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Study on Microstructural and Mechanical Properties of Joining 3CR12 Stainless Steel and S355 Carbon Steel by GMAW Using 308L Filler Wire

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Abstract: Stainless steel (SS) is an iron-chromium alloy containing at least 10.5% chromium (Cr) with other additives dependent on the grade requested and intended use of the steel. The Cr present creates a barrier between the metal's iron content and environmental oxygen making it resist corrosion. On the other hand, carbon steel is an iron-carbon alloy with very low corrosion resistance. This steel is high in strength and is often welded with stainless steel in areas that are prone to corrosion attack. The aim of this work was to study the butt and fillet weld properties of 3CR12 stainless steel and S355 carbon steel, and this was done by welding the two materials with a 308L filler wire using gas metal arc welding (GMAW). To ensure satisfactory performance of the welds, microstructural analysis and hardness testing were conducted for both the fillet and the butt samples and in addition, tensile testing was conducted for butt welded samples. The microstructures of both weld zones were found to contain austenite with less than 10% of ferrite. Martensite and Ferrite grains were found in the heat affected zones (HAZ) of the S355 whilst the HAZ of the 3CR12 was predominantly ferrite grains with martensitic islands. The butt weldments revealed higher hardness values than the fillet welds due to the high cooling rates and the S355 HAZ had higher hardness than 3CR12 HAZ. The tensile properties of the butt welds were higher than that of the individual materials.

Keywords: Dissimilar Welding, S355 Carbon Steel, 3CR12 Stainless Steel, 308L Filler Wire

1. Introduction

There is a worldwide drive to reduce production & operational costs as well as reducing the weight of railway cars. This means manufacturers are looking at various material combinations for lightweight solutions and cost reduction, hence joining of dissimilar metal arises. Dissimilar welding refers to the joining of different alloys to provide a wide variety of properties [1]. This type of welding is not only beneficial in railway cars but also in construction industries, assembly lines and power plants [2]. Welding of different metals involves welding materials with different chemical composition, mechanical properties, and thermal properties, for example, welding stainless steel and carbon steel together. Dissimilar welding is done with the purpose of combining several metal properties to increase equipment reliability, reduce material cost, improve mechanical & functional properties and/or reduce weight [3, 4]. It however poses a challenge due to the different properties of the base metals which results in difficulty when deciding on a filler metal, shielding gas and welding parameters such as the current, voltage, and welding speed [5]. Better control of corrosion resistance and mechanical properties is determined by the usage of a filler wire [6]. For example, ER309L filler wire is normally used in dissimilar welding of ferritic stainless steels to low carbon steels and recent studies have shown that ER308L is a more cost-effective filler material that can be used in substitution.

Ferritic stainless steel, 3CR12, was developed as a cost-effective alternative to AISI 409 ferritic stainless steel, with good weldability and affordability for mildly corrosive environments [7]. The chemical composition is carefully balanced such that some austenite is formed on heating to limit the grain growth at higher temperatures. Structural steel, S355 is a low alloyed carbon steel that can be obtained in various heat-treated conditions. The normalized and as-rolled conditions provide a pearlitic-ferritic microstructure suitable for welded construction for rolling stock of railway components [8]. S355 has a low carbon content which results in good weldability and less crack sensitive microstructures depending on the thickness and heat input used [9].

Grobler et al. [10] reported that the low carbon ferritic steel has poor weldability as after welding, there is martensite that forms on the grain boundaries which increases the hardness but decreases the ductility and corrosion resistance. The heat affected zone (HAZ) has grain growth which decreases the toughness and ductility of the material. The relationship between grain size and yield strength can be explained using the Hall-Petch equation which states that increasing grain size decreases yield strength [11]. From theory, a decrease in yield strength results in a decrease in ductility.

Previous researchers have focused on the effect of gas tungsten arc welding (GTAW) parameters for joining dissimilar metals using ER 308L filler metal [12]. Luijan et al. [12] studied the effect of welding parameters on joining low carbon steel and 3CR12 stainless steel by GTAW using an ER308L filler material and the results indicated that the influence of the welding parameters have significant effects on the microstructure and mechanical properties of the welded metal. GTAW is used for welding thin sections, up to 7mm, and to weld thicker sections, other welding processes such as GMAW, SMAW, etc. are used [13]. The aim of this paper was to study the microstructural and mechanical behavior of joining 3CR12 ferritic stainless steel with S355 structural steel by GMAW using ER308L filler metal in butt and fillet welds. This paper can be used in the selection of welding parameters in the manufacturing of coal wagons and beet sugar processing equipment, amongst others.

