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PROJECT: NSC 422

**Properties of dissimilar welds between austenitic stainless steel
314L/316L and lean duplex stainless steel 2001**

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ABSTRACT

A study of 304L joined to 2001 and 316L austenitic joined to 2001 lean duplex by shielded Metal Arc Welding (SMAW) also known as Stick welding using filler materials that includes, E309LMo ,highly alloyed and E2209 duplex stainless steel. Tests done to determine the effect of welding on mechanical properties across the welded joint properties of the dissimilar welds are the following, hardness, tensile and impact test. The 316L to 2001 weld joint using E2209 showed higher impact energy values. Higher hardness obtained for 316L-2001 by E2209. For all the weldments the 304L to 2001 joint for all the filler materials have higher ultimate tensile and yield strength values when compared to 316 to 2001 joints.

From the microstructural evaluations it was observed that no hot cracks were in weld metal deposits. The weld metal microstructures consists of δ -ferrite grains, with grain boundary austenite and Widmanstätten austenite side-plates after cooling. It was observed that area of the lowest resistance to corrosion is at the duplex steel side of dissimilar joins.

Keywords: dissimilar welding, weld metal, mechanical properties, (304L/316L) austenitic stainless steel, Lean duplex stainless steel (2001).

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1. INTRODUCTION

Welding is one of the most used joining techniques. According to the American Welding Institute (AWI), welding can be classified into four groups on the basis of properties such as the:

- Nature of the energy source
- Heat source (electric arc, electrical resistance, radiation, induction or conduction)
- Application of mechanical energy (pressure, deformation or both)
- Shielding mechanism (flux/slag, gas, combination of gas and flux or vacuum).

In practice, welding is not just done randomly but it is done according to certain rules and sequential steps. These rules and steps of welding are called welding procedure specifications (WPS) and must be strictly followed during welding.

The dissimilar metal weld is demanding as well as the similar weld, however, dissimilar weld is more complex than similar weld due to the necessity of being applied in zones where a requirement is to improve some properties.

Ideally a weldment which is a complete joint made of the weld metal, heat affected zones (HAZ) and the adjacent parent metal and the weldment should have the same properties as the parent metal. But practically it is difficult to achieve this and the features and defects that may contribute to the loss of properties include the following:

- Oxide inclusions and oxide filming.
- Solidification (hot) cracking or liquation cracks.
- Reduced strength in the weld and HAZ.
- Lack of fusion.
- Reduced corrosion resistance.

1.1 INDUSTRIAL BACKGROUND

Nowadays the main target is the development of lean duplex, which have much fewer alloying elements (cost). Lean duplex has been replacing 316L and even 304L grades because of their better properties. In the structural industry design engineers are faced with the need of dissimilar weld joints in structural applications and the weld's strength must be sufficient enough to handle stresses the joint will see in service.

Structural sections like beams, channels and angles made of lean duplex stainless steel achieve equivalent performance at a lower cost. The high performing structural sections satisfy the needs of the engineers and designers for light, innovative and cost-effective structures in stainless steel which at the same time fulfill the criteria of safety and durability [2].

The main drive for the development of Lean Duplex Stainless Steels is the rising of raw material costs (nickel and molybdenum) along with increasing demand for improved corrosion resistance and strength. Lean duplex stainless steels have been used and in various applications are being considered as substitutes for austenitic stainless steel types 304L and 316L.

Examples of Lean duplex stainless steels of industry end users are structural supports for the onshore and offshore oil industry, gas industry, architectural and building, desalination equipment, wastewater treatment facilities, pulp & paper, chemical processing, automotive and transportation, [2].

In choosing duplex in a construction it is often possible to reduce plate thickness due to the higher strength and thereby reduce weight of the construction. In addition to this the world market prices for alloying elements as Ni has increased a lot and therefore the lean duplex grades have increased in popularity [6]. Successful dissimilar metal welding is possible by the development of welding procedure specification to optimize the weld joint properties [12].

1.2 SCIENTIFIC BACKGROUND

Type 304L, 316L and 2001 are weldable using all popular the fusion welding methods. AISI 304L and 316L are austenitic stainless steels, whereas 2001 is a duplex austenitic-ferritic stainless steel. The ferrite content of the duplex stainless steel weld is critical, and should not exceed 70 FN.

Lean duplex stainless steel microstructure combines properties of both phases that may even be enhanced in the combination:

- the ferrite provides high strength
- austenite contributes good ductility and general corrosion resistance.

1.3 PROBLEM STATEMENT

Mechanical properties, microstructure and corrosion resistance of dissimilar stainless steel welds.

2. LITERATURE REVIEW

Review of the materials to be used for the project, methods and tests.

2.1 STAINLESS STEEL

Stainless steels also known as corrosion resistance steels are iron based steel alloys and their predominant alloying element is chromium with a minimum of 10.5 wt% Cr is required and as observed from figure 1 below, a content of more than 12.6 wt% Cr is preferred for the steel to be stainless, resistant to corrosion by formation of a passive layer that prevents oxidation and corrosion of the underlying metal at ambient and noncorrosive conditions

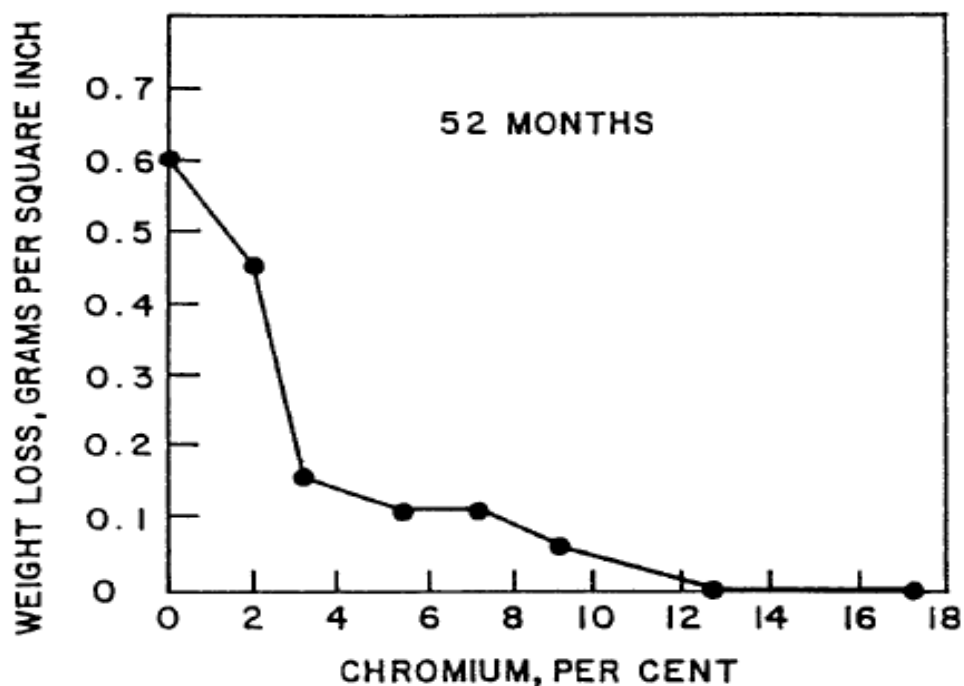


Figure 1: Influence of chromium wt% on corrosion of stainless steel

The corrosion resistance of stainless steel is enhanced by addition of nickel and molybdenum. A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability [calister]. Stainless steels can be classified into five groups on the basis of their microstructure. The five groups are detailed below:

- Austenitic stainless steels which contain 12 - 27% chromium and 7 - 25% nickel.
- Ferritic stainless steels which contain 12 - 30% chromium with a carbon content below 0.1%.
- Martensitic stainless steels which have chromium content of between 12 and 18% with 0.15 – 0.30% carbon.
- Ferritic-austenitic stainless steels which contain 18 - 25% chromium, 3 - 5% nickel and up to 3% molybdenum.
- Martensitic-austenitic steels which have 13 - 16% chromium, 5 - 6% nickel and 1 - 2% molybdenum.

Of the above mentioned stainless steels groups, austenitic, ferritic and ferritic-austenitic (duplex) are the mostly used.

Table 1: Stainless steel examples.

	Material	EN	ASTM/UNS	C	N	Cr	Ni	Mo	Others	PRE*
Ferritics	409	1.4003	S40977	0.02	-	11.5	0.5	-	-	12
	430	1.4016	430	0.04	-	16,5	-	-	-	17
	444	1.4521	444	0.02	0.01	17.8	-	2.1	Ti	25
Duplex	LDX 2101®	1.4162	S32101	0.03	0.22	21.5	1.5	0.3	5Mn	26
	2304	1.4362	S32304	0.02	0.10	23	4.8	0.3	-	26
	2205	1.4462	S32205	0.02	0.17	22	5.7	3.1	-	35
	2507	1.4410	S32750	0.02	0.27	25	7	4	-	43
Austenitics	304	1.4301	304	0.04	-	18.1	8.1	-	-	18
	304L	1.4307	304L	0.02	-	18.1	8.1	-	-	18
	321	1.4541	321	0.04	-	17.3	9.1	-	Ti	17
	316	1.4401	316	0.04	-	17.2	10.1	2.1	-	24
	316L	1.4404	316L	0.02	-	17.2	10.1	2.1	-	24
	316L	1.4432	316L	0.02	-	16.9	10.7	2.6	-	25
	316Ti	1.4571	316Ti	0.04	-	16.8	10.9	2.1	Ti	24
Superaustenitics	904L	1.4539	904L	0.01	-	20	25	4.3	1.5Cu	34
	254 SMO®	1.4547	S31254	0.01	0.20	20	18	6.1	Cu	43
	1.4565	1.4565	S34565	0.02	0.45	24	17	4.5	5.5Mn	46
	654 SMO®	1.4652	S32654	0.01	0.50	24	22	7.3	3.5Mn,Cu	56

*Pitting resistance equivalent, $PRE = Cr + 3.3 \times \% Mo + 16 \times \% N$

The main focus of this project is the weldability of the dissimilar stainless steels (austenitics to lean duplex stainless steels) and their weld metal properties. Most stainless steels are weldable, but may require special procedures. The final weld properties like mechanical and corrosion properties are determined; a complex mixture of metallurgical, geometrical and surface effects [1].

2.1.1 AUSTENITIC STAINLESS STEEL

Austenitic stainless steels group is the largest group of stainless steel that contains chromium and nickel as the main alloying elements. The austenitic stainless steels were developed for use in both mild and severe corrosive conditions. Austenitic stainless steels are used at temperatures that range from cryogenic temperatures, where they exhibit high toughness, to elevated temperatures, where they exhibit good oxidation resistance [2].

The most common types of austenitic stainless steels are the AISI 200 and AISI 300 series. The AISI 300 series of the austenitic stainless steel are the oldest and mostly used and typically composition of 8 to 20 wt% Ni and from 16 to 25 wt% Cr. The Cr-Ni-Mn (304L) austenitics are the most versatile and widely used of all stainless steels. The Cr-Ni-Mo (306L) austenitics are the bearing molybdenum austenitic stainless steels for increased localised (pitting and crevice) corrosion resistance in chloride containing environments. This type of austenitics has excellent ductility, formability and toughness even at temperatures below zero.

The 304L and 316L austenitic stainless steels are called L grades. These low carbon grades reduces the intergranular attack and intergranular stress corrosion cracking caused by chromium carbide precipitates in the grain boundaries of the heat affected zone (HAZ). These grades exhibit excellent weldability and can be welded with all fusion and resistance welding processes and can often be welded without filler metal.

Their chemical composition, mechanical properties, weldability and corrosion resistance provide the best performance at relatively stainless steels low cost. They are often used in applications requiring good atmospheric or elevated temperature corrosion resistance.

