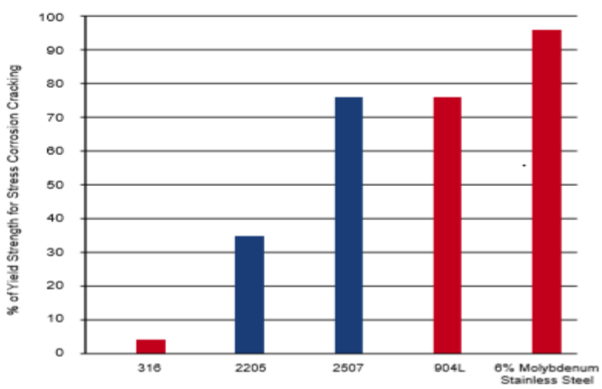


Aceros inoxidables dúplex: se considera que tienen aproximadamente la misma cantidad de ferrita y austenita.

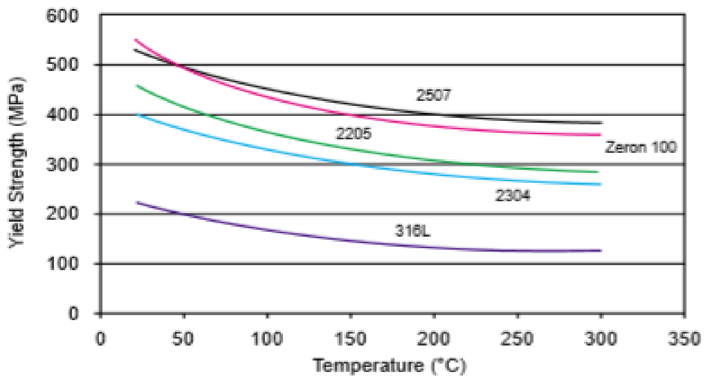
Los aceros inoxidables dúplex exhiben un alto nivel de resistencia a la corrosión en la mayoría de los ambientes donde los grados austeníticos estándar son útiles. 2205 y otros grados dúplex son superiores en muchos procesos que involucran ácidos orgánicos a altas temperaturas.

Algunos de los primeros usos de los aceros inoxidables dúplex se basaron en su resistencia al agrietamiento por corrosión bajo tensión de cloruro (SCC).





Los aceros inoxidables dúplex tienen propiedades mecánicas excepcionales. Su límite elástico a temperatura ambiente es más del doble del de los aceros inoxidables austeníticos estándar no aleados con nitrógeno.



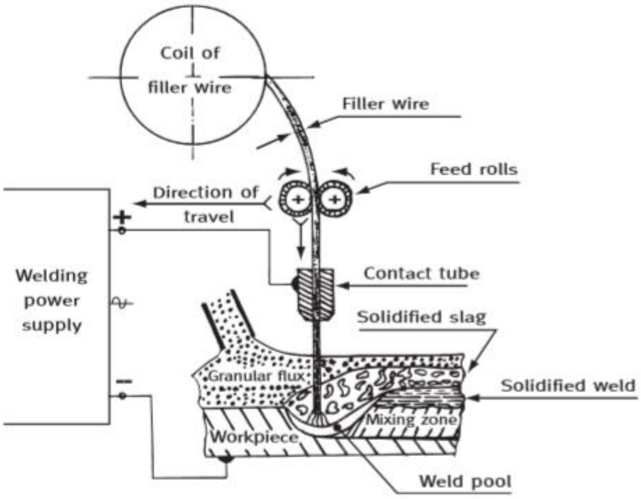
Sus propiedades físicas están entre las de los aceros inoxidables austeníticos y ferríticos, pero tienden a estar más cerca de las de los ferríticos y del acero al carbono.

La resistencia a la corrosión del acero inoxidable dúplex 2205 es superior a la del acero inoxidable 316L utilizado en intercambiadores de calor, depuradores de gas, ventiladores, tanques químicos y aplicaciones marinas y de refinería.

