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The effect of welding speed variations on stainless steel – carbon steel fillet joints with the TIG welding method on the quality of the welded joint

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Abstract

Dissimilar welding between stainless steel and carbon steel is widely applied in industries such as power plants, petrochemical facilities, pressure vessels, and heat exchangers due to its ability to combine the advantages of both materials; however, studies investigating the effect of welding speed on TIG-welded fillet joints between ASTM A36 carbon steel and SS316 stainless steel remain limited, particularly regarding weld quality evaluation through non-destructive and destructive testing. This study aims to determine the effect of welding speed on the quality of TIG-welded fillet joints of ASTM A36 carbon steel and SS316 stainless steel. The welding process was performed using the Gas Tungsten Arc Welding (GTAW/TIG) method with ER309L filler metal and welding speed variations of 83, 86, and 93 mm/min in the 1F fillet position. Weld quality was evaluated through dye penetrant testing, radiography testing, and macrostructure examination to assess weld defects, fusion quality, and penetration characteristics. The results of dye penetrant testing indicated that specimens welded at 93 and 86 mm/min were free from surface defects, while the specimen welded at 83 mm/min exhibited a minor porosity defect of 0.5 mm. Radiography testing showed no internal defects, such as cracks, slag inclusions, lack of fusion, or lack of penetration, in all specimens. Macrostructural observations confirmed sound fusion between ASTM A36 and SS316 materials and revealed that welding speed significantly affected weld penetration. The deepest penetration was obtained at the lowest welding speed of 83 mm/min, reaching 1.25 mm, while penetration decreased with increasing welding speed. It can be concluded that all welding speed variations produced acceptable weld quality; however, a welding speed of 83 mm/min provided the best penetration performance due to higher heat input during the welding process.

1. Introduction

The steel construction industry has made significant technological progress during the era of globalization. The increasing use of metal materials such as iron, steel, stainless steel, and aluminum, both in small and large scale projects, marks this progress [1]. Welding technology is also developing rapidly in line with the increasing industrial demand for high-quality products. Welding plays a crucial role in the construction of various structures, from simple to highly complex and technically demanding ones [2].

Welding is a crucial and highly sought-after field in the industrial world, particularly in manufacturing, general engineering, and various aspects of construction joints. In this process, welding plays a key role in determining the quality of joints. To achieve high-quality welded joints, the design of the welding construction must be meticulously planned. This planning should encompass welding methods, inspection procedures, selection of welding materials, types of welding, and the shape of the weld to be utilized [3]. In today's industrial era, there is a growing need for innovations in welding, particularly regarding methods and materials. One significant advancement in this field is the ability to join dissimilar materials, specifically dissimilar metals [4].

Generally, the joining process is performed on similar materials, even if they belong to different series, and this practice is quite common. One disadvantage of dissimilar metal welding is the emergence of high stress concentrations due to changes in the microstructure in the weld zone. This condition can lead to a decrease in material strength. Furthermore, the welding process can also create residual stresses, weld defects, and cracks that affect the quality of the joint [5].

Dissimilar welding between stainless steel and carbon steel has been widely applied in various industrial sectors, such as power plants and the petrochemical industry. In addition, this welding process is also used in general industrial applications, for example, in the construction of pressure vessels and heat exchangers [6]. For example, in power plants, components work under different operating conditions, thus requiring the selection of appropriate materials. Boiler parts that operate at high temperatures generally use stainless steel because it has better creep and oxidation resistance, while parts that work at lower temperatures use carbon steel because it is more economical. [7].

TIG (Tungsten Inert Gas) welding is widely used in sectors such as aerospace and automotive because it is effective for welding materials such as stainless steel, aluminum and its alloys, copper-based alloys, and nickel-based alloys. Furthermore, the TIG method is superior to other arc welding techniques because it is able to produce strong, durable, corrosion-resistant, and ductile joints [8].

The final properties of the weld are directly influenced by welding parameters, such as voltage (polarity), current, welding speed, interpass temperature, and preheat temperature. Controlling these welding parameters allows for improved quality and properties of the resulting components [9].