There is a concern when welding austenitic stainless steels, is the susceptibility to solidification and liquation cracking [7]. The solidification cracks form in the weld metal, impurities may be concentrated to the grain boundaries or the inter-dendritic regions, resulting in low melting phases and susceptibility to solidification. Liquation cracks are formed in the HAZ of the base metal or/and in the HAZ's of previously deposited welds during multiple-pass weld due to grain boundary segregation and enrichment, which leads to the development of low melting phases at grain boundaries in the high

temperature zone which borders immediately on the liquid weld metal[notes]. These cracks are primarily due, to low-melting liquid phases, which allow boundaries to separate under the thermal and shrinkage stresses during weld solidification and cooling [7].

Welding of austenitic stainless steel grades can cause distortion problems during welding. This is because the heat produced by welding does not disperse but remains in the weld area due to the lower thermal conductivity of austenitic stainless steels. This results in large thermal gradients across the weld, and since the heated area has a high expansion rate, distortion occurs. The following techniques can be used to reduce the problem:

- Use rigid clamps, jigs or fixtures.
- Do not overweld (excessive weld metal increases distortion).
- Use a welding sequence that balances the shrinkage forces.
- Preset parts.
- Weld near the neutral axis of the component.
- Balance welds around the centre of gravity.
- Prebend the plates.
- Position the welds to balance shrinkage.
- Use joints with minimum weld metal requirements

Welding of austenitic stainless steel should be at with a moderate heat input ($< 1.5 \text{ kJ/mm}$), with an interpass temperature not exceeding 100°C and the lowest possible dilution of the base metal [1].

2.1.2 DUPLEX STAINLESS STEEL

Duplex ferrite-austenite stainless steels are stainless steel grades with a mixed microstructure of approximately equal proportions of austenite and ferrite. The microstructure of the duplex stainless steel combines properties of both phases that may even be enhanced in the combination of the two phases, the ferrite provides high strength and resistance to stress corrosion cracking and austenite contributes good ductility and general corrosion resistance [1]. The specific advantages offered by duplex stainless steels over conventional 300 series stainless steels are strength, chloride stress-corrosion cracking resistance, and pitting corrosion resistance.

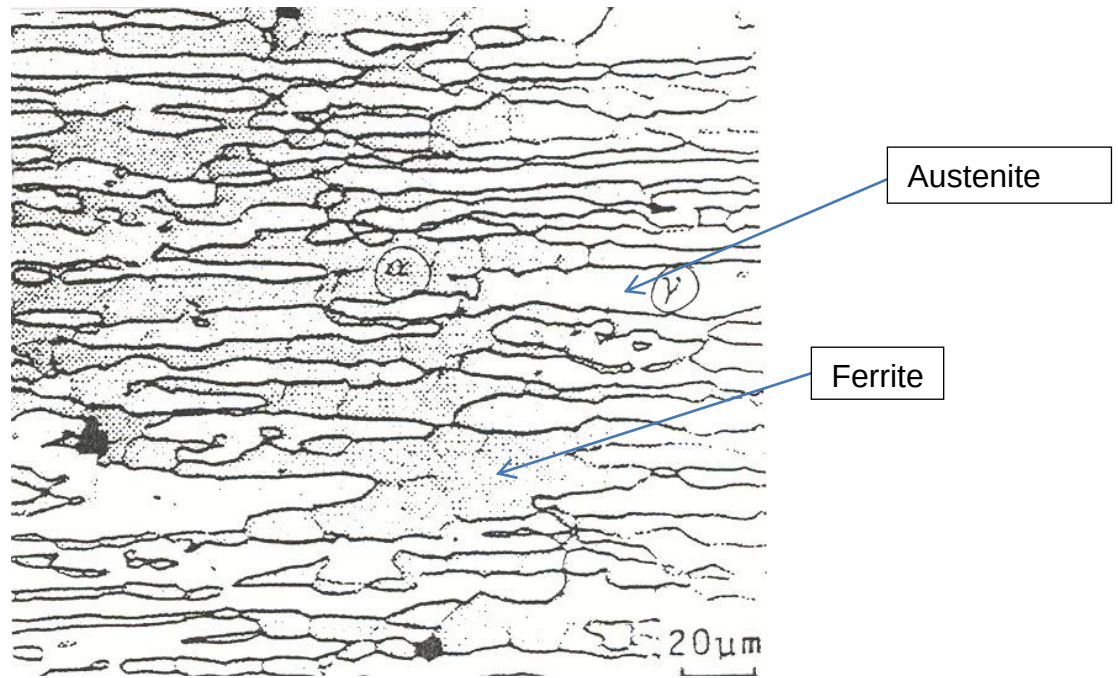


Figure 2: The microstructure of type 2205 duplex stainless steel.

On figure 2 above, the light phase is austenite, and the gray phase is ferrite. Duplex stainless steels are used in a wide range of application that takes advantage of their superior combination of strength and corrosion resistance. Duplex stainless form a number of a number of embrittling precipitates at relatively low temperatures, so they are recommended for service applications exceeding about 280°C [2].

Duplex stainless steel can be classified into four types on the basis of their microstructure. The four main types are detailed below

- Standard duplex
- Lean duplex (lower alloyed)
- super duplex (highly alloyed)
- Hyper duplex.

The differences between them are the chemical analysis and their mechanical and corrosion properties. Their similarities are that they all have a ferritic solidification and that the austenite formation starts at approximately 1420°C and at approximately 800°C the austenite formation is finalised [6]. Generally all fusion welding methods can be used for welding duplex stainless steels on condition that suitable welding procedures and consumables are used.

2.1.3 LEAN DUPLEX STAINLESS

The lean duplex steel is the lower alloyed duplex. The fluctuating alloying element prices (especially nickel and molybdenum) during the last decade has accelerated the development and the amount of applications for these steels [1]. The benefits in the lean duplex steel are better resistance to stress corrosion, better corrosion resistance in chloride containing environments, twice the yield strength and thereby savings in material consumption as thinner material can be selected. When general weight is reduced for road, rail and water moving transport containers the fuel efficiency is improved and has a positive effect on environment [6].

The lean duplex grades have typically 20-24% chromium, 1-5% nickel, 0.1-0.3% molybdenum and 0.10-0.22% nitrogen. These alloys, unlike most other duplex grades, are only alloyed with small amounts of molybdenum and the lean alloying content results in lower cost [1].

2.2. ALLOYING ELEMENTS

The desired corrosion and mechanical properties of stainless steels are obtained by optimizing the balance of the important alloying elements. From now on, the focus will be on duplex grades [elen].

2.2.1 FERRITE PROMOTERS

- Chromium – provides basic corrosion resistance.
- Molybdenum – provides high temperature strength and increases corrosion resistance.
- Niobium (Columbium), Titanium –strong carbide formers.

2.2.2 AUSTENITE PROMOTERS

- Nickel – provides high temperature strength and ductility.
- Carbon – carbide former, strengthener.
- Nitrogen – increases strength, reduces toughness

2.3 FILLER MATERIAL

The equilibrium phase balance and corrosion resistance of the annealed base metal cannot be attained when welding autogenously due to higher ferrite fractions, possible element loss and segregation of important alloying elements. Use of over-alloyed consumables is for this reason generally recommended for welding of all duplex grades, in order to achieve corrosion resistance and impact toughness close to that of the base metal. Consumables higher chromium and molybdenum contents and may be alloyed with nitrogen for desirable optimum weld metal corrosion resistance.

2.4 WELDING METHODS

There are many methods available for joining stainless steel, but fusion welding, where the material is joined by melting and filler metal added when needed, dominates. The choice of welding method depends on what is available and practically suitable for the specific application. The steel grade, required properties, material thickness, welding position and surrounding environment are normally taken into account when choosing the welding method.

Dissimilar metal welds involving stainless steels can be done using most full fusion weld methods, including Gas Tungsten Arc Welding (GTAW) also known as Tungsten Inert Gas (TIG) below and Gas Metal Arc Welding (GMAS) also known as Metal Inert Gas (MIG).

2.4.1 GAS TUNGSTEN ARC WELDING

An arc welding process in which the heat for welding is supplied by an arc that forms between the workpiece and a nonconsumable tungsten electrode. The electrode, weld pool, arc and adjacent base metal are protected from atmospheric contamination by a gaseous shield [notes].

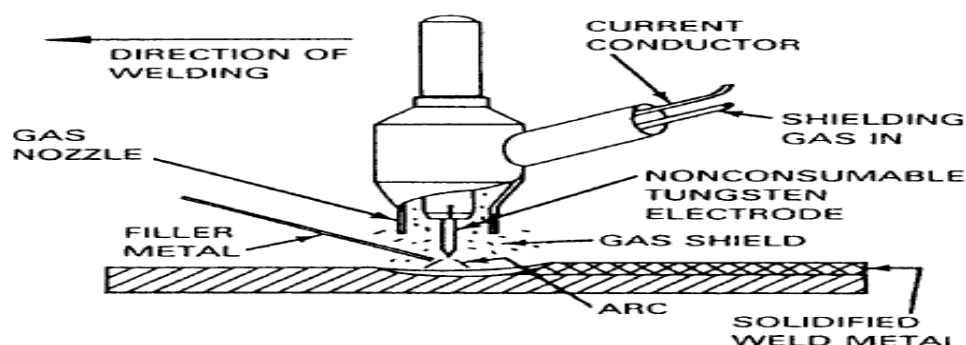


Figure 3: The GTAW welding process.

Protections are carefully supplied to exclude the atmosphere from the high-temperature welding regions. Protective agents are usually in the form of inert gases, fluxes, and electrode coatings.

2.4.2 GAS METAL ARC WELDING

An arc welding process in which the heat for welding is generated by an arc that forms between a consumable electrode and the workpiece. The electrode, a bare solid wire that is continuously fed to the weld area, becomes the filler metal as it is consumed. Shielding is provided by a stream of gas that flows through the torch, and protects the weld pool, electrode, arc and adjacent base metal [notes].

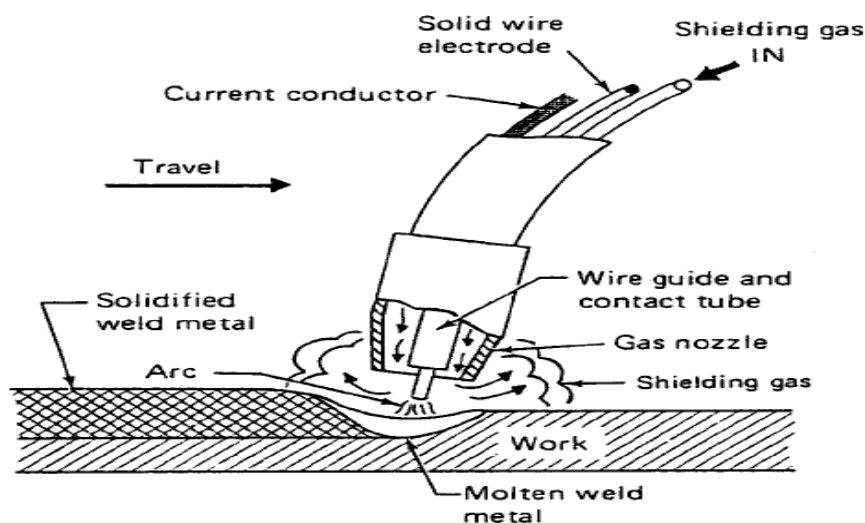


Figure 3: Operating principles of the GMAW process.

2.4.3 SHIELDED METAL ARC WELDING

Shielded Metal Arc Welding (SMAW) also known as Stick welding is a process which melts and joins metals by heating them with an arc between a coated metal electrode and the workpiece. The electrode's outer coating, called flux, assists in creating the arc and provides the shielding gas and slag covering to protect the weld from contamination. The electrode core provides most of the weld filler metal.