2. Methodology

2.1. Materials

Low carbon structural steel S355 and 3CR12 ferritic stainless steel were sectioned into 150mm x 400mm x 6mm plates and welded together using 308L filler wire. Gas metal arc welding (GMAW) was used to weld the samples with 99.99% helium used as the shielding gas and with a gas flowrate of 18l/min. Two types of welds were produced, namely, a butt weld and a fillet weld. The butt had two runs whilst the fillet weld had one. The chemical composition of the materials including the welding electrode is given in Table 1 and the welding parameters are given in Table 2. To quantify the ratio of ferrite to austenite forming elements in the steel, the ferrite factor (FF) was calculated using Equation 1.

$$FF = Cr + 6Si + 8Ti + 4Mo + 2Al - 40\,(C+N) - 2Mn - 4Ni \tag{1}$$

Table 1. *Chemical composition for S355 and 3CR12.*

Element	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Ni	%Cu	FF
3CR12	0.0099	0.740	0.790	0.027	0.00058	11.28	0.019	0.706	0.124	11.0
S355	0.094	0.343	1.363	0.014	0.0026	0.023	0.0025	0.0058	0.0089	-4.4
ER 308L	0.03	0.3-0.65	1.0-2.5	0.03	0.03	19.5-22.0	0.75 max	9.0-11.0	0.75 max	-30

Table 2. *Welding parameters.*

Test No.	Weld type	Current (A)	Wire Feed speed	Gas flow rate (l/min)	Heat Input (KJ/mm)
FW	Fillet	110	7664	18	0,5
BW	Butt	112	7032	18	0,7
		104	7032	18	0,5

2.2. Metallurgical Examination

The metallographic specimens were prepared by following the standard metallographic techniques i.e., cutting, mounting, polishing and etching. The samples were sectioned using an automatic cutting machine and then mounted using multifast resin at 160°C for 390s. The specimens were ground and then polished down to a 1µm finish using an automatic grinding and polishing machine. Water was used as a lubricant for all the grinding steps while polishing suspensions were used for the polishing steps. The samples were then etched using three different etchants, namely, nital for S355, Viella for 3CR12 and aqua regia for the weld. The microstructural analysis was carried out using an optical microscope and the micrographs were taken at a magnification of 10x and 20x with the areas of focus being the heat affected zones (HAZ) and the welds.

2.3. Mechanical Examination

Microhardness profile was conducted to determine the effect of welding parameters on the hardness of the weld by making use of the micro-Vickers hardness tester. A load of 0.5kgf was used and the indents were spaced 1mm apart to avoid any deformation from previous indents.

Tensile testing was done on the butt-welded samples using a tensile testing machine to determine the tensile properties and to evaluate the strength of the dissimilar joint.

3. Results

3.1. Microstructural Analysis

Microstructural analysis of the weld, the heat affected zones and the parent metal was conducted. Figures 1 and 2 shows the microstructures of the S355 and 3CR12 parent metals, respectively, before welding.

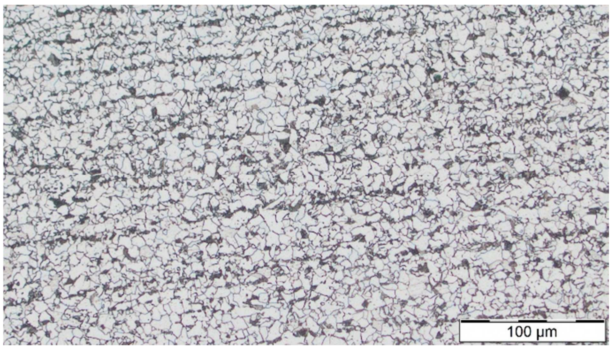


Figure 1. *Microstructure of the S355 parent metal showing a mixture of ferrite (light phase) and pearlite (dark phase).*

