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Weldability of welded joint alloy steel grade 91 to stainless steel grade 316L using filler metal ER NiCrMo-3 and ER 309LMo in power boiler piping and tubing

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Abstract

Welded joints between high alloy steel and austenitic stainless steel are commonly used in the power plant industry. In this research, the materials used were SA-335 P91 and 316L stainless steel with ERNiCrMo-3 and 309LMo fillers designed with a butt joint configuration. Several mechanical test (tensile test ASTM E8, Hardness Test ASTM E92) and microstructure examination was carried out to determine the tensile strength, hardness and microstructure of welded joint. The highest tensile strength is found in the ERNiCrMo-3 filler metal, namely 354.085 MPa, while the lowest is found in the 309LMo filler metal, namely 349.87 MPa. The highest hardness values for the ERNiCrMo-3 filler metal are found in base metal P91, HAZ P91, weld metal, HAZ stainless steel 316L, and base metal stainless steel 316L, with values respectively 212.77 HVN, 278 HVN, 239.53 HVN , 189.32 HVN, and 180.40 HVN. The lowest values for the 309LMo filler metal are 210.13 HVN, 266.12 HVN, 206.48 HVN, 175.59 HVN, and 172.32 HVN. Microstructural observations show the formation of a dendrite phase in the weld metal area with ERNiCrMo-3 filler metal and a delta ferrite phase in the weld metal area with 309LMo filler metal. No phase changes were observed in the P91 base metal, P91 HAZ, 316L stainless steel base metal, or 316L stainless steel HAZ areas. The results of the corrosion resistance test show that specimens with the ERNiCrMo-3 filler metal are more resistant to pitting corrosion compared to specimens with the 309LMo filler metal. The corrosion rate is 12,50 mm/years for ERNiCrMo-3, and 18,94 mm/years for 309LMo filler metal.

1. Introduction

Power generation plants require special steels that can be utilized for long periods under such high temperature and pressure steam conditions, such as high chromium (Cr) ferritic heat resisting steels containing 9-12% Cr. Grade 91 steel is the main high Cr ferritic steel that always used as piping and tubing in power plant component. Thus, steels withincreased creep resistance have emerged. Grade 91 was originally developed by Oak Ridge National Laboratory in Tennessee, USA, typically consisting of 9% Cr and 1% Mo, which were initially called P9 steel presented as its main focus use in power plants.

The weldability of these steels presents well-known challenges, which are usually overcome using complex thermal cycles before and after the welding process [1]. The materials used in power plants operating at high temperature and high pressure are creep strength enhanced ferritic (CSEF) steels and austenitic stainless steels. The CSEF steels such as P22, P23, P24, P91, P911, and P92 are mainly used at high-temperature applications due to their excellent fatigue strength and creep resistant at high temperatures and lower cost as compared to Ni-based alloys [2]. They also have a good toughness if PWHT is perform after welding [3]. Sometime grade 91 steel should be joined to the other alloy steel such as stainless steel. the dissimilar welding method is a used for materials that have different characteristics. such as different mechanical, thermal properties and chemical compositions. What is very important in the dissimilar welding method is choosing the right filler metal.

In research on dissimilar welding, the choice of filler metal is something that needs to be considered. Especially for alloy material grade P91 and Austenitic Stainless steel Grade 316L, considering that these two materials have very different characteristics. The heat affected zone (HAZ) area has a critical role in dissimilar welding methods. This research used two types of filler metal, namely filler metal ERNiCrMo-3 and 309LMo, both filler metals contain nickel in different percentages. Therefore, the aim of this research is to investigate the mechanical and structural properties of dissimilar welding and to study the effect of differences in filler metals ERNiCrMo-3 and 309LMo.

2. Research Methods

This research was carried out by welding dissimilar material SA 335 Grade P91 with Stainless Steel Grade 316L using the GTAW welding process with a 6G welding position. Filler metal ER NiCr Mo-3 and ER 309LMo are used to weld this joint. Preheat 150^{o}C and PWHT at a temperature of 750^{o}C with a holding time of 35 minutes were carried out only on the SA 335 Grade P91 material. This process can be seen in the Fig. 4. Test specimen cutting was carried out using the number of test specimens in accordance with the ASME Section IX code [4]with addition microstructure observations, hardness testing and corrosion rate testing using the ASTM G48 immersion method.[5]

Tensile testing was carried out using the ASTM E8 method[6], while hardness testing was carried out using the ASTM E92 method[7], hardness testing was carried out on each weld metal HAZ and base metal area with 6 indentation each. In Fig. 1 Joint preparation single V groove was used with 60^{o} included angle. The finish weld shown in the Fig. 2 and Fig. 3. PWHT test piece in the grade 91 steel side shown in Fig. 4.