The power in a welding circuit is measured in voltage and current. The voltage (Volts) is governed by the arc length between the electrode and the workpiece and is influenced by electrode diameter. Current is a more practical measure of the power in a weld circuit and is measured in amperes (Amps).

The amperage needed to weld depends on electrode diameter, the size and thickness of the pieces to be welded, and the position of the welding. Thin metals require less current than thick metals, and a small electrode requires less amperage than a large one.

It is preferable to weld on work in the flat or horizontal position. However, when forced to weld in vertical or overhead positions it is helpful to reduce the amperage from that used when welding horizontally. Best welding results are achieved by maintaining a short arc, moving the electrode at a uniform speed, and feeding the electrode downward at a constant speed as it melts.

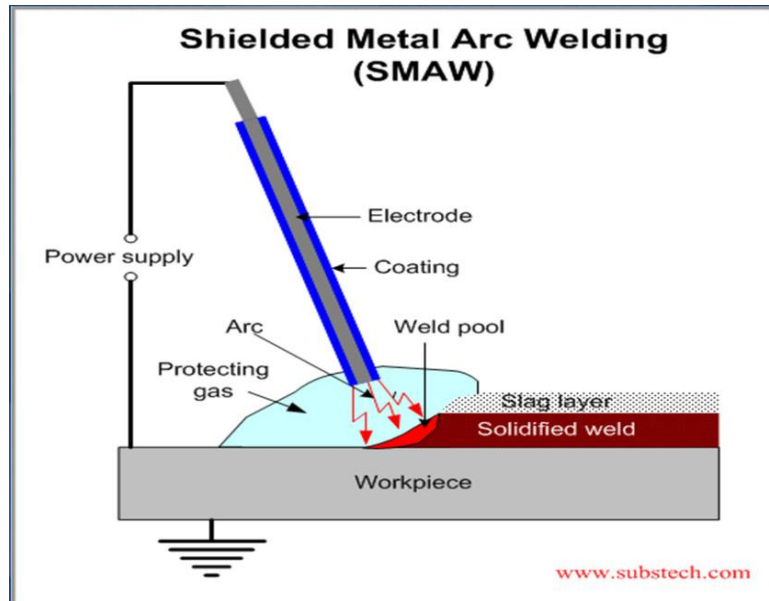


Figure 4: Shielded Metal Arc Welding (www.substech.com)

When comparing SMAW to other fusion welding processes, SMAW has very low metal deposition rates. Electrodes have fixed lengths, so welding has to be interrupted after each electrode is consumed. Deslagging using tools in figure 5 below is required after each pass.

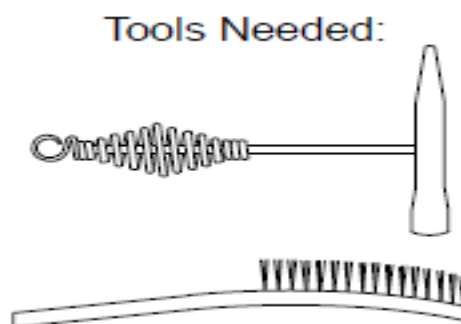


Figure 5: Tools needed During SMAW process

2.5 WELD JOINT

The goal of the designs is full penetration with minimal risk of burn-through. For duplex stainless steels, a weld joint design must enable 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 to the land thickness or gap. When grinding must be done, special attention should be given to uniformity of the weld preparation and the fit up. Any grinding burr should be removed to maintain complete fusion and penetration.

For an austenitic stainless steel, a skilled welder can overcome some deficiencies in joint preparation by manipulation of the torch. For a duplex stainless steel, 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.

2.6 MECHANICAL AND CORROSION PROPERTIES

A critically important factor for all types of stainless steels is that the surfaces must be thoroughly cleaned prior to and after welding for optimum corrosion resistance. A post-weld cleaning treatment it is often necessary to restore the stainless steel surface and achieve good corrosion resistance after fabrication. Post-weld cleaning is primarily used to remove weld oxides and surface defects such as e.g. spatter, slag inclusions and undercut. The most reliable test method to verify if a material is corrosion resistant or not, test it in the specified environment in real conditions.

MECHANICAL TESTING

In welded structures, the welds typically have a mechanical purpose. Loads must be carried across the weld joint. Standard mechanical tests have been devised to demonstrate that not only the base metals but also the entire welded joint can fulfill this mechanical purpose.

2.6.1 TENSILE TEST

Tensile testing is performed to evaluate the strength and ductility of the weld metal. Often the weld metal strength is higher and the ductility lower than the base metal.

The most important characteristic values which are determined by this test are: yield stress, tensile strength, and elongation [9].

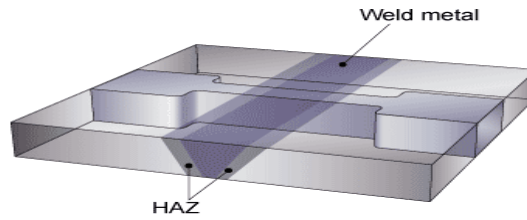


Figure 6: Square or rectangular cross tensile test piece (www.gantep.edu.tr)

The tension testing of welds is somewhat more involved than for base metal because the weld test section is heterogeneous in nature, composed of the deposit weld metal, the HAZ and the unaffected base metal. Tensile test specimen can be either transverse or longitudinal depends on the loading on the welded joint.

Figure 5 below shows an example of how a transverse specimen is prepared from the welded joint [11].

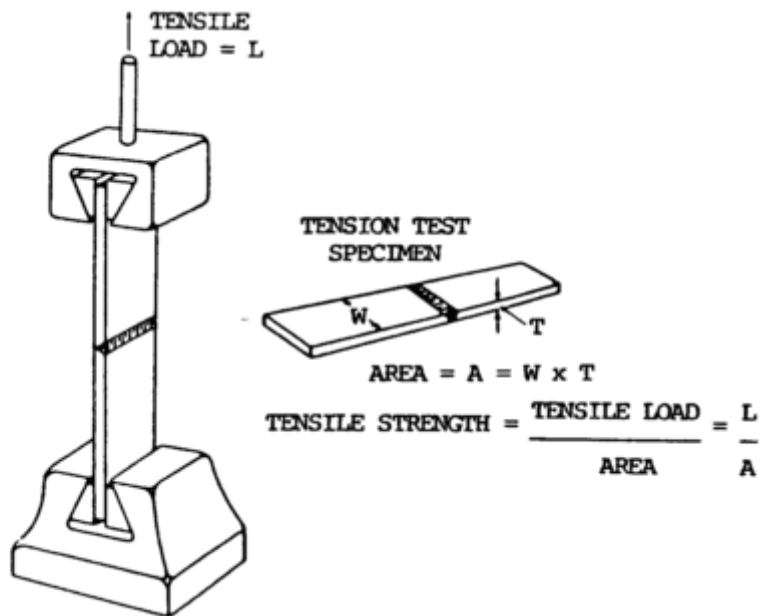


Figure 7: tensile strength test specimen and test method (www.angelfire.com).

2.6.2 BEND TEST

The guided bend test determines the quality (deformability) of the weld metal at the face and root of the weld joint, as well as the degree of penetration and fusion to the base metal [11]. The specimens are machined from the weld joint and figure 6 below shows the guided bend test. If a surface crack develops, the test will be stopped and the angle to which the specimen could be bent is measured [10].

Various types of bend tests are used to evaluate the ductility and soundness of welded joints as the technological bend test in figure 7 below. Bend specimens may be longitudinal or transverse to the weld axis and may be bent in simple three-or four-point bending (free bend) or around a mandrel of specified diameter (guided bend). The top and bottom surfaces of a welded plate frequently designated as the face and root surfaces, respectively. Face bends have the weld face on the tension side of the bend specimen; with root bends, the weld root is on the convex side. In bend testing of thick plates, transverse slices are usually cut from the welded joint and bent so that one of the cut side surfaces becomes the convex side of the bend specimen; these are referred to as side bends [10].

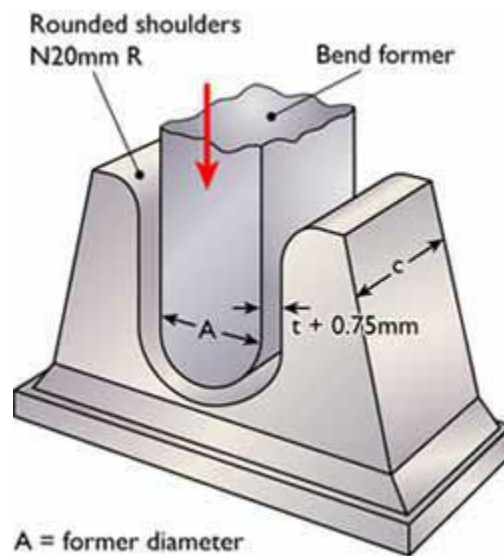


Figure 8: Guided bend test jig (www.gantep.edu.tr)

Technological Bend Test

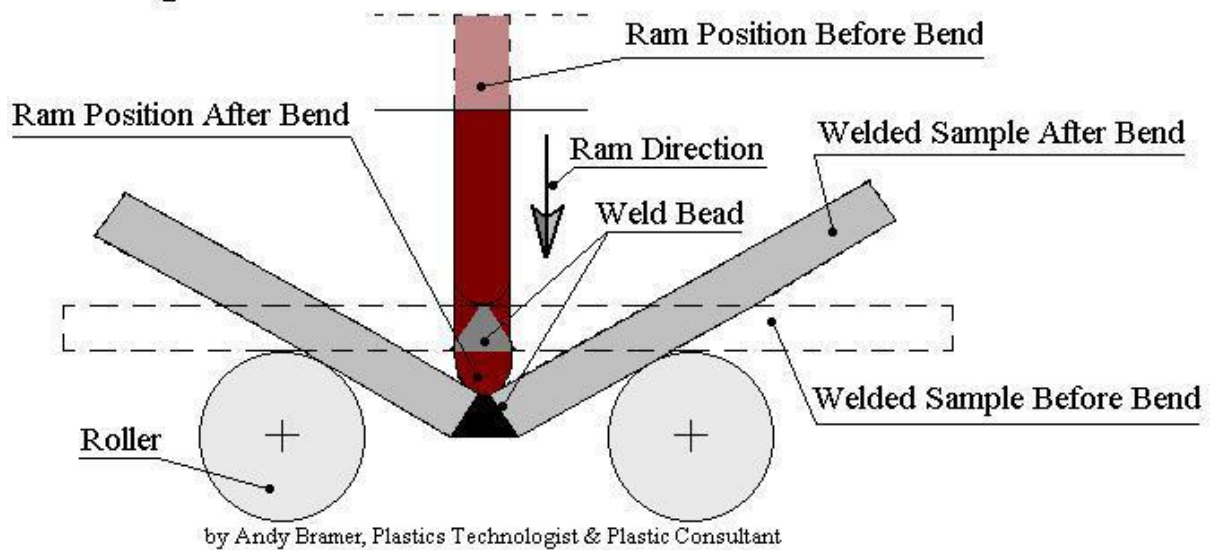


Figure 9: Technological Bend test

2.6.3 HARDNESS TEST

Each microstructure has its particular characteristics and one of the important characteristics is the hardness of the microstructure throughout the weld area. Brinell, Rockwell, Vickers and Knoop hardness tests can be applicable to welds. Hardness measurements can provide information about the metallurgical changes caused by welding [9].

In construction steels, for example, rapid cooling from high HAZ temperature may cause the formation of martensite of much higher hardness than the base metal. Hardness values in a welded joint are usually sensitive to such conditions of welding, as the process used, heat input, preheat or interpass temp, electrode compositions, and plate thickness. Hardness testing of welds is performed on ground, polished or polished and etched cross-section of the joint area.