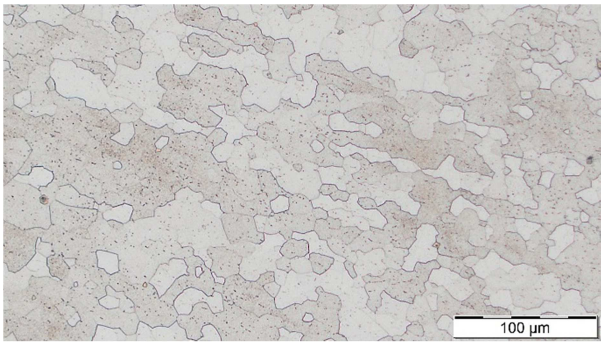
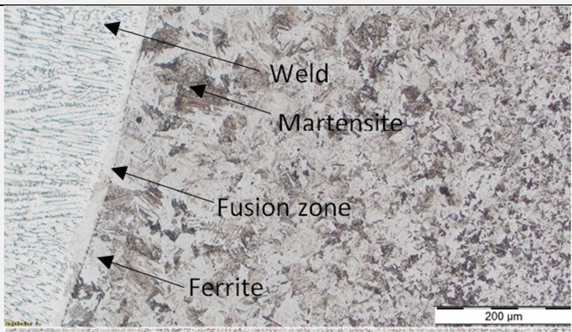
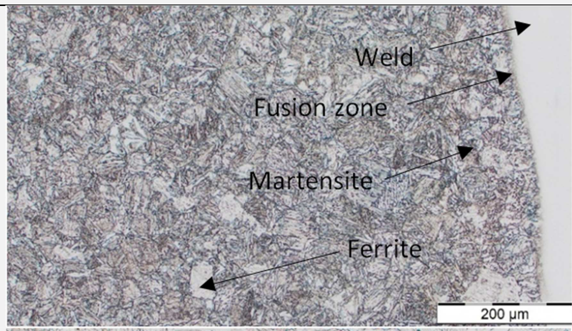
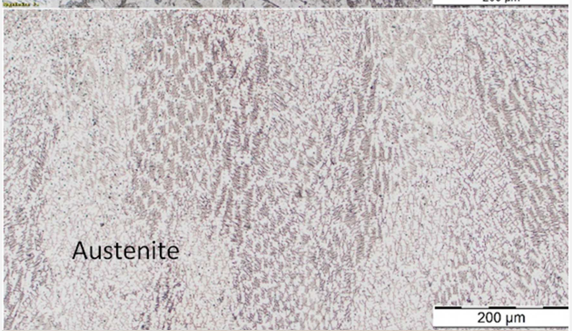
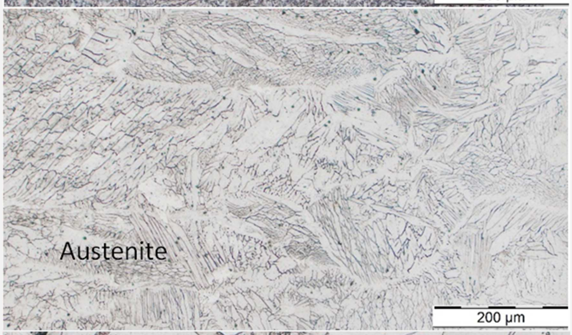
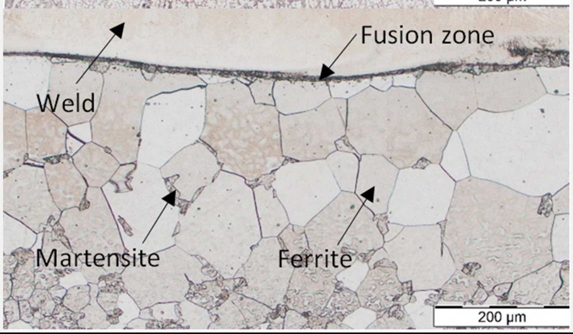
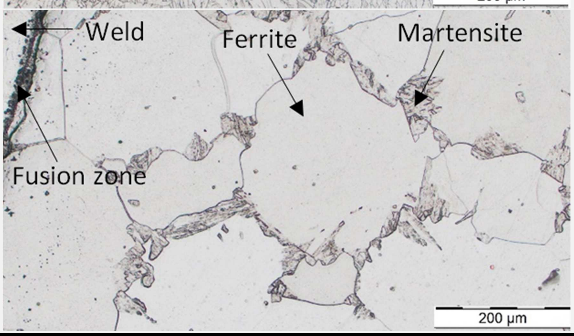


Figure 2. *Microstructure of the 3CR12 parent metal showing a fully ferritic structure.*

The microstructural analysis of the HAZ and weld metal for both fillet and butt-welds are summarised in Table 3.