Soldadura por Arco Sumergido 121

Es un proceso común de soldadura por arco. Originalmente desarrollado y patentado por Jones, Kennedy y Rothermund, el proceso requiere un electrodo consumible sólido o tubular (con núcleo metálico) de alimentación continua.

La soldadura fundida y la zona del arco están protegidas de la contaminación atmosférica por estar "sumergidas" bajo un manto de fundente fusible granular compuesto de cal, sílice, óxido de manganeso, fluoruro de calcio y otros compuestos.



Cuando se funde, el flujo se vuelve conductivo y proporciona una trayectoria de corriente entre el electrodo y el trabajo.

Ventajas :

- Altas tasas de deposición.
- Altos factores de funcionamiento en aplicaciones mecanizadas
- Soldadura de alta velocidad
- Alta eficiencia y alta entrada de calor

Algunas aplicaciones son: industria química, calderas, intercambiadores de calor, recipientes a presión, farmacia, maquinaria de construcción, industria militar y nuclear.

EXPERIMENTAL

1. Material y Consumibles

El plato: Se utilizaron 15 mm de espesor de acero inoxidable dúplex 2205 X2CrNiMoCuN22-5-3 según EN 10088-2 (1.4462).

A continuación se muestra su composición química y sus características mecánicas.

C	Si	Mn	P	S	Cr	Mo	Ni	N
0,027	0,41	0,80	0,013	0,001	22,8	3,11	5,33	

TS [MPa]	YP [MPa]	Amin [%]	HBW	KV(T) min [J]
640-840	460	25	290	40

Metal de soldadura: Se utilizó metal de aportación de acero inoxidable dúplex con un mayor contenido de níquel en relación con el material de base. Autrod 16.86 (22Cr9Ni3Mo) wg EN 10204

A continuación se muestra su composición química y sus características mecánicas.

C	Si	Mn	Cr	Ni	Mo	Cu	N
0,02	0,46	1,6	23,0	8,6	3,10	-	0,16

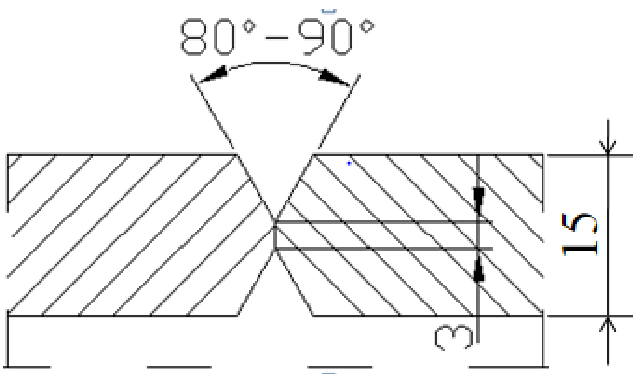
$R_{p0,2}$ (MPa)	R_m (MPa)	Elogation (%)	Impact value, KV [J]		
			-60ºC	-20ºC	20ºC
600	765	28	60	85	100

Flujo: 10,93 SAW wg EN 760 se utilizó

2. Preparación de la especificación del procedimiento de soldadura

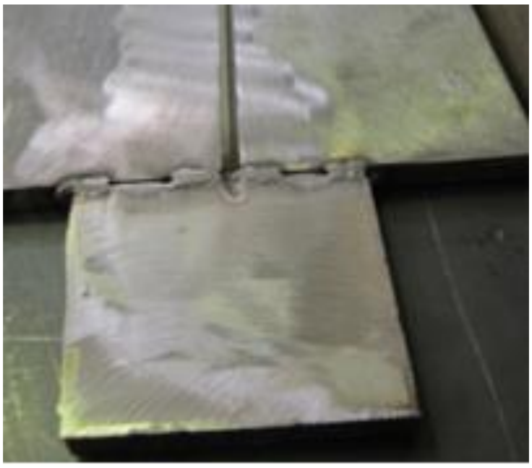
Se han preparado dos secciones de láminas de 15 × 150 × 500 mm para realizar una junta soldada.

La unión a tope se realizó utilizando la preparación de cantos "2Y" sin dejar ningún hueco. La altura del umbral era de 3,0 mm para obtener diluciones correctas entre los metales base y los metales soldados.