Indentations are made in the specific areas of interests, including the weld center line, face or root regions of the deposit, the HAZ, and the base metal. Which hardness test is used depends primarily on the hardness or strength of the material, the size of the welded joint, and the type of information desired. The Brinell test produces a large indentation, typically 2 to 5.6 mm in diameter, and it is thus suited on for large welds [10].

The Rockwell test produces a much smaller indentation more suited for hardness traverses. The Vickers and Knoop tests make relatively small indentations and thus are well-suited for hardness measurements of the various regions of the HAZ and for fine-scale traverses [10].

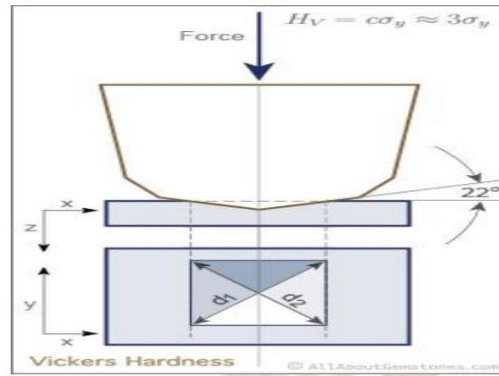


Figure 10: Vickers Hardness test (www.gantep.edu.tr)

2.6.4 CHARPY-V TOUGHNESS TEST

A determination of the toughness of a welded joint is carried out with the notched bar impact test. A cuboid specimen with a V-notch is placed on a support and then hit by a pendulum ram of the impact testing machine (with very tough materials, the specimen will be bent and drawn through the supports) and the energy used is measured [9].



Figure 11: Charpy test specimen (www.kau.ac.kr).

2.7 CORROSION TESTING

Corrosion testing is done in a ferric chloride solution at a constant temperature, +/- 25°C for welds for 72 hours. The corrosion sample is immersed inside a 6% ferric chloride solution. According to the ASTM G48A-test standard, the ferric chloride solution is very corrosive due to the simultaneous presence of chloride ions and oxidising ferric ions. After the test time the samples are cleaned and weighed and the surfaces are examined for pitting.

2.8 DISSIMILAR WELDING OF STAINLESS STEEL

The desired microstructure, mechanical and corrosion of stainless steels are obtained by optimizing the balance of the important alloying elements. From now on, the focus will be on dissimilar welding of austenitic and lean duplex grades.

Dissimilar metal welding is joining of two different stainless steel grades. One stainless steel can be joined to another stainless steel, and varying degrees of dissimilarity are possible. This transition is often used where a transition in mechanical properties and/or performance in service are required [2].

One stainless steel can be joined to another stainless steel, and varying degrees of dissimilarity are possible. For example, steels with different alloy content but similar microstructure may be joined, or steels of different alloy content and microstructure may be joined. A common convenience issue is to identify a single metal suitable for a job involving more than one combination of base metals in order to eliminate the risk of interchanging filler materials or to reduce costs by reducing the required inventory of filler materials [2].

When welding to austenitic grades, the austenitic filler metals with low carbon and a molybdenum content intermediate between the two steels are typically used. AWS E309LMo/ER309LMo is frequently used for these joints. Duplex stainless steels can be welded to other duplex stainless steels, to austenitic stainless steels, and to carbon and low alloy steels.

Austenitic stainless steel joined to Lean duplex stainless steel, the joining of 304L/316L stainless steel to 2001 lean duplex stainless steel, filler material selection to obtain ferrite either 309LMo filler material or 2209 filler material is acceptable. Choice is based on availability and cost. The two base materials contain molybdenum and it makes them to be resistant to localized corrosion (particularly pitting corrosion).

3. RESEARCH FOCUS

For this project the focus will be to determine the influence of welding on microstructure, mechanical and corrosion properties.

3.1 HYPOTHESIS STATEMENT / RESEARCH OBJECTIVE

Verify whether joining types 304L or 316L austenitic stainless steel to 2001 lean duplex stainless steel compromises the mechanical, properties and microstructure of the welds in any significant way.

The mechanical properties and microstructures of dissimilar welds are influenced by welding. Weld metal strength should be equal to or higher than the weaker material being joined.

Weld joint to be used for structural purposes-Strength and performance are very important, so the welding method, joint design and filler metals (alloying elements plays a bigger role) chosen should create the right kind of microstructure and mechanical properties desired by the weld metal.

3.2 RESEARCH OUTCOMES

Welding variables

In this case, the welding variables are the:

- Welding speed
- Welding current
- Heat Input (HI) –max. 1.5kJmm

The above welding variables are controlled variables and they create the right kind of microstructure and mechanical properties desired by the weld metal if controlled and maintained at the right window period for the dissimilar materials.

Good impact results are good indication that the material has been successfully welded. Looking at the metallurgy of the weld, mechanical and corrosion properties, each start and stop of the arc is critical.

4. EXPERIMENTAL WORK

A welding procedure formulated for the weld joint to fulfil the minimum properties of the base metal and mechanical, corrosion properties and Microstructural examination for the study of properties of dissimilar weld joint.

4.1 EXPERIMENTAL PLAN

During welding the following must be taken into account:

- Use of right heat input (1-1.5kJ/mm) and avoid rapid cooling.
- Avoid striking the arc outside the joint.
- Use correct root gap.
- Not draw long arc when welding.
- Interpass temp between 150°C.

After welding the following should be done:

- Thorough cleaning of all slag and oxide on and around the weld must be removed.
- Brushing done manually.
- Post weld heat treatment not required for 304L/316L austenitic stainless steel and normally not required for Lean Duplex stainless steel 2001.
- The weld discoloration should be removed by pickling and passivation to restore maximum corrosion resistance.

4.2 EXPERIMENTAL PROCEDURE

Butt joints of plates 5mm in thickness was performed with the use of Shielded metal arc welding method (SMAW).

4.2.1 MATERIALS AND WELDING METHODS

Two dissimilar types of stainless steel including AISI 304L/316L austenitics and lean duplex (2001) as base metals supplied by Columbus stainless steel were used for this project, chemical composition and mechanical properties of the stainless steels presented in table 2 and table 3 below. L type of stainless steel contains less than 0.03 wt% carbon and it is fabricated with the aim to avoid chromium carbide precipitation in heat affected zone (HAZ).

Table 2: Chemical composition of base metals and filler materials with their Ni and Cr equivalents.

Alloy	C	Si	Mn	P	S	N	Cr	Ni	Mo	Others	Ni _{eq}	Cr _{eq}
304L	0.03	0.75	2	0.045	0.015	0.1	19.5	10.5			13.55	29.5
316L	0.03	0.75	2	0.045	0.015	0.1	18	13	2.5		16.05	20.5
LDX 2001	0.03	1	6	0.035	0.015	0.17	21.5	1.3	0.6	Cu: 1.0 max	7.7	23.1
ER309LMo	0.03	0.65	2.5	0.03	0.03	-	25	14	3	Cu: 0.75 max	15.24	28
ER2209	0.03	0.9	2	0.03	0.03	0.2	23.5	9.5	3.5	Cu: 0.75 max	14.73	25.3

The steel grade, required properties, material thickness, welding position and surrounding environment were taken into account when choosing the welding method.

Table 3: Mechanical properties of base and filler materials.

Alloy	Yield strength (MPa)	Tensile Strength (MPa)	%elongation
314L	220	520-700	45
316L	240	530-630	55
2001	450	620 M	25
309LMo	440	620	25
2209	560	720	26

4.2.2 WRC-1992 TO THE MICROSTRUCTURE

By using the WRC-1992 diagram, in Figure 12 below, to predict the weld microstructure, it was found that by using E309LMo and E2209 electrodes, the final weld will have some ferrite ($FN \pm 28$), and this is good since it will prevent hot cracking in the joint.

Using the WRC-1992 diagram to predict the effects of dilution during dissimilar welding, the nickel and chromium equivalents were calculated (included in table 2 above) and an assumption of each base metal contributing equally to the weld metal, Mixing (50%) and normal 30% base metal dilution with the GMAW method was made:

Table 4: 1992 WRC predicted ferrite numbers

Green - ER309LMo	Blue- ER2209
316L/2001 FN=29	316L/2001 FN=28
304L/2001 FN=34	304L/2001 FN=29

Both the filler Metals alloys are situated in the Ferrite phase fields, they solidify as primary δ -ferrite and will be resistant to solidification hot cracking. Figure 12 below shows the WRC-1992 to predict dilution effects in dissimilar metal joints with the calculated regions of the weldments.

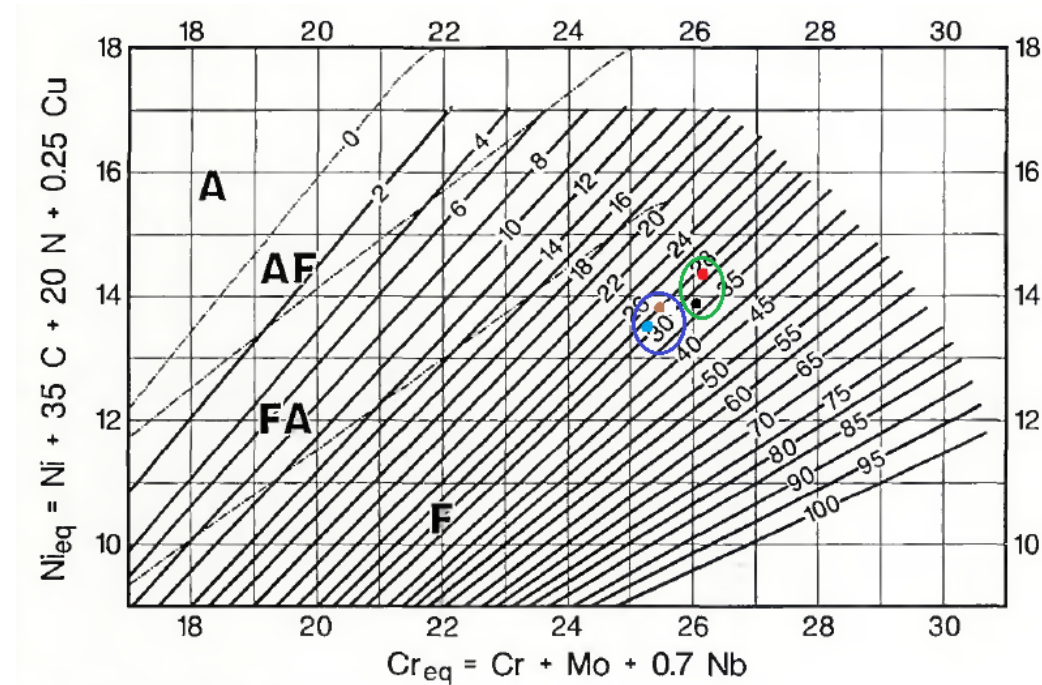


Figure 12: WRC-1992 to predict dilution effects in dissimilar metal joints.

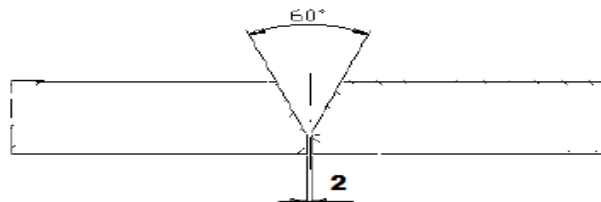


Figure 13: Edge preparation for dissimilar welded joints.

Welded joint in Figure 13 above was performed using a V groove butt weld preparation in order to obtain dilutions between base and welded metal. An austenite 309LMo and duplex 2209 stainless steel filler metals, both with a diameter of 2mm were used for this project. A root pass and two more passes were performed to fill the whole joint with a heat input of 1.15kJ.