Table 3. *Microstructures for the weld and the heat affected zones for S355 and 3CR12.*

	FW	BW
S355 HAZ		
Weld		
3CR12 HAZ		

The microstructure of the S355 HAZ consists of martensite and ferrite, the 3CR12 HAZ has ferrite grains with martensite islands and the weld is mainly austenite and has some traces of ferrite. The weld microstructures both contains of austenite and minimal ferrite and the butt-welded sample has coarser grains due to the high heat input it received which resulted in the re-crystallisation of the structure thus forming coarser grains.

3.2. Hardness

The hardness profile of the welded metal and the hardness values of both S355 and 3CR12 is indicated in Figure 3 and Table 4. The hardness of the weld metal is higher than that of the parent metal of both 3CR12 and S355 material. It is also clear from Figure 3 that the hardness of S355 HAZ is higher than that of 3CR12 HAZ, apart from one indentation. The difference can be explained by presence of high-volume fraction of martensite in the S355 HAZ compared to coarse ferrite grains with island of martensite. It must also be stated that the hardness of martensite is a function of carbon content and this means that the higher the carbon content, the harder the martensite, hence the average HAZ of the S355 is harder than that of 3CR12.

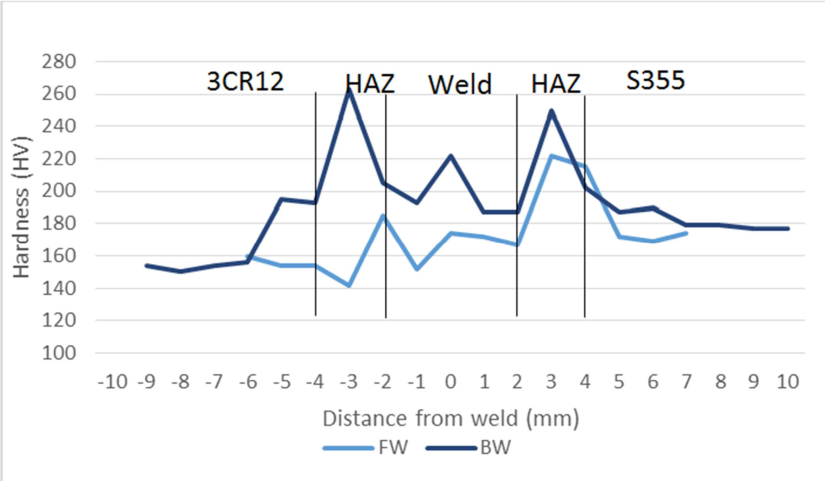


Figure 3. *Microhardness profile of the weld samples.*

Table 4. *Microhardness average values for the parent metals, weld and the heat affected zones.*

	3CR12 Parent	3CR12 HAZ	Weld	S355 HAZ	S355 Parent
FW	152.5	185	166.3	218.5	171.7
BW	153.5	217	198.8	226	180

The butt weld has a higher average hardness on the heat affected zone due to one indent that recorded a value higher than 260HV. A possible cause for this is the micro-indenter indenting on the martensitic island of the structure, which has high hardness.

3.3. Tensile Testing

Tensile testing was done on the butt-welded samples, two samples were tested for repeatability. The results are represented graphically in Figure 4 and summarized in Table 5.

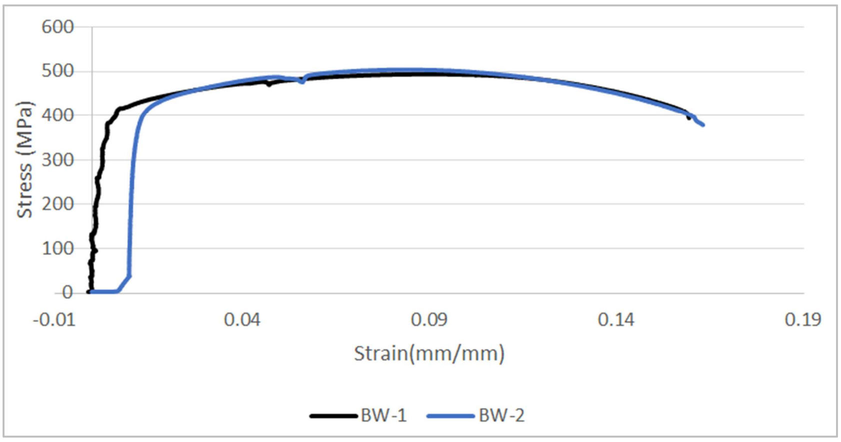


Figure 4. *Stress-strain graph for butt-welded samples.*

Table 5. *Tensile properties for butt welded samples.*

Property	BW-1	BW-2	3CR12	S355
Yield strength	394	398	≥320	≥355
Tensile strength	494	504	450-650	470-630
Elongation%	15.9	16.3	≥20	≥22