Fig. 1. Joint Configuration

Fig. 2. Finished weld filler ERNiCrMo-3

Fig. 3. Finished weld filler ER 309Lmo

Fig. 4. PWHT test piece in the grade 91 steel side

3. Results and Discussion.

3.1. Tensile Strentgh

From the results of the tensile tests carried out, it shows that all specimens representing each variable can be declared to meet the tensile test acceptance requirements according to the minimum tensile strength of the filler and material. In Table 1 data on tensile test results for each specimen.

Table 1. Tensile strength

Filler Metal	Yield Strength (*Mpa)*	Tensile strength (*Mpa)*
ERNiCrMo-3	346.11	574.19
ERNiCrMo-3	362.06	567.96
ER 309 LMo	343.49	572.15
ER 309 LMo	356.25	548.25

From the average yield strength and ultimate strength, the highest yield strength results were obtained, the highest value was for the specimen with filler metal ERNiCrMo-3 with an average value of 354.085 Mpa and the lowest value was for the specimen with filler metal 309LMo with an average of 349.87. Mpa. The ultimate strength value was the highest for the specimen with ERNiCrMo-3 filler metal with an average of 571.075 Mpa and the lowest value for the specimen with 309LMo filler metal was obtained with an average of 560.195 Mpa. Fig. 5 shows the specimen after the tensile test, all fracture locations occurred in the base metal area.

Fig. 5. Fracture location at tensile specimen

Based on Fig. 5, it can be observed that the four specimens were broken in the 316L grade stainless steel base metal area. Referring to ASME Sec. IX, the acceptance requirements for the transverse tensile test if the test specimen breaks at the base metal outside the weld metal, the test must still be accepted as long as the strength is no more than 5% below the specified minimum tensile strength. Austenitic materials utilize the transformation induced plasticity (TRIP) effect through the presence of austenite retained in their microstructure to increase strength and ductility. This transformation of retained austenite into martensite during plastic deformation increases strength and ductility.

3.2. Hardness

The hardness test was carried out on the base metal, HAZ and weld metal areas with a total of 30 hardness testing points on each specimen located at 6 points in the A-335 grade P91 base metal area, 6 points in the A-335 grade P91 HAZ, 6 points on weld metal, 6 points on HAZ stainless steel grade 316L, and 6 points on base metal stainless steel grade 316L. The Vickers hardness test results can be seen in Fig. 6.

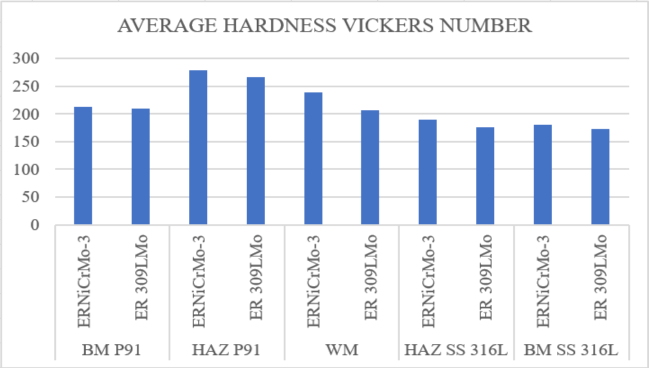

Fig. 6. Average hardness value

Based on the results of the Vickers hardness test above, it can be concluded that the average hardness value of the ERNiCrMo-3 filler metal specimen is higher than that of the ER 309LMo filler metal with the same PWHT temperature and the A-335 grade P91 part. With the results obtained, the base metal stainless steel grade 316L is the area with the lowest average hardness value in each test specimen for both ERNiCrMo-3 and 309LMo fillers, while HAZ A335 grade P91 is the area with the average hardness value the tallest. The hardness value of A335 grade P91 material must not exceed 265 HV. A hardness value exceeding 265 HV will cause the formation of a brittle martemsite structure in the material which will cause brittle cracking[8]

3.3. Microstructure examination results

Microstructure testing in this research was carried out in the base metal, HAZ and weld metal areas for each variation. The results of microstructure testing in each area are shown in Fig. 7-12.