4.2.3 WELDING METHOD

Shielded Metal Arc Welding (SMAW) process, because it is a suitable welding process for it can be used to weld both stainless steels with whatever plate thickness in any position and no shielding gas is required because self shielded filler material were used.

Table 5: Welding Parameters and conditions.

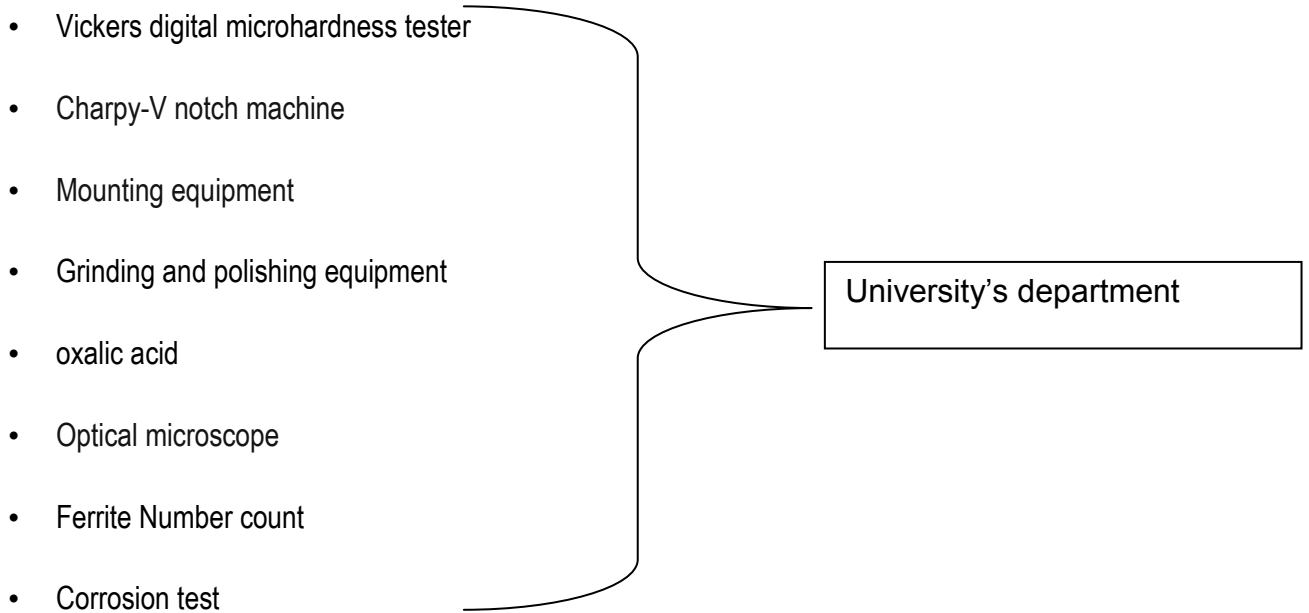
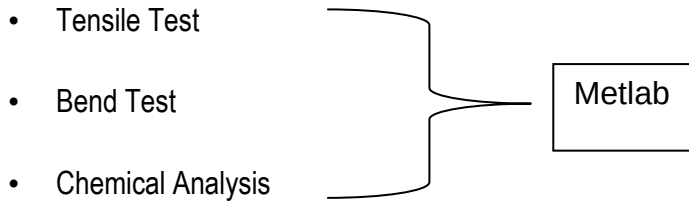
Materials	Filler materials Material	Diameter of filler materials (mm)	Current (A)	Welding Groove	No of Passes	Average Welding speed (mms ⁻¹)
304L to 2001	E309LMo	φ2	1. Root pass 86	V	3	6.4
			2. Cover pass 93			
			3. Close pass 93			
316L to 2001	E2209	φ2	1. Root pass 86	V	3	6.4
			2. Cover pass 93			
			3. Close pass 93			
304L to 2001	E2209	φ2	1. Root pass 86	V	3	6.4
			2. Cover pass 93			
			3. Close pass 93			
316L to 2001	E309LMo	φ2	1. Root pass 86	V	3	6.4
			2. Cover pass 93			
			3. Close pass 93			

The welding parameters and conditions used for this project are given in table 5 above.

4.2.6 APPARATUS USED

The following equipments will be used for this project:

- Edge preparation – Orion Engineering
- Southern African Institute of Welding (SAIW) GMAW welding equipment



5. TEST METHODS

5.1 MECHANICAL AND CORROSION PROPERTIES

A definite procedure for testing of welds is not a normal standard procedure. The tests proposed are from standards that describe how welding procedure specifications are qualified. Mechanical properties of the weldments will be determined by the following methods:

5.1.1 HARDNESS MEASUREMENTS

Property of hardness largely determines the resistance to scratching, wear, penetration, machinability and the ability to resist permanent deformation. Microhardness tests were carried out using a calibrated Vickers digital microhardness tester.

The microhardness measurements were carried across the first base metal, the HAZ, weld metal and through to the second base metal. The load of 300g was used to carry out the hardness readings using digital Vickers hardness tester, with a diamond pyramid. All the hardness tests were carried under ambient temperature.

Figure 12 below shows the location used when carrying out the experiment.

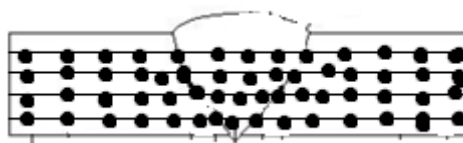


Figure 13: Location Points



Figure 14: Microhardness tester

5.1.2 CHARPY IMPACT TESTS

Impact tests will be done for the fusion welds carried out for the samples prepared from the welded joints. Charpy impact test will be used to determine the amount of energy absorbed by the dissimilar welds during fracture. Charpy-V specimens in parent base and weld metal in accordance with standard EN 10045-1.

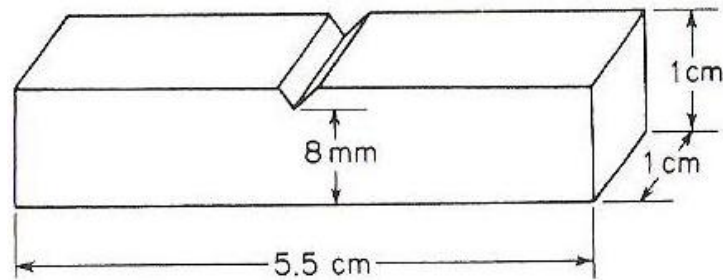


Figure 15: Standard sample specimen for the Charpy impact test.

Samples were notched using the Chris Machine shown in Figure 17 below before the experiment to have a standard sample shown in Figure 15 above.



Figure 16: Chris notching machine model number SRC-CH 1B and SN: 55/300/19 that was used to notch the samples

Stainless steel samples, austenitics (304L/316L) and lean duplex (2001) that had been welded with two different filler materials (E309LMo and E2209) were used to conduct the Charpy impact test at room temperature. The Mohr and Federhaff AG, pendulum impact test machine, machine no 1046 type

PSW30 (shown below in Figure18) was used to perform the experiment. The values measured by the machine were multiplied by 9.81 m/s^2 to get the energy absorbed.



Figure 18: The Mohr and Federhaff AG, pendulum impact test machine, machine number 1046 type PSW30 that was used during the test

Three prepared specimen from each of the four welded samples were tested and an average of the three results was recorded.

5.1.3 TENSILE TEST

The test specimens were prepared according to the British standard EN 10002-1:895 from the welded samples, the design is shown in Figure 19 below and the test report for the results was according to the British standard EN 10204 3.1. The direction of the tensile was transverse to the weld and the tests were done at Metlab. Mechanical properties of supplied Columbus stainless steel and filler material used in this project were given in table 3. Tensile tests were carried out on the weldment of samples 304L-2001 and 316L-2001 stainless steel welded by E309LMo and E2209. Two prepared specimens per sample were used in tensile test for each four welded sample and average value was reported. Tensile properties of the weld and fracture location were determined.

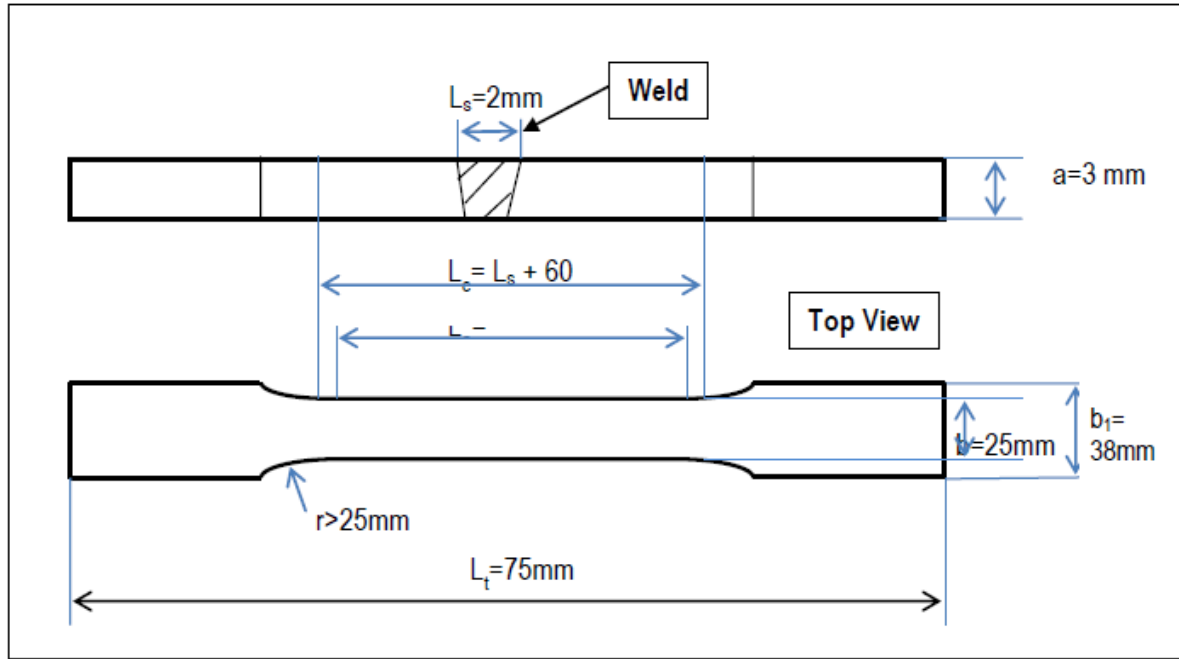


Figure 17: Tensile design of the transverse to weld according to BS EN 10204 3.1

Transverse to weld parameters used to test the specimens are in table 6 below.

Table 6: Tensile test parameters

Width (mm)	12.47
Thickness (mm)	4.07
Area (mm)	50.75
Gauge (mm)	50
Yield Load (kN)	15.36
Max Load (kN)	29.38

5.1.4 BEND TEST

A bend test will demonstrate both the quality control of the weld, determines its overall ductility and the effectiveness of the weld process. A transverse root bend and face bend tests were performed on prepared specimen from the welded plates as specified by the British standard EN 910:1996. The transverse and face bend tests were done at Metlab and the specimen containing the weld was loaded at the center point while supported at the end. The specimen was bent plastically between rollers to a maximum angle of 180°. The diameter of the rollers used was 20mm as according to the standard.

5.1.5 MICROSTRUCTURAL EXAMINATION

Microstructural examination was carried out on cross section of the austenitic and duplex stainless steel weldments studied in this project. The samples were cut from the weldment plate and mounted. Mounted samples were flatted by a rough 60 and 240 grid SiC abrasive paper to expose surface for evaluation and samples were ground on sequentially finer grades of silicon carbide paper down from 400 to 1200 grid. The samples were then polished to remove the remaining scratches using 9, 3 and 1 μ m polishing solutions. After getting the mirror image from polishing the samples were washed with a fabricating liquid and cleaned. Samples were etched using oxalic acid prepared by dissolving 10g of oxalic acid into 100ml of water. Then the microstructures of parent materials, the high temperature heat affected zone (HTHAZ), weld metal were observed by optical microscope.