Current strength affects heat input in welding. Huang et al. [10], regarding GMAW dissimilar welded joints on SUS304 and SS400 steel showed that the BW-4 sample had a higher Ultimate Tensile Strength (UTS) value and a lower corrosion current density than the other samples. This condition indicates that the use of welding parameters in the form of a current of 170 A, a voltage of 20 V, and a welding speed of 40 cm/minute was able to produce good mechanical strength while increasing corrosion resistance. From this study, the researchers used a current range of 165-175 A (both layer 1 and layer 2)

The selection of the right filler in the welding process can produce better joint results. Pahlawan et al. [11], showed that the tensile test results on both electrode variations showed higher values than the maximum tensile strength of the base material. This shows that the dissimilar joint process between ST41 steel and Stainless Steel 316 using E6013 or E309L electrodes is able to improve the quality of the tensile strength of the material. However, the use of E6013 electrodes has a weakness in the form of a wider Heat Affected Zone (HAZ), which can cause a decrease in the mechanical properties of the material in certain parts. In the study of Tembhurkar et al. [12], they compared the effect of E-309L electrodes with E-316L and concluded that the welding results using ER309L filler metal have higher pitting corrosion resistance than ER316L or autogenous welding, due to the higher chromium (Cr) content in ER309L. The E309 electrode is a stainless steel filler commonly used in the Gas Tungsten Arc Welding (GTAW) process. When welding using stainless steel electrodes must pay attention to the specifications of the material to be joined. Choosing an inappropriate electrode can cause various problems, such as cracks, porosity, imperfections in the weld metal union, and other losses, including low weld joint strength [13]. From the study, it shows that fillet weld joints have not been studied; this is an opportunity for researchers, so researchers use a welding process with the TIG method and ER 309L filler.

Welding position affects the results of welding. Research by Júnior et al. [14] concluded that the combination of the E7018 electrode with welding position 1G (flat potition) showed the best mechanical performance, which was characterized by the highest fracture load and total displacement before fracture values among all welding variations tested. Therefore, the authors used welding position 1F (flat potition) in this study.

Welding speed has a very important influence on the quality of GTAW welding results because it directly determines the amount of heat input received by the material. Increasing welding speed causes a decrease in heat input per unit length of the weld, resulting in a reduction in penetration depth and weld width, as well as a smaller volume of molten metal formed. If the welding speed is too high, this can cause defects such as undercuts, porosity, and uneven bead shape. Conversely, a welding speed that is too low will increase heat input so that cooling becomes slower, potentially causing distortion, microstructural changes, and a decrease in mechanical properties. Therefore, an optimum welding speed is needed to achieve a balance between heat input and weld formation quality, thus producing a weld joint with good penetration, a stable structure, and minimal defects [15]. This was proven in the research of Magusdeeswaran et al. [16], which proved that specimens with a welding speed of 100 mm/min, a welding current of 140 A, and a voltage of 16.5 V produced the deepest penetration depth when compared to higher welding speeds (115 and 130 mm/min), which was 5.5 mm deep. Therefore, the researchers used a welding speed range below 100 mm/min.

To determine the quality of welding results, testing is carried out in the form of NDT, Non-Destructive Testing (NDT), which is a material testing method without causing damage to the material. This method is used to examine and evaluate welded joints, components, and defects found in welding results, as well as identify differences in material characteristics without damaging the test object. Thus, components such as casting, welding, and forging results can still be used after the testing process is carried out because the NDT method does not cause damage to the material [17]. Therefore, researchers evaluate the quality of welding with NDT tests (penetrant and radiography tests) and DT (macro tests).

In this study, using the TIG welding process with welding speed variations (83, 86, and 93 mm/min), filler ER 309L with a diameter of 1.6 mm on layer 1 and a diameter of 2.4 mm on layer 2, with fillet joints (1F) of different materials (dissimilar metals), namely carbon steel ASTM A36 and stainless steel 316. While the evaluation of the quality of the weld used is NDT (Penetrant Test and Radiography Test) and DT (Macro Test on welded joints), research on fillet joints ASTM A36 - SS316 is rarely studied, and variations in welding speed also affect the quality of the weld. So the purpose of this study is to determine the effect of welding welding speed on the quality of the results of TIG-welded fillet joints between carbon steel ASTM A36 and stainless steel 316.