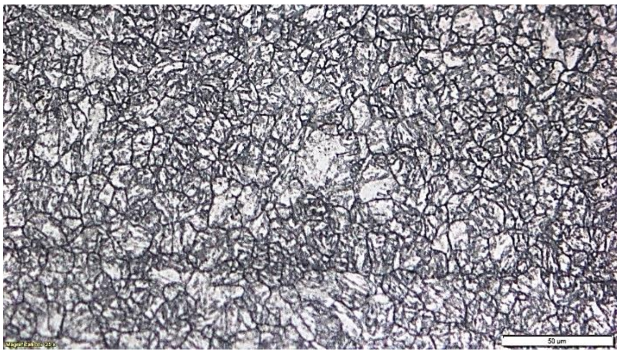

Fig. 7.HAZ A335P91 Filler ERNiCrMo-3

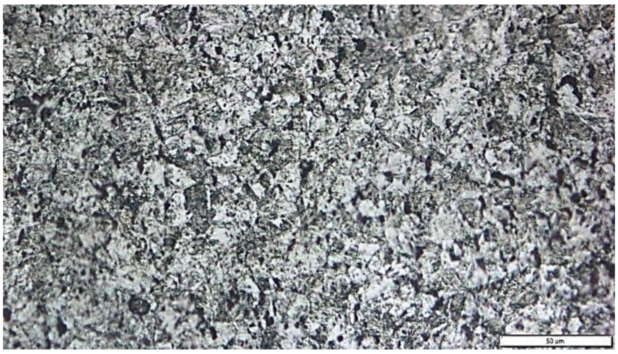

Fig. 8. HAZ A335 P91 Filler 309LMo

Fig. 7 shows the microstructure of the HAZ area experiencing a reduction in ferrite percentage, with the pearlite phase formed from layers or lamellae between ferrite and Fe3C during the transformation process. At temperatures just below the eutectoid, relatively thick lamellae will form consisting of layers of ferrite and Fe3C, this structure is called coarse pearlite. At this temperature, the diffusion rate is higher so that during the transformation process, carbon atoms can diffuse relatively long distances, forming thicker lamellae. As the temperature decreases, the diffusion rate will also decrease and the lamellae will become thin. The structure that occurs at this temperature of around 540°C is called fine pearlite[9]. The HAZ area of grade 91 material is dominated by the pearlite phase with a greater percentage compared to the base metal area. This is caused by the welding process where the HAZ area receives heat input or a higher temperature increase when compared to the base metal area with a fast cooling rate. However, there was an improvement in the martensite structure after the PWHT process was carried out.

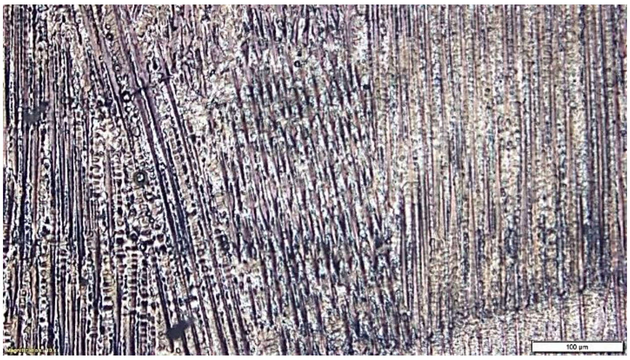

Fig. 9. Weld Metal Filler Metal ERNiCrMo-3

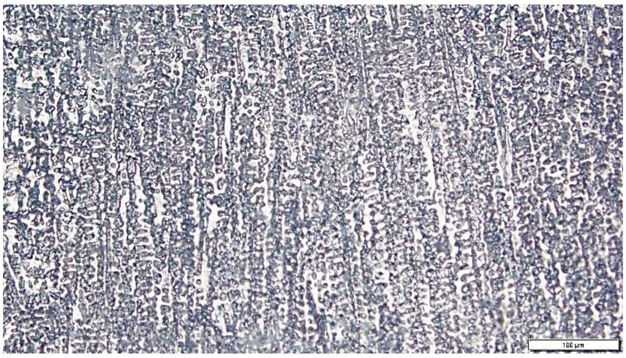

Fig. 10. Weld Metal Filler Metal 309LMo

Fig. 9 and Fig. 10 shown that the microstructure results in the weld metal area show that the microstructure is different between the ERNiCrMo-3 and 309LMo fillers. In the weld metal area of the ERNiCrMo-3 filler metal specimen, columnar and equiaxed dendrite phases can be seen. Meanwhile, in the 309LMo filler metal variation specimen, it was found that delta ferrite and austenite phases were formed. Both specimens underwent a heat treatment process in the form of PWHT with a temperature of 750ºC and a holding time of 30 minutes. In specimens with filler metal ERNiCrMo-3, the columnar dendrite phase appears to have vertical or columnar growth, with a structure layered and primary and secondary branches.