5.1.6 FERRITE COUNT

FERITSCOPE was used to do Measurement of the Ferrite Content in the weld metal of Austenitic and Duplex Stainless steel. If the ferrite content is too low, then the welded material is susceptible to cracking, if the ferrite content is too high, the toughness, ductility as well as the corrosion resistance of the steel is reduced.

5.1.7 CORROSION TEST

Corrosion test was done in a ferric chloride solution at a constant temperature, 25 °C for welds for 72 hours. The corrosion samples were immersed inside a 6% ferric chloride solution according to the ASTM G48A-test standard.

6. RESULTS AND DISCUSSION

6.1 HARDNESS

The hardness was measured by Vickers hardness measurements along the cross-section of welded specimens in three zones the base metals, weld metal zone (W. M) and heat affected zone (HAZ). Microhardness done on the first base metal across the weld metal to the second base metal shown in figure 20, 21 below. Hardness tests showed that the highest hardness value appears in the 2001 Lean duplex (LDX) stainless steel and the HAZ with higher hardness values is that made of LDX 2001 and both the filler material. It is evident from the two graphs below, that the austenitics 304L and 316L have the lowest hardness values.

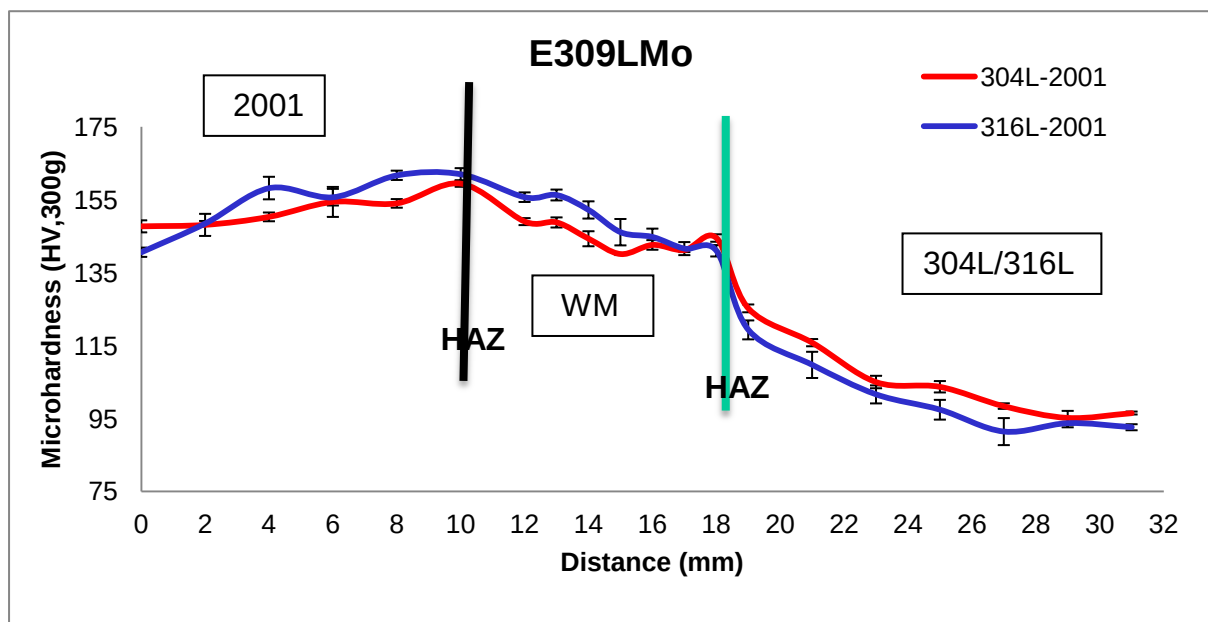


Figure 18: Base materials and weldment welded using 309LMo

From figure 20 above, it is evident that the weldment for 316L to 2001 using filler material E309LMo has the higher hardness as compared to 304L to 2001 (location points 10 to 18).

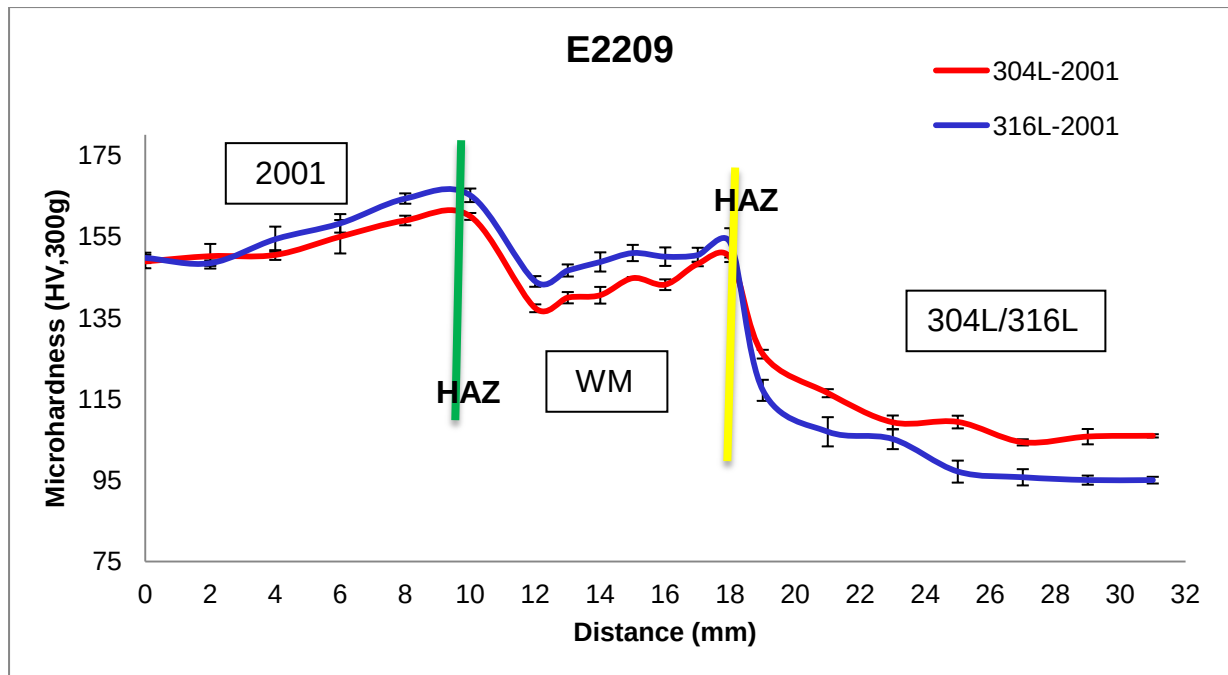


Figure 19: Base and weldment for 316L to 2001 welded using 2209

Hardness values in figure 21 above for both sets of base metals using filler material E2209 behave in a similar manner, a huge drop in hardness values is witnessed from point 10 (HAZ on the lean duplex side base material) to point 12 (Weld metal) but remains constant throughout the weldmetal.

6.2 CHARPY IMPACT TEST

Charpy Impact energies absorbed by the weldment joined by Shielded metal arc welding (SMAW) is given in table 7 below, which shows that the materials joined using E2209, a duplex filler material absorbed more energy than the one joined by a highly alloyed filler material, E309LMo.

Table 7: Charpy Impact test results of weldments

Materials	Filler materials	Impact Energy (J)	STDEV
304L- 2001	309LMo	84	2
316L - 2001	309LMo	88	2
304L - 2001	2209	114	3
316L - 2001	2209	122	4

As seen from the table 7, impact energy of 304L is a bit lower than that of 316 L weldment for both welding consumables. As the charpy impact test provides the energy needed to break a material under impact loading, only the samples welded with E309LMo filler material broke under impact and the samples welded with the E2209 stainless steel duplex did not break under impact, as shown in Figure 22, Figure 23 respectively. Samples welded with 309LMo fractured in a more brittle manner than the 2209 filler metal

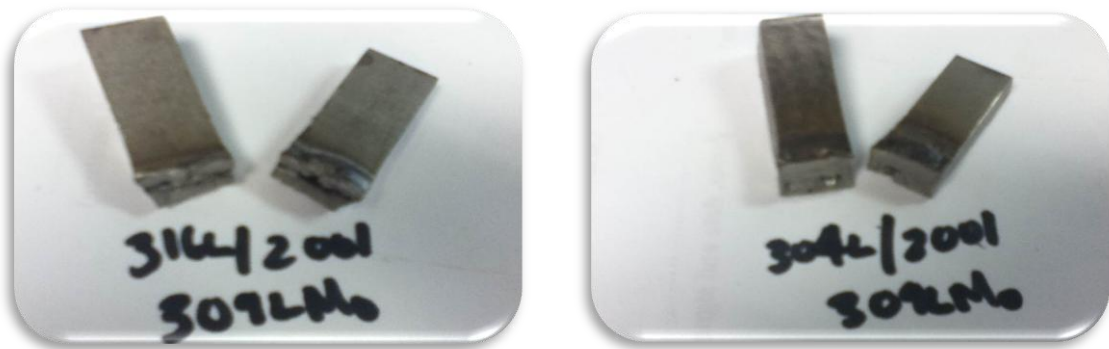


Figure 20: Photographs of impact samples welded using 309LMo austenitic stainless steel.



Figure 21: Photographs of impact samples welded using 2209 duplex stainless steel

The multipass of the weld deposits used when welding also contributed to the higher notch toughness as a result of further austenite formation in the reheated regions of the weld metal and the heat affected zone (HAZ).

6.3 TENSILE TEST

Table 8 shows the results of tensile test specimens of dissimilar welds of stainless steel 304L/316L and lean duplex 2001 stainless steel welded by SMAW process with using two different electrodes, E309LMo and E2209. The highest tensile strength was obtained by using the electrode E309LMo and the test results are good results. The strength of dissimilar welds is not to be below the minimum tensile strength for the weaker stainless steel grade. The results listed in table 8 show that this condition was fulfilled for tested joints. For all specimens, the fracture location was at weld. It can also be observed that for all the weldments the 304L to 2001 joint for all the filler materials have higher UTS and yield strength values when compared to 316 to 2001 joints.

Table 8: Tensile results for the weldments.

Materials	Filler Materials	Ultimate strength (MPa) (Mean values)	Yield strength (MPa) (Mean values)	% elongation (Mean values)
316L-2001	E2209	602	308	18
304L-2001	E2209	654	347	29
316L-2001	E309LMo	518	328	20
304L-2001	E309LMo	587	352	16

6.4 BEND TEST

Table 8 below shows the results of bending test for dissimilar welds of austenitics 304L/316L and lean duplex 2001 stainless steel.

Table 8: Bend Test Results

Base Materials	Filler Material	Quantity tested	Bending Angle	Visual Inspection
304L – 2001	E309LMo	2 Face	180°	1 Acceptable 1 Not acceptable
		2 Root		1 Acceptable 1 Not acceptable
304L - 2001	E2209	2 Face	180°	Acceptable
		2 Root		1 Acceptable 1 Not acceptable
316L – 2001	E309LMo	2 Face	180°	1 Acceptable 1 Not acceptable
		2 Root		Not Acceptable
316L - 2001	E2209	2 Face	180°	1 Acceptable 1 Not acceptable
		2 Root		Not Acceptable

For the specimen that failed the face bend test it was because they lacked fusion on the side of the walls and the root bend test specimen failed because of lack of root fusion. For the specimen welded using filler material E309LMo, with base materials 316L and failed the root bend test because of lack of root fusion and there was also slag visible on the specimen.