Los bordes de las láminas se fresaron y limpiaron antes de soldar con una amoladora angular.

Los paneles de las placas de la pista de 100 mm de longitud se soldaron a ambos lados de las secciones soldadas.



3. Especificación preliminar del procedimiento de soldadura

Técnica de soldadura manual: pWPS Nr: 121_01

Fabricación: PWSZ Elbląg

Proceso de soldadura: 121 (SAW)

Modelo de transferencia metálica: spray

Tipo de articulación: BW

Método de preparación y limpieza: Corte mecánico o por plasma, rectificado.

Especificación de material matriz: Grupo de artículos

CR ISO 15608: 10; Materiał wg PN EN 10088-2 X2CrNiMoN22-5-3 (1.4462)

Espesor del material[mm]: 15

Posición de soldadura: PA

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<tr><td>PWSZ
Elbląg</td><td colspan="2">pWPS</td><td>WPS 121_01</td></tr>
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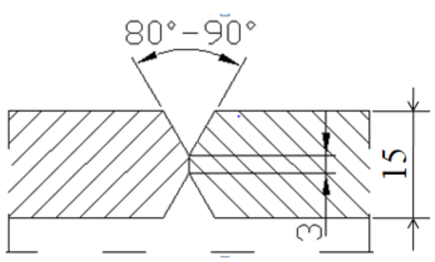
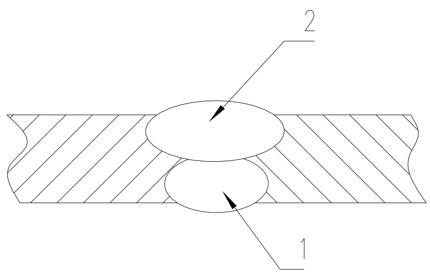
<tr><td colspan="2">
</td><td colspan="2">
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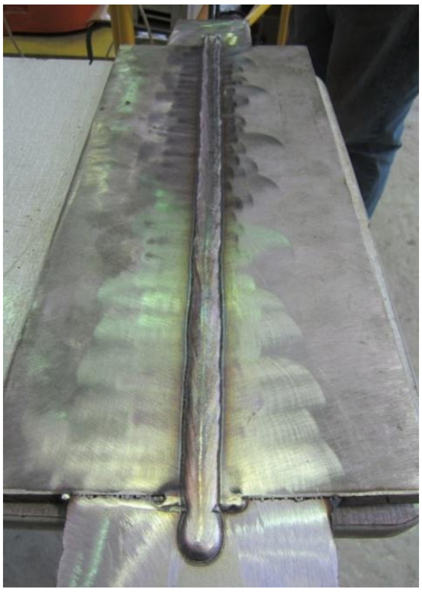
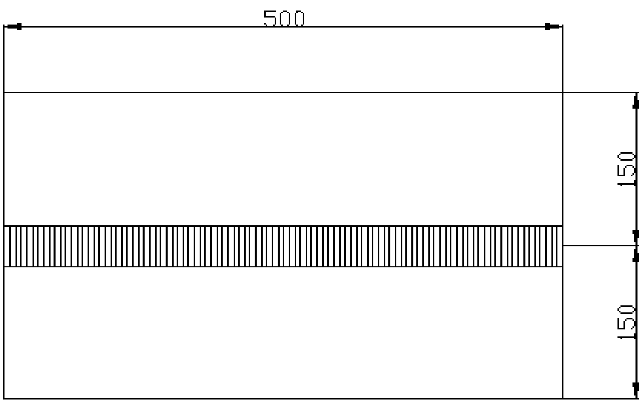
Run	Process	Size of fillet metal (mm)	Current (A)	Voltage (V)	Type of current/polarity	Wire feed speed (m/min)	Travel speed vs (cm/min)	Heat input, Q (Kj/mm)
1	121	3,2	460÷500	32	DC (+)	-	38-40	2,4
2	121	3,2	560÷580	33	DC (+)	-	30	3,4

Unidad ESAB de soldadura por arco sumergido utilizada para las juntas de prueba de soldadura.