This columnar dendrite type phase is very likely to form in the weld metal area of disimilar welding between grade 91 material and grade 316L stainless steel material using nickel based filler metal. If the weld metal has a high chromium content while the base metal has little or no chromium, the tendency for carbon to migrate from the HAZ to the weld metal is very high. The difference in cooling levels at the weld center and the weld surface can result in the formation of columnar dendrites[10]. The formation of columnar type dendrites due to the steep thermal gradient between the fusion boundary and the center, this will result in the formation of MGBs.

Meanwhile, MGBs are migration grain boundaries or migrating grain boundaries. This is a phenomenon in the microstructure of materials where the fusion boundaries move or migrate during heating, cooling or deformation processes. This grain boundary migration can further influence the mechanical properties of a material. Another phase that forms in the weld metal filler area of ERNiCrMo-3 is equiaxed dendrite. The formation of an equiaxed dendrite phase has many advantages, such as lower susceptibility to compaction cracking, superior mechanical properties, high ductility and fracture toughness [8]. Equiaxed dendrite structures can deform more easily under stress than columnar dendritic structures, thus having a lower susceptibility to cracking.

In the 309LMo filler specimen, it can be observed that the phases formed in the weld metal area are delta ferrite with a skeletal shape and austenite which is flat and with a lighter color. There are basically four possible solid-state solidification and transformation processes for austenitic stainless steel weld metal. This reaction is related to the Fe-Cr-Ni phase diagram. Solidification modes A and AF are related to primary austenitic solidification, where austenite is the first phase formed after the solidification process. Meanwhile, types FA and F have delta ferrite as the primary phase. The presence of a delta ferrite type phase will tend to reduce the ductility, toughness and corrosion resistance of a welded joint, while too little delta-ferrite can cause solidification cracks[11].

Fig. 11 and 12 shown the results of microstructure documentation in the HAZ area of grade 316L stainless steel, the same microstructure was obtained for specimens with filler metal ERNiCrMo-3 and 309LMo. There is no significant difference in the HAZ area of stainless steel because this area is not affected by heat from the PWHT process, only affected by heat from the welding process. It can be seen that both specimens only contain ferrite and austenite phases, which are the most common phases found in austenitic stainless steel materials.

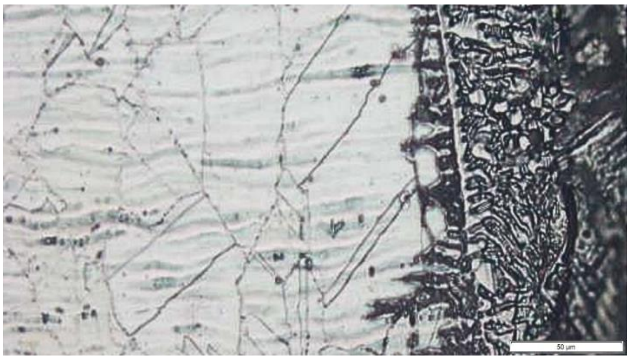

Fig. 11. HAZ Stainless Steel 316L Filler ERNiCrMo-3

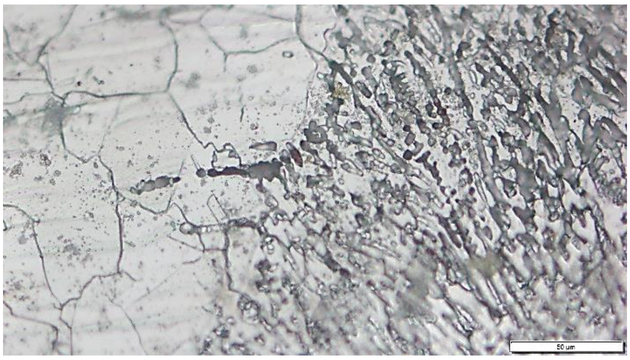

Fig. 12. HAZ Stainless Steel 316L Filler 309LMo

From the corrosion testing process that has been carried out, data is obtained in the form of mass loss (weight loss) from each test specimen. This test was carried out based on ASTM G48-11[6] (method A) which evaluates weight loss per unit area. The solution used is 100 gr FeCl36H2O and 900ml Aquades or type IV purified water. The immersion time used in this study was in accordance with ASTM G48-11[6] recommendations of 72 hours at a temperature of 24ºC.