6.5 MICROSTRUCTURAL EXAMINATION

Microstructural examinations were aimed to determine the general microstructure of the welded metal and heat affected zones. Special attention was paid to the fusion line for seeking any solidification cracking in the weld structure. Microstructures of 304L/316L austenitic to 2001 lean duplex stainless steel base materials shown in figure 22 (a, b and c) respectively and weldment using filler material for dissimilar welding using a highly alloyed E309LMo and a duplex E2209 filler material are shown in Figures 23 respectively.

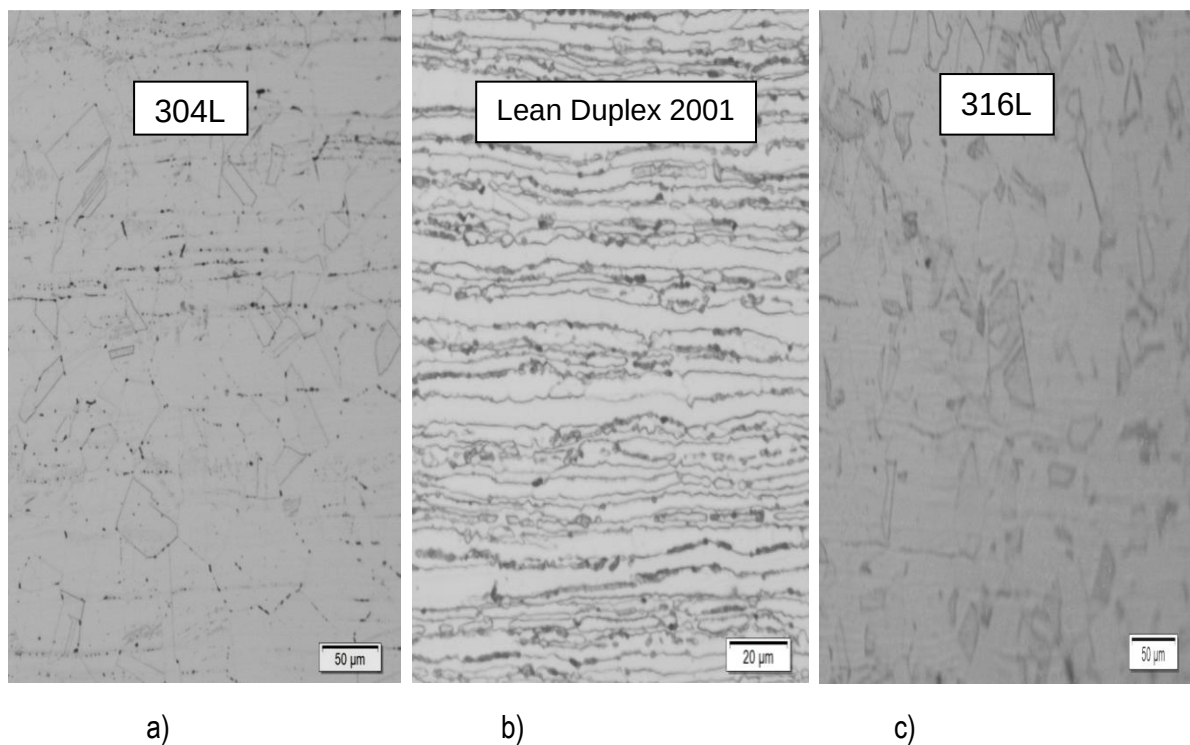


Figure 22: Microstructures of types 304L, 316L and 2001 base metals

The microstructures of the weld metals for all the joints are similar as it can be seen from figure 25 below. The weld metal microstructures in Figure 25 below consists of δ -ferrite grains, with grain boundary austenite and Widmanstätten austenite side-plates. It is evident in figure 25 (b) that the weld metal has a well balanced mix of ferrite and austenite. The microstructure of weld metal and δ -ferrite ratio was assessed using WRC diagrams with consideration of chemical composition of base metals

and filler material before welding. It was mentioned by El Batahgy in his study that transition in solidification from austenite to ferrite is related with cooling rate rather than composition of the austenitic stainless steel and austenite and ferrite microstructure occur [11].

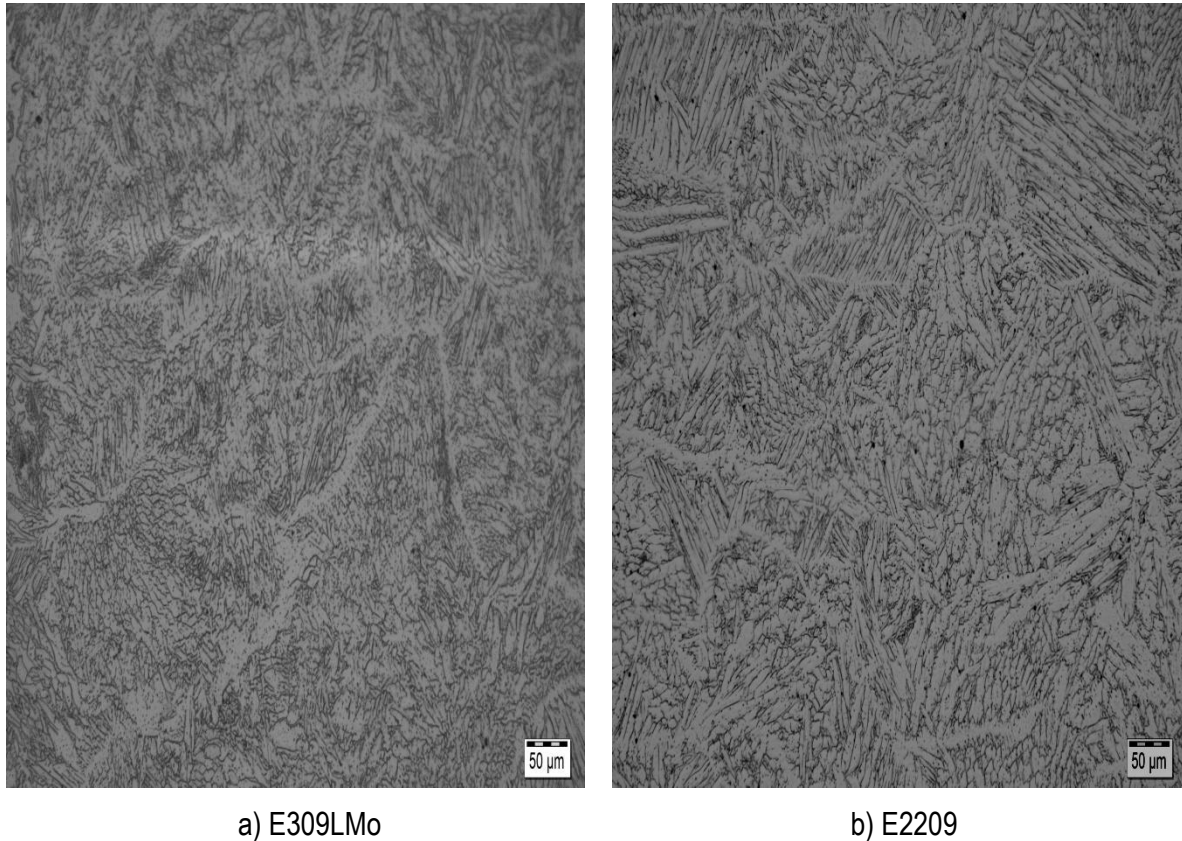


Figure 23: Microstructures of weld metal

The heat affected zone microstructure is a critical portion of the weld joint as it affects the properties of the weld joint. From the weld metal and the HAZ from both sides of the base metals there was no evidence of any solidification cracking as shown in figure 24, 25 and 26 respectively. High Temperature Heat affected zone (HTHAZ) microstructure could be critical for welded joint properties [13]. For examined welds the very narrow zones of about 500-750μm were observed on the lean duplex steel side (Fig. 24 & 26). The ferrite content in that zone should be higher in comparison to bulk weld metal as it the duplex side. The widths of HTHAZ from 304L and 316L stainless steel sides was extremely narrow and reach 113-120 μm.

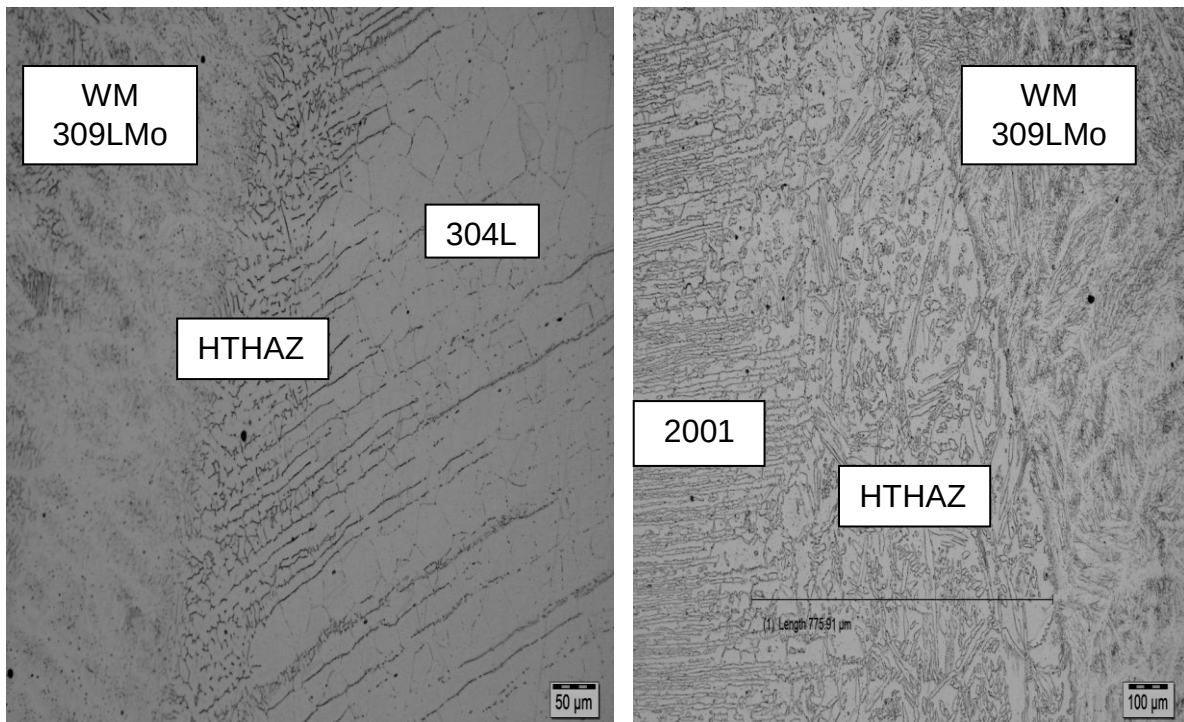


Figure 24: Microstructures of types 304L, 2001 and the high temperature heat affected zone (HTHAZ) with 309LMo weld metal