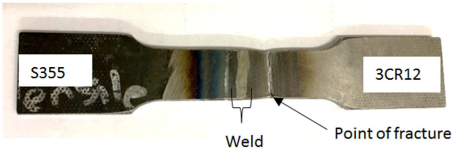


Figure 5. *Tensile sample showing weld and point of fracture.*

Table 5 indicates that the tensile strength of all the welded samples is higher than base substrate strength, however, the elongations were found to be inferior to that of the base substrates. The inferior elongations can be attributed to the presence of martensite in the HAZ.

4. Discussion

The microstructure of the weld metal can be explained using the Schaeffler diagram with the chemical composition of both the base metals and filler metals. This is done by calculating Ni_{eq} and Cr_{eq} of the parent metals and the filler metal using equation 2 and 3 below:

$$Ni_{eq} = \%Ni + 30\ x\%C + 0.5\ x\%Mn \quad (2)$$

$$Cr_{eq} = \%Cr + \%Mo + 1.5\ x\%Si + 0.5\ x\%Nb + 2\ x\%Ti \quad (3)$$

Table 6. *Nieq and Creq of the alloys used in this experiment.*

	S355JR+AR	3CR12	AISI 308
Ni_{eq}	3.50	1.40	11.08
Cr_{eq}	0.54	12.41	20.21

Figure 6 shows the Schaeffler diagram with the location of the various alloys. The 308L filler has a structure consisting of approximately 8% ferrite and 92% austenite. The tie line represents how the structure will vary with different dilutions of the filler metal. Literature [13] suggests that the dilution percentage ranges between 20-40% for most frequent welding processes, so if the parent metals contribute 30% to the dilution, the weld metal will consist of a mixture of austenite, martensite, and ferrite, see arrow in Figure 6.