2. Research Methods

The specimens used in this study were ASTM A36 carbon steel and 316 stainless steel, measuring 200 mm x 125 mm x 8 mm. The dimensions used in this study comply with ISO 9606 standards.

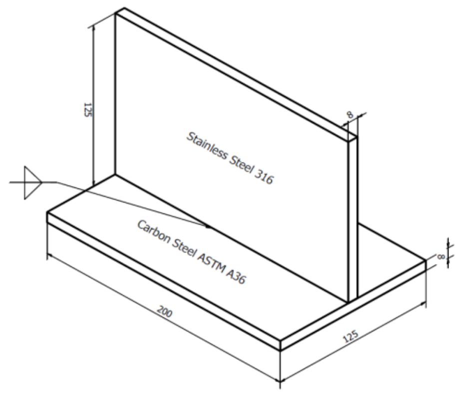


Fig. 1. Specimen size in mm

In this study, the research flow begins with a literature review, then continues with determining welding parameters and creating a Welding Procedure System (WPS). After that, the welding process and non-destructive testing (NDT) are carried out in the form of a penetrant test and radiography test to determine the presence of defects in the welded joints. If defects are found, the welding parameters are evaluated, and the process is repeated, while if no defects are found, it is continued with macro and etching testing. Furthermore, the test results are analyzed in the results and discussion section, and then conclusions and suggestions are drawn from the research conducted.

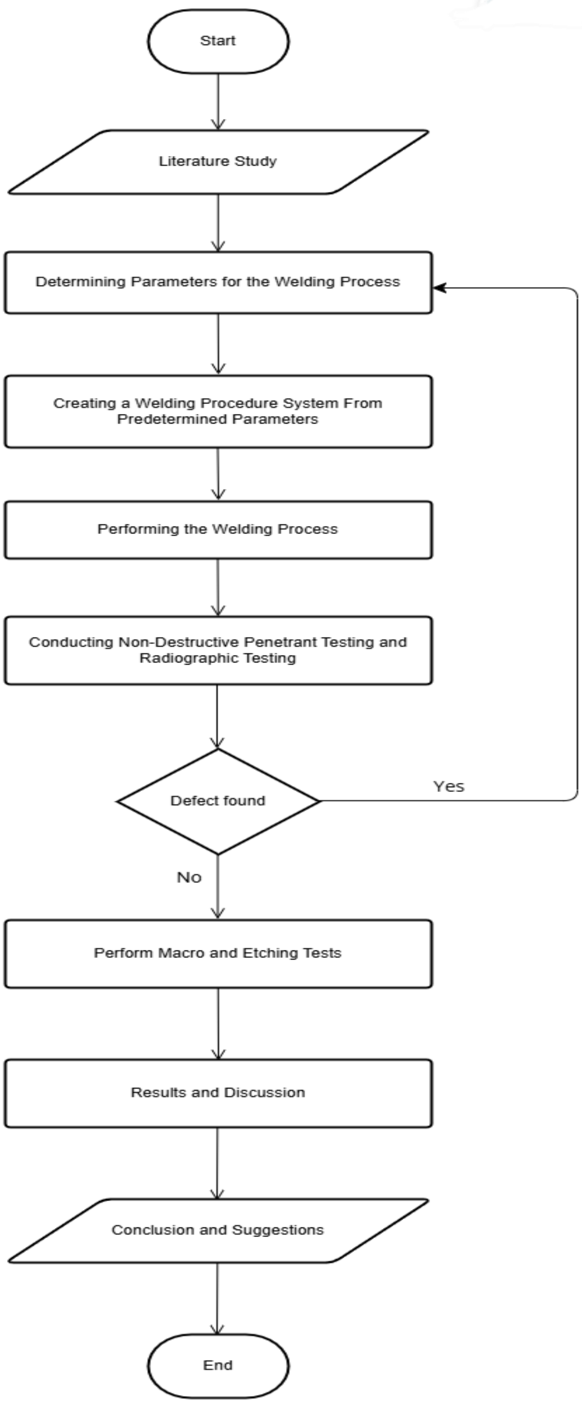


Fig. 2. Research flow chart

This experiment uses GTAW welding to connect two different types of plate materials, namely carbon steel A36 and stainless steel 316, with a T-joint fillet connection shape as in Figure 1. The welding process follows WPS; the following is the welding procedure system for the following 3 specimens:

Table 1. Welding Procedure System (WPS)

	Spesimen 1	Spesimen 2
Material	Stainless Steel 316	Carbon Steel ASTM A 36
Joint Type	Fillet T Joint	Fillet T Joint
Welding Position	1F	1F
Consumable Class	CHG 309L	CHG 309L
Fillet Metal (Dia)	1,6 mm & 2.4 mm	1,6 mm & 2,4 mm
Current		
Number Of Layer	2 Layers	2 Layers
Cleaning Method	Grinding	Grinding
Shielding Gas	Argon	Argon
Gas Flow Rate	15 L/min	15 L/min
Voltage	11 V	11 V

Table 2 contains the parameters of specimen 1, specimen 2, and specimen 3.

Table 2. Parameter variation

Parameter	Ampere Range (A)		Welding Speed (mm/min)	Welding Pattern
	Filler	Cap		
Specimen 1	165	175	93	Zig-zag weave
Specimen 2	165	175	86	Zig-zag weave
Specimen 3	165	175	83	Zig-zag weave

After welding, non-destructive testing was performed to ensure there were no defects in the weld. In this study, non-destructive testing used dye penetrant testing and radiography testing.

Dye Penetrant Testing uses Magnaflux SKC-S cleaner fluid, Magnaflux SKL-SP2 penetrant fluid, and Magnaflux SKD-S2 developer fluid. The penetrant process is carried out by cleaning with a cleaner fluid and wiping with a cloth. Next, spray with penetrant fluid with a dwell time of 15 minutes. After being doused with penetrant fluid, wipe with a cloth and spray with developer fluid. After all processes are carried out, observe if there is penetrant fluid coming out of the welding.

(a)

(b)

Fig. 3. Penetrant test process (a) Applying penetrant liquid (b) Spraying developer

The radiography process uses the SMSV technique with Radioflex Machine model and CR-IPS film paper type, a radiation exposure time of 120 s, a voltage of 120 kV, and a distance of the film paper to the radiation transmitter of 830 mm.

Fig. 4 Radiography process

The material that had been inspected using the non-destructive test method was then cut into 3 cm sections and subjected to macro testing to determine the depth of penetration of the weld into the material. Prior to macro testing, the specimen was first sanded with sandpaper until it appeared smooth and shiny.

Etching test using liquid as in Table 3

Table 3. Etching fluid composition in ASME Handbook Volume 9 [18].

Material	Compotition	Command
Stainless Steel	(a) 15 g $(NH_4)_2S_2O_8$ (ammonium persulfate) and 75 mL H_2O (b) 250 g $FeCl_3$ and 100 mL, H_2O (c) 30 mL HNO_3	Lepito's No. 1 etch. Combine (a) and (b), then add (c); immerse specimen at room temperature; use fresh
Carbon Steel	15 mL HNO_3 + 85 mL H_2O + 5 mL methanol or ethanol	Swab; macroetch brings out fusion line, heat-affected zone, reheated zones, columnar zones; scrub gently under running water to remove any black residue

Etching fluids are listed in Table 3, based on the ASME Handbook Volume 9. For stainless steel etching fluids, apply them to the stainless steel joint area and let them sit for 1 minute and 30 seconds, then rinse with running water and dry. While etching fluids for carbon steel are applied to the carbon steel joint area and let them sit for 1 minute, then rinse with running water and dry.

After the macroetching test is performed, the weld penetration depth will be visible. Fig. 5 shows the quantities to be calculated, including vertical leg thickness, horizontal leg thickness, throat thickness, and welding penetration.