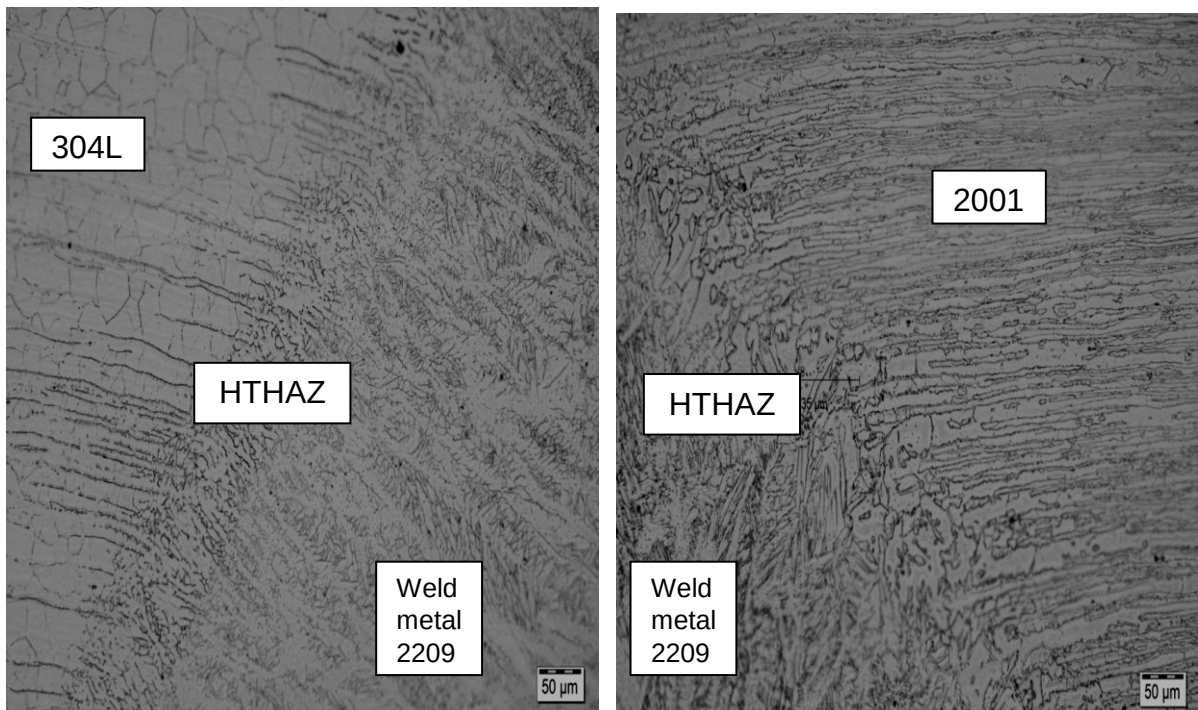


Figure 25: Microstructures of types 304L, 2001 and the high temperature heat affected zone (HTHAZ) with 2209 weld metal

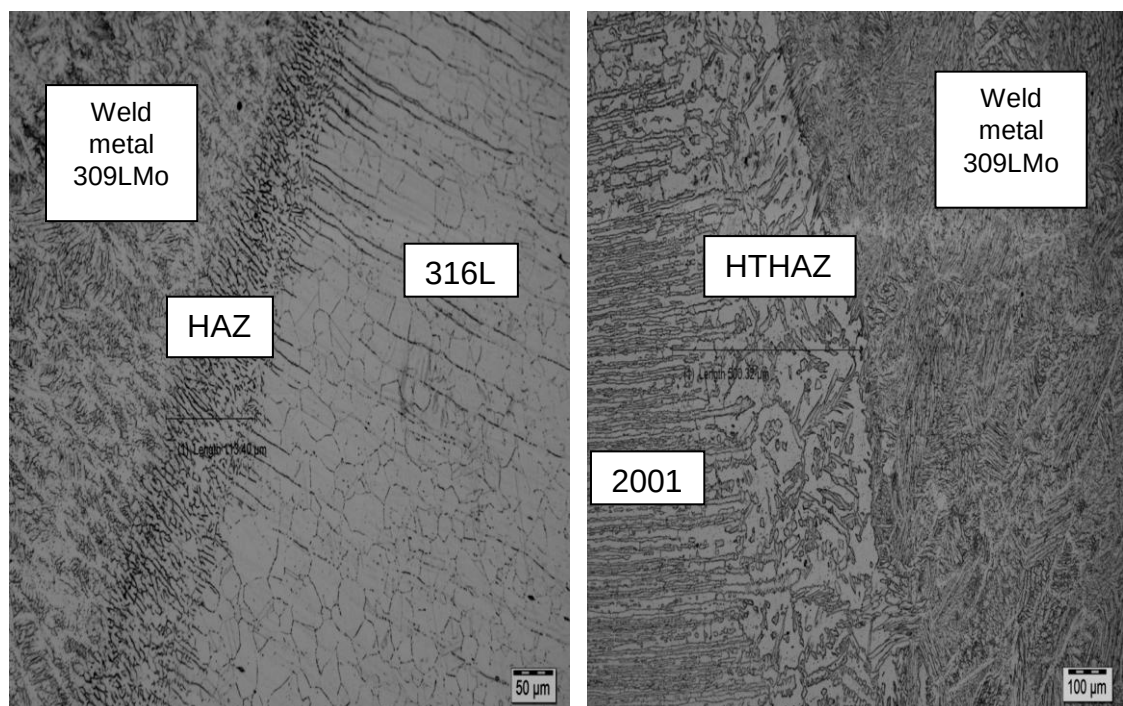


Figure 26: Microstructures of types 316L, 2001 and the high temperature heat affected zone (HTHAZ) with 309LMo weld metal

6.6 FERRITE COUNT

Table 12 below shows that ferrite content in the weld metal for all specimen vary between an average 29% and 31% which acceptable and necessary to reduce the probability of forming microcracks in the weld zone.

Table 10: Ferrite content in the weld metal

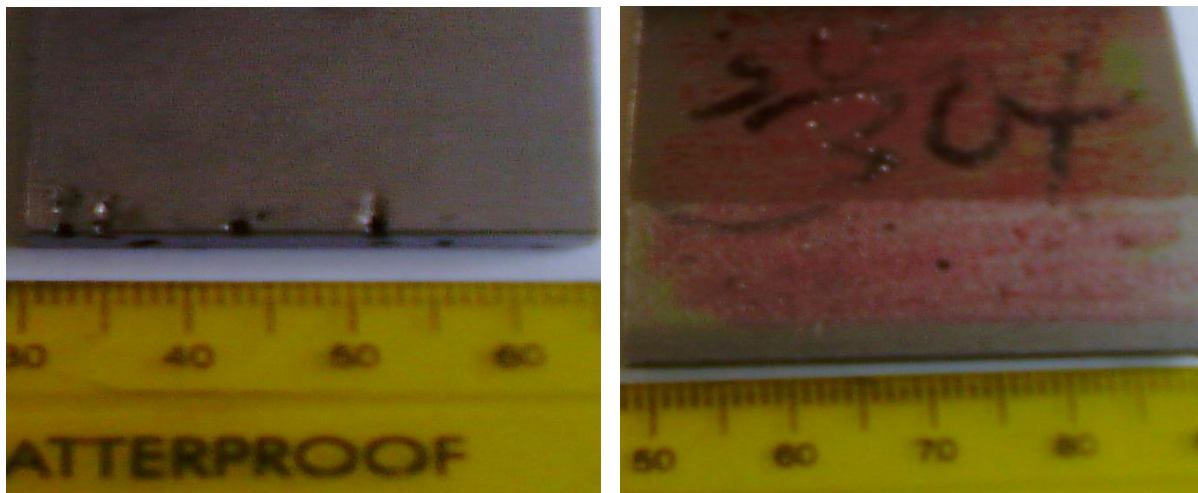
309LMo Weld metal	2209 Weld metal
316L/2001 FN=29	316L/2001 FN=30
STDEV = 5	STDEV = 4
304L/2001 FN=31	304/L2001 FN=28
STDEV = 3	STDEV = 3

6.5 CORROSION TEST

Table 9: Corrosion test results after 72 hours

Specimen	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)	Weight (72 hrs)	Weight loss (72 hrs)	Area mm ²	Corrosion < 4 g/m ²
316L-2209	90	36	4.99	170.78	170.41	0.37	3240	1.142
304L-2209	87	29	4.99	126.94	126.17	0.77	2523	3.052
316L-309LMo	87	35	4.99	157.4	156.69	0.71	3045	2.332
304L-309LMo	83	32	4.99	162.22	161.92	0.3	2656	0.163

In table 9 above for the corrosion tests done on all the four samples immersed in 6% ferric chloride solution for 72 hours at a constant temperature of about 25°C had an acceptable corrosion of less than 4 g/m². Corrosion was observed on the 304L plate as expected and bigger pits were observed on the lean duplex plate as shown in figure 27 below and no corrosion was observed on the weld metal for both filler materials.



a) Lean duplex 2001

b) austenitic 304L

Figure 27: Pitting corrosion on 2001 and 304L

Table 10: Corrosion test results after 168 hours

Specimen	Weight (g)	Weight (168 hrs)	Weight loss (168 hrs)	Area mm ²	Corrosion g/m ²
316L-2209	170.78	170.15	0.63	3240	1.944
304L-2209	126.94	125.78	1.16	2523	4.597
316L-309LMo	157.4	156.17	1.23	3045	4.039
304L-309LMo	162.22	161.73	0.49	2656	1.845

From table 10 above, it is evident that more weight loss was experienced by all the specimen and two of the specimen, 316L welded to 2001 by E309LMo and 304L welded to 2001 by E2209 experienced a corrosion of more the 4g/m².

7. Feasibility

- Edge preparation – Orion Engineering
- Welding – SAIW

- Tensile Test
- Bend Test
- Chemical Analysis

Metlab

- Hardness Test
- Charpy Test
- Microstructural evaluation
- Ferrite Number count
- Corrosion test

Department

Costs

- Edge preparation – R 3 169.20
- Tensile specimen preparation – R 5 909.76
- Tensile Test – R 2 982.24
- Bend Test – R 3 648
- Chemical Analysis – R 1 299.6

Costs in Total = R 17 008.8

8. SAFETY

Welding hazards pose an unusual combination of safety and health risks. Welding produces fumes, slag, sparks, gives off radiation, noise, involves gases and electricity, has the potential of burns, shock, fire and explosions.

When welding the following precautions were followed to make the welding environment more safely:

- Protective clothing worn at all times to cover all the exposed areas of the body for protection of sparks, hot spatter and radiation.
- Fire extinguisher located before welding.
- Before welding made sure there is no flammable material in the welding area
- Equipment operated after 2 hours of training on how to use the complex equipment by a supervisor.
- Welding was done in designated areas.
- Knowledge of materials (base and filler materials) and any coatings on them was known.
- Had to ground both the frame of the welding equipment and the metals being welded.
- Everybody close to the welding area was warned so that they are protected against arcs, fumes and other welding hazards.

List extracted from (statefundca.com) [4].

When etching,

- Worked in a well ventilated area
- Rubber gloves worn and safety goggles to protect the hand skin and eyes from etching liquid.
- Always had clean water nearby to flush eyes or skin if accidentally exposed to acid.
- When diluting the acid, acid was poured into water and not water into acid as this will cause the acid to heat up and splash out of the container.
- Once acid is too weak to be used for etching it was taken to a hazardous waste collection area and was never be poured down the drain.

When doing the Charpy V-notch test

- Always had a helping partner for the set up for the test is dangerous.

Corrosion Test

- PPE (glasses, gloves and lab coat)

9. CONCLUSION

The combination of austenitic E309LMO duplex E2209 filler and basic flux seems to be a good choice for dissimilar austenite- lean duplex joints.

- 316L to 2001 welded using E2209 showed higher impact energy values.
- Higher hardness obtained for 316L-2001 by E2209.
- Tensile test results show that the joint with the higher strength is that of welded with E309LMO and the fracture of dissimilar welds happened in the weld.
- Bending test showed that all the electrodes chosen for dissimilar welds are suitable and will need a skilled welder to fulfil the minimum requirements of the welds.
- No hot cracks were observed in weld metal deposits
- The weld metal microstructures consists of δ -ferrite grains, with grain boundary austenite and Widmanstätten austenite side-plates after cooling.

Weld metal seems to have met the minimum requirements for the joint.

10. References

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