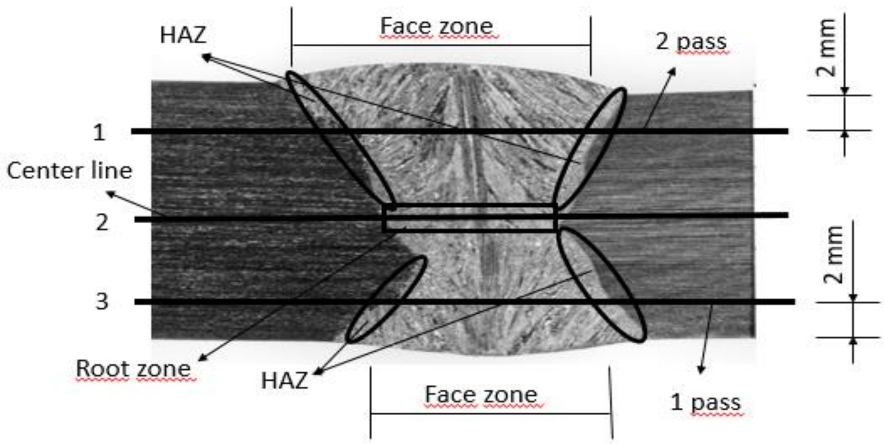
Cada soldadura fue sometida a una prueba de rayos X y de grietas, y resultó satisfactoria con la clase de calidad B de acuerdo con la norma EN 25817.





4.Exámenes Metalográficos

Se cortaron placas soldadas para muestras para exámenes metalográficos. La preparación de las muestras metalográficas consistió en la molienda con grano de papel de lija, respectivamente, 80, 120, 300, 600, 800 y 1.000.

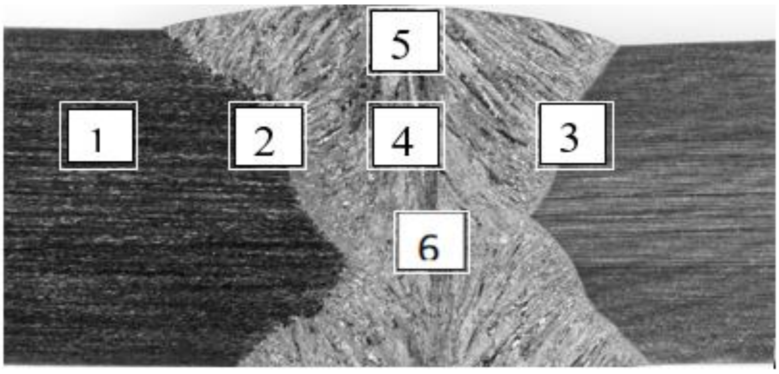


Las muestras para los exámenes macroscópicos fueron grabadas en mármol, un reactivo (4g $CuSO_4$, 20 ml HCl, 20 ml H_2O).

La geometría de la soldadura, el ancho de la soldadura en la zona frontal (ambos lados) es de 17 mm. No se han detectado grietas ni otros defectos.

Para los exámenes microscópicos se grabaron muestras con el uso del reactivo de Berah'a (HCl + $K_2S_2O_4$). Los exámenes se realizaron en el microscopio óptico Neophot 2.

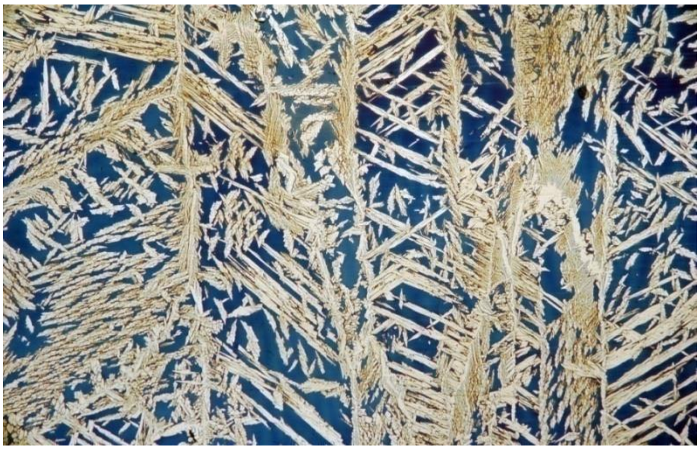
Los puntos de observación con el microscopio de las uniones soldadas se muestran en esta foto