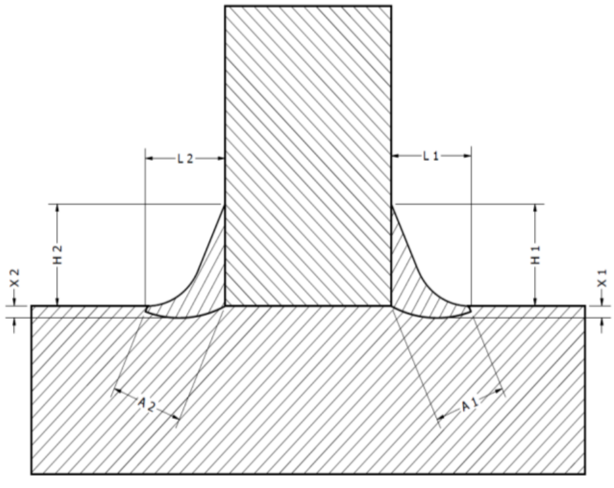


Fig. 5. Instructions for macro etch test calculation results (H) vertical leg thickness (L) horizontal leg thickness (A) throat thickness (X) Welding penetration

3. Results and Discussion.

The results of the analysis of the influence of variations in welding speed on welding results using TIG welding in dye penetrant testing, radiography tests, and macro tests can be explained in the explanation below.

3.1 Liquid Penetrant Test

Penetrant testing (PT) is a testing method that involves applying a wetting fluid with low surface tension to the surface of a test object. The fluid penetrates through capillary action into open defects or discontinuities in the surface, then reappears, producing observable indications [19].

Liquid penetrant testing was conducted to determine the number and type of visual defects. Based on the results of liquid penetrant testing of six specimens that had undergone welding at different welding speeds, no defects were found in the welds.

The image of the liquid penetrant test results on the T-fillet welding joint with welding speed variations of 83, 86, and 93 can be shown in Table 2. From the test results on the welding, no defects were found in the welding.

(a)

(b)

Fig. 6. Penetrant test on specimen 1 (a) side A and (b) side B

In Figure 3, no penetrant fluid appears to be leaking from the weld joint surface. This indicates that no defects were found after penetrant testing on specimen 1.

Table 4. Penetrant test results of specimen 1

Imperfection Designation	Penetrant Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	-	Accepted
Undercut	-	Accepted
Lack of Fusion	-	Accepted
Spatter	-	Accepted

(a)

(b)

Fig. 7. Penetrant test on specimen 2 (a) Side A and (b) Side B

Penetrant testing on specimen 2 can be seen in Fig. 4, showing that there are no defects in specimen 2. This is proven by the absence of penetrant liquid appearing on the surface of the welding results when sprayed with developer liquid.

Table 5. Penetrant test results of specimen 2

Imperfection Designation	Penetrant Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	-	Accepted
Undercut	-	Accepted
Lack of Fusion	-	Accepted
Spatter	-	Accepted

(a)

(b)

Fig. 8. Penetrant test on specimen 3

Table 6. Penetrant test results of specimen 3

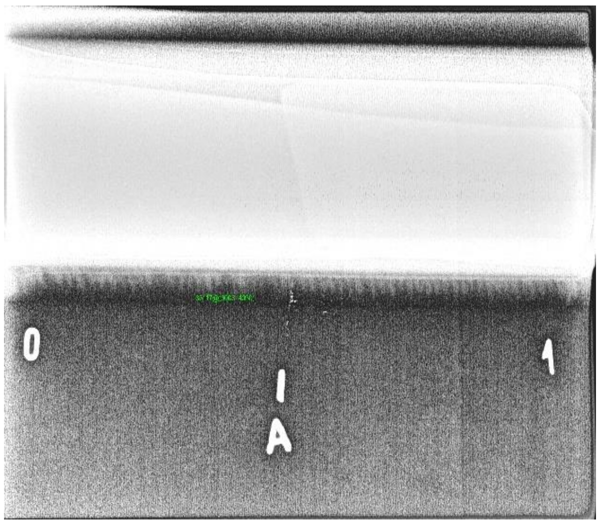
Imperfection Designation	Penetrant Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	0.5 mm	Accepted
Undercut	-	Accepted
Lack of Fusion	-	Accepted
Spatter	-	Accepted

Specimen 3 exhibited a porosity defect with a diameter of 0.5 mm. Heat input conditions during the welding process can influence the formation of porosity in the weld [20]. This is because welding speed affects the amount of heat input. The slower the welding speed, the greater the heat input. In specimen 3, the welding speed was slower than that of the other specimens, at 83 mm/min. This caused the heat input in specimen 3 to be higher than that of the other specimens, resulting in porosity defects.