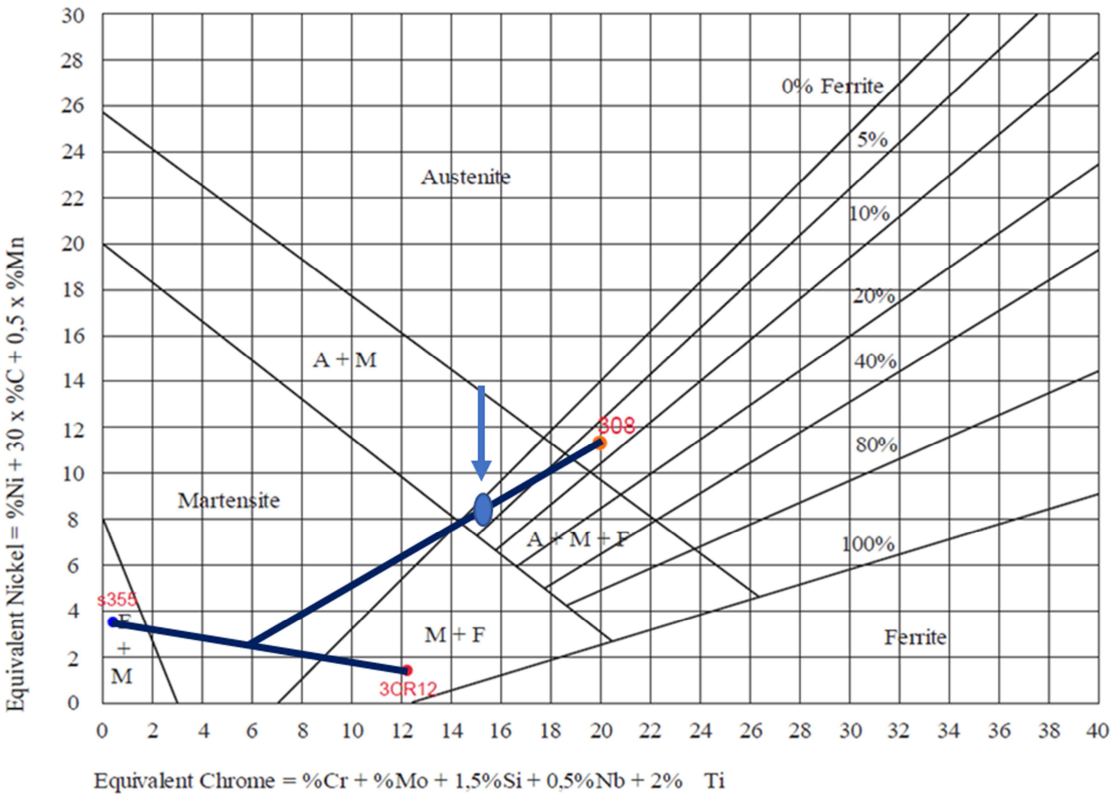


Figure 6. *Schaeffler diagram for the prediction of the weld metal microstructures [14].*

According to the Schaeffler diagram the weld metal should contain less than 5% ferrite. A proper amount of ferrite in the weld metal is essential as the ferrite structure inhibits hot cracks in the weld metal. This is because ferrite is able to dissolve harmful elements such as sulfur and phosphorus which can segregate to the weld metal and increases the risk of cracks when the residual stresses increase. Literature [14] has shown that weld metal containing between 2-10% ferrite structures in a stainless-steel weld metal is desirable.

The microstructures of the high temperature heat affected zone (HTHAZ) adjacent to weld interface on the S355 side consists mostly of martensite with ferrite structure. The S355 material has a low FF which indicates the higher possibility of forming austenite during heating which will transform to martensite upon rapid cooling, hence the presence of martensite on the HTHAZ adjacent to weld interface on the S355 side. The microstructure of the high temperature heat affected zone adjacent to weld interface or fusion line on the 3CR12 side after cooling showed excessive grain growth which consisted of δ-ferrite with grain boundary martensite.

3CR12 material has a higher FF which indicates lower possibility of forming austenite and that little austenite that has formed transformed to martensite upon rapid cooling. The microstructure of the weldment consists of ferrite with widmanstatten austenite. The Widmanstatten austenite occurred due to continuous cooling within the weldment [15]. The grains on the 3CR12 heat affected zone butt weld are bigger than those on the fillet weld and this can be attributed to the high heat input the butt weld receives in comparison to the fillet weld.

The hardness profile of the welded metal and the hardness values are indicated in Figure 3 and Table 4. The heat affected zone of S355 has a higher hardness than 3CR12 and this is because the hardness of steel is a function of carbon content. S355 has a higher carbon content than 3CR12 which increases the hardness of a material. The higher hardness can also be attributed to the large amounts of martensite present in S355 than in 3CR12. The weldment of the butt weld has a higher hardness than the fillet weld, this is because the butt weld has two weld runs and the second run has a lower heat input applied which contributed to higher cooling rates and formation of martensite. From Figure 4, the maximum hardness was about 263HV and the hardness values vary as the HAZ consists of martensite (harder) and ferrite (softer) and since microhardness can indent on specific phases, the higher values are of the martensite and lower values are of ferrite. This is due to the presence of fine acicular ferrite with small volume fraction of martensite.

During tensile testing, both samples failed on the 3CR12 side and both exhibited a ductile fracture face. The minimum yield and tensile strengths were met although the elongation was lower than the minimum stipulated in the Columbus Stainless material data sheet. The Hall-Petch equation shows that there is an inverse relationship between the grain size and the yield strength. Bigger grains equate less grain boundaries thus less opposition to dislocation movement and in turn, decreased strength of the material, making the 3CR12 HAZ to be more prone to fracture. The fracture being on the 3CR12 proves the weld to be of sound quality with the material and parameters used.

5. Conclusion

In this project, the microstructural and mechanical properties of butt and fillet welds were investigated. From the tests conducted, the following conclusions can be drawn:

1. The weldment of the butt weld has a higher hardness than that of the fillet welds.
2. The heat affected zone of the S355 has a higher hardness than that of 3CR12 due to the high carbon content and the large amounts of martensite formed after welding.
3. Both butt and fillet weldment microstructures are ferrite and widmanstatten austenite.
4. The 3CR12 heat affected zone has bigger grains on the butt weld than the fillet weld due to the high heat input on the butt weld.
5. The yield and tensile strength of the butt welds are higher than that of the individual materials.

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