1. Material de base
2. HAZ-1 zona
3. HAZ-2 zona
4. Metal de soldadura
5. Metal de soldadura - Zona frontal
6. Metal de soldadura - Zona de la raíz

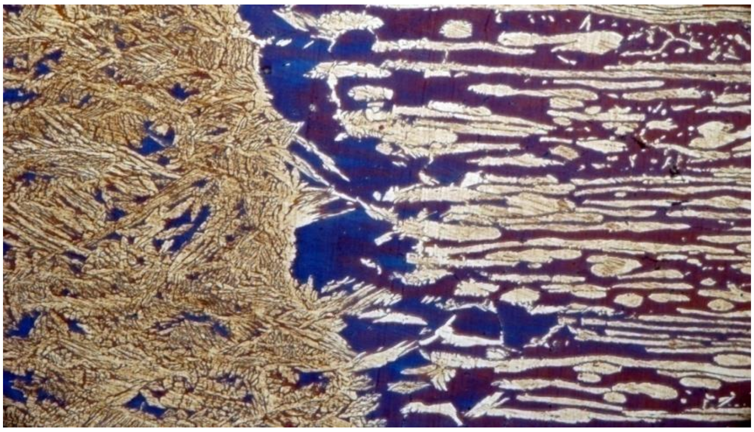
En la zona del material de base (1), una estructura ferrítica-austenítica con una estructura característica similar a una banda es visible durante el trabajo del plástico (laminado) de la lámina.

El reactivo de grabado utilizado no revela completamente los límites de grano en áreas ferríticas y austeníticas. El porcentaje de ambas fases es de aproximadamente el 50%.



La estructura del metal de soldadura (4). La estructura del metal de soldadura consiste en ferrita (azul) y austenita (brillante). Durante la solidificación del metal de soldadura dúplex se forma una estructura de ferrita casi por completo.

Un enfriamiento adicional inicia la formación de la fase austenítica que se nuclea en los límites del grano de ferrita. La estructura dendrítica es visible.



La estructura del HAZ (2,3). En la zona afectada por el calor de la unión soldada, son visibles grandes granos de ferrita con un número limitado de precipitaciones aciculares de austenita. Las separaciones de austenita se localizan principalmente en los límites de los granos de ferrita y en menor medida dentro de los granos de ferrita. Los granos de ferrita han crecido considerablemente.

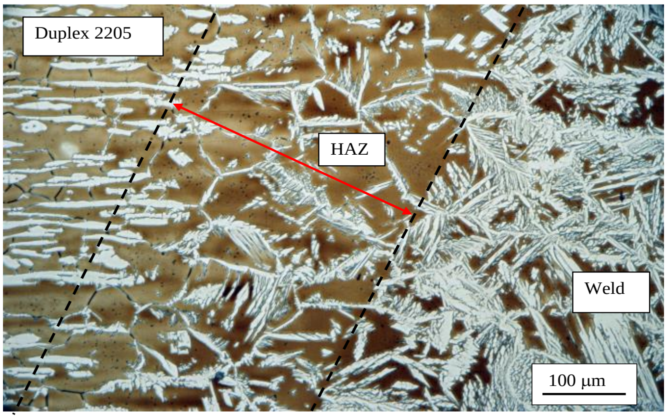
Esta construcción de la ZAE es característica de las uniones de acero dúplex soldadas. Cuando la ZAE se calienta a una temperatura de unos 1400ºC, esta área obtiene una estructura casi completamente ferrítica. Durante el enfriamiento, la austenita evoluciona, pero el proceso está limitado por un ciclo térmico corto.