Pitting corrosion caused by immersion tests or immersion in FeCl6H2O solution only occurs on grade 91 material, whereas on grade 316L stainless steel material there is no indication of pitting corrosion occurring. This is because grade 91 material has a lower chromium content when compared to grade 316L stainless steel material. The chromium content of grade 91 material ranges from 8.0 - 9.5%, while in stainless steel grade 316L material it ranges from 16 -18%. The percentage of chromium content of 316L stainless steel grade makes this material more resistant to corrosion, especially pitting corrosion. The ERNiCrMo-3 filler variation specimen experienced a thickness reduction of 0.86 mm, while the specimen with the 309LMo filler variation experienced a thickness value reduction of 1.06 mm.

After visual observation, the corrosion rate will be calculated. To find out the corrosion rate per year, it can be done manually using an equation based on ASTM-G1-90-1999[12] as follows:

$$\text{Milimetre per years} = (87600 \times W) / (A \times t \times d) \qquad (1)$$

W :is Weight loss (g), A is Area (cm^2), t is Time of exposure (h), d is Density (g/cm^3)

Table 2. Corrosion rate

Filler Metal	Weight loss (*g*)	Corrosion rate (*mm/years*)
ERNiCrMo-3	2.665	12.50
ER 309 LMo	4.115	18.94

The highest corrosion rate value occurred in the 309LMo filler metal specimen with a value of 18.94 (mm/years) while the lowest corrosion rate value occurred in the ERNiCrMo-3 filler metal variation with a value of 12.50 (mm/years). The Cr content in the 309LMo filler metal is greater with a percentage of 23-25%, while the ERNiCrMo-3 filler metal with a percentage of 20 - 23% of the chromium content in the filler metal is corrosion. However, the Mo percentage of ERNiCrMo-3 filler metal is greater, 8.0 - 10.0%, while 309LMo filler metal has a lower Mo percentage of 2.0 - 3.0%. Filler metal ERNiCrMo-4 has better resistance to corrosion when compared to filler metal ERNiCrMo-3 and its properties are almost not significantly different. Filler metal ERNiCrMo-3 or Inconel 625 helps increase the pitting corrosion resistance and impact toughness of welded specimens, in the as-welded state and after PWHT heat treatment[13].

4. Conclusions.

The conclusion of this study is the highest yield strength was obtained in the specimen with ERNiCrMo-3 filler metal variation, with an average value of 354.085 MPa, while the lowest yield strength was found in the specimen with 309LMo filler metal variation, with an average of 349.87 MPa. As for the ultimate strength, the highest value was obtained in the ERNiCrMo-3 filler metal variation, with an average of 571.075 MPa, while the lowest value was obtained in the 309LMo filler metal variation, with an average of 560.195 MPa. the highest average hardness was found in the ERNiCrMo-3 filler metal variation. This value was obtained in each area tested for hardness, including the base metal of grade 91, HAZ of grade 91, weld metal, base metal of grade 316L, and HAZ of grade 316L. Significant microstructure differences between each filler metal variation, especially in the weld metal area. In the weld metal area of the ERNiCrMo-3 filler, dendritic phases with equiaxed and columnar shapes were formed. Meanwhile, in the HAZ of P91 and HAZ of stainless steel 316L, only ferrite, pearlite, and austenite phases were formed. In the weld metal area of the 309LMo filler, skeletal delta ferrite and austenite phases were formed, while in the HAZ of P91 and HAZ of stainless steel 316L, only ferrite, pearlite, and austenite phases were present. there is no martensite. ERNiCrMo-3 filler metal has better corrosion resistance than specimen with the 309LMo filler metal. The value is of 12.50 mm/year for specimen ERNiCrMo-3, while specimen ER 309LMo showed a corrosion rate of 18.94 mm/year.

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