Como resultado, grandes cantidades de ferrita pueden permanecer en los acoplamientos en la ZAE, lo cual es indeseable debido a la disminución de las propiedades mecánicas y la resistencia a la corrosión de las juntas. Las zonas afectadas por el calor son muy estrechas y su anchura varía según la posición de la articulación.

5. Mediciones de Ancho del HAZ

El ancho de la ZAE (ζ) se midió trazando una línea perpendicular a la línea de fusión y luego leyendo el ancho de la ZAE a lo largo de esta línea, fig.

Las mediciones se realizaron en secciones transversales de la articulación en 3 líneas: línea 1, a una distancia de más o menos 2 mm de la cara de la articulación, línea 2, en el centro del espesor de la articulación, línea 3 a una distancia de más o menos 2 mm de la cresta de la articulación.



En cada una de las líneas se tomaron n = 9 mediciones, para las cuales se determinó una desviación (s) estándar promedio.

El ancho de la ZAV de la junta probada osciló entre 0,105 mm y 0,488 mm. Se encontró una mayor anchura de la ZAV en la cara y en la cresta en relación con el centro del grosor de la junta.

No line	HAZ width , mm			
	n	$\bar{\zeta}$	s	
Weld1				
1	9	0,210	0,010	
2	9	0,152	0,008	
3	9	0,374	0,012	

6. Mediciones del contenido de ferrita en las estructuras de las juntas

Las mediciones del contenido de ferrita se realizaron con el método metalográfico y magnético, utilizando un ferritómetro fabricado por la empresa Fisher MP30.

La tabla muestra la participación porcentual (valor medio de 6 mediciones) del volumen de ferrita determinado por el método metalográfico y el ferritómetro.

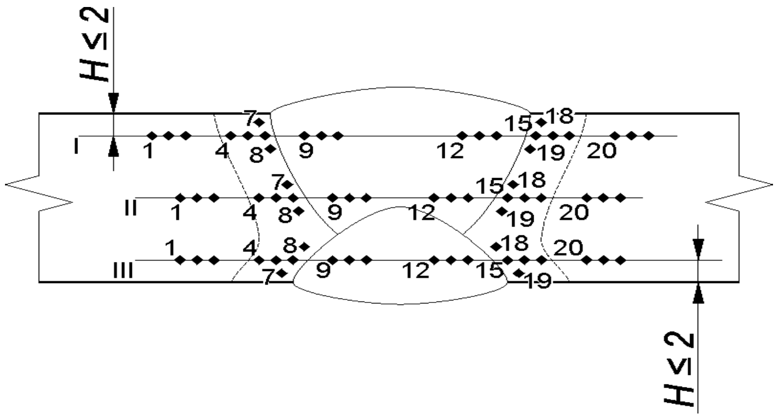
Connection area	Ferrite content (%)	
	n	α
Duplex steel 2205	6	52,2
	Connector 3	
HAZ duplex face	6	67,5
HAZ dúplex measure	6	72,8
HAZ dúplex ridge	6	70,8
Weld face	6	51,2
Weld measure	6	45,9
Weld ridge	6	39,7

En el material base del dúplex de acero inoxidable la cantidad media de ferrita fue del 52,2%. Las uniones soldadas SAW mostraron un aumento en el contenido de ferrita en la ZAE incluso por encima del 70%.

7.Test de Dureza

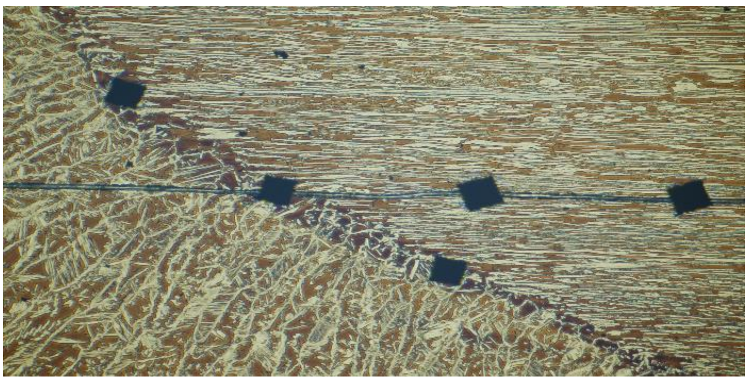
Los especímenes fueron grabados con el reactivo de Marble para revelar las líneas de fusión y los límites de la zona afectada por el calor de soldadura.

Las mediciones de dureza de las uniones soldadas se realizaron de acuerdo con la norma EN ISO 9015-1 con el durómetro HPO-250. Los ensayos se realizaron por el método Vickers según EN 6507: 2007 a 49 N (HV5) de carga.



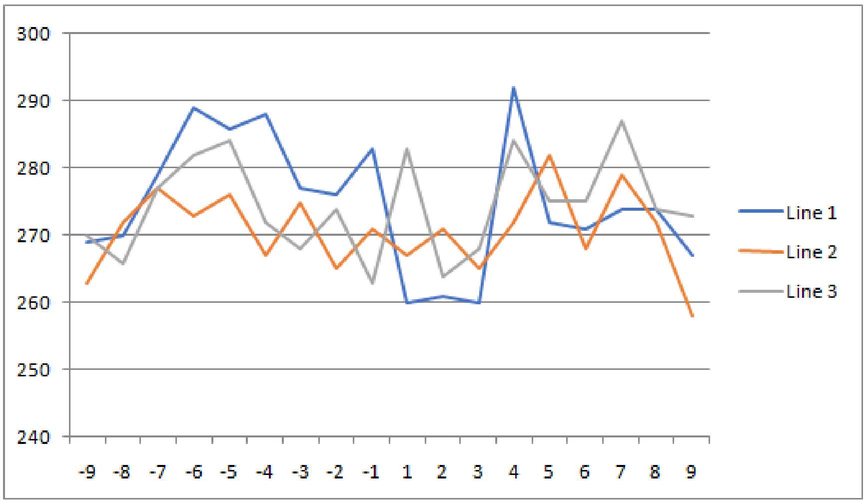
Las impresiones se tomaron en tres líneas de medición que pasaban a través del material madre, la ZAE y la soldadura de cada espécimen.

La primera línea y la tercera línea estaban a 2 mm de la superficie de la chapa, la segunda línea estaba en el centro de las juntas.



Debido al área muy estrecha de la zona afectada por el calor, las mediciones de la dureza en esta zona se tomaron en la línea de medición y adicionalmente por encima y por debajo de la línea de medición.

Distance from the weld centreline	Joint area	HV5 Line 1 (face)	HV5 Line 2 (root)	HV5 Line 3 (face)
-9	BASE	269	263	270
-8		270	272	266
-7		279	277	277
-6	HAZ	289	273	282
-5		286	276	284
-4		288	267	272
-3	WELD	277	275	268
-2		276	265	274
-1		283	271	263
1		260	267	283
2		261	271	264
3		260	265	268
4	HAZ	292	272	284
5		272	282	275
6		271	268	275
7	BASE	274	279	287
8		274	272	274
9		267	258	273



Base HAZ Weld HAZ Base

En una junta soldada SAW, la dureza de la junta no varía significativamente en la sección transversal - va de 260 a 283HV5 en toda la junta.

Sólo se encontró una dureza ligeramente superior en la zona afectada de la junta, lo que está relacionado con el aumento del contenido de ferrita en esta zona.

CONCLUSIONES

- Se encontró una mayor anchura de la ZAV en la cara y en la cresta en relación con el centro del espesor de la junta.
- En los aceros inoxidables dúplex hay un claro aumento en el porcentaje de ferrita tanto en la ZAE como en la soldadura.
- La junta se realizó con una entrada de calor relativamente alta de 3,4 kJ/mm. Se hicieron dos pases.
- La tecnología de soldadura desarrollada de chapa de 15 mm de acero inoxidable dúplex 2205 dio buenos resultados.
- A pesar del uso de un alto aporte de calor, la junta obtenida mostró la microestructura adecuada.
- Se utiliza para aplicaciones de procesos y tuberías de recolección de gas en plataformas marinas. La alta resistencia de estos aceros permite reducir el espesor de las paredes y el peso en las plataformas.