3.2 Radiography Test

Radiographic Testing (RT) is a non-destructive testing (NDT) method commonly used to detect internal defects in welds. This method relies on the ability of X-rays or gamma rays to penetrate metals and other materials impermeable to ordinary light, producing a photographic record of the transmitted radiation energy [21].

The radiographic test analysis is closely related to the macroscopic examination of various welds shown in Fig. 4, Fig. 5, and Fig. 6, which show perfect penetration of the weld joints. The images also show excellent weld fusion quality in various specimens, with no visible discontinuities in the dissimilar metal joints between ASTM A36 and SS 316 made using the GTAW welding process with different welding speed variations.



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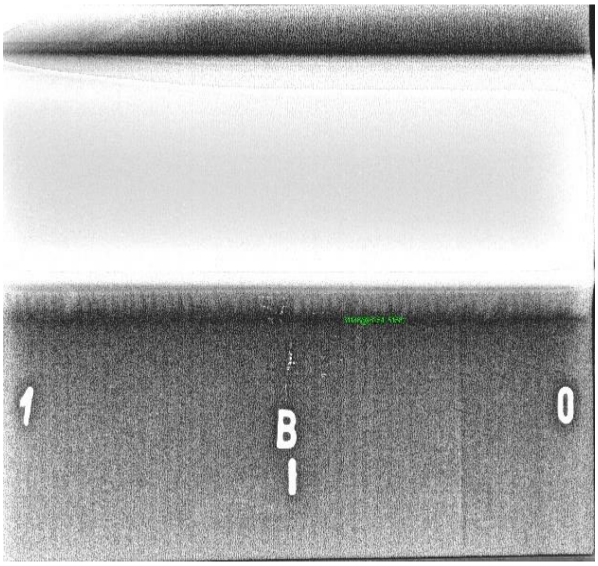


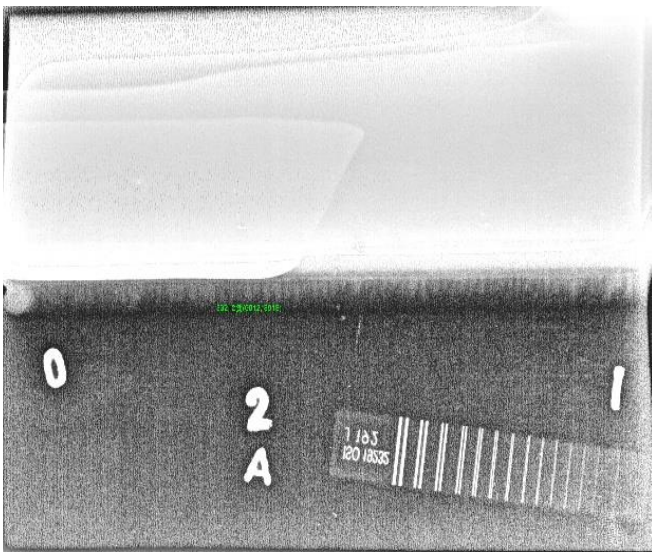
(b)

Fig. 9. Radiography test on specimen 1 (a) side A (b) side B

Table 7. Radiography test results of specimen 1

Imperfection Designation	Radiography Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	-	Accepted
Slag Inclusions	-	Accepted
Lack of Fusion	-	Accepted
Lack of Penetration	-	Accepted

After conducting radiography testing on specimen 1, no defects were found. This indicates that the welding parameters used were appropriate. This can be seen in Fig. 6 and Table 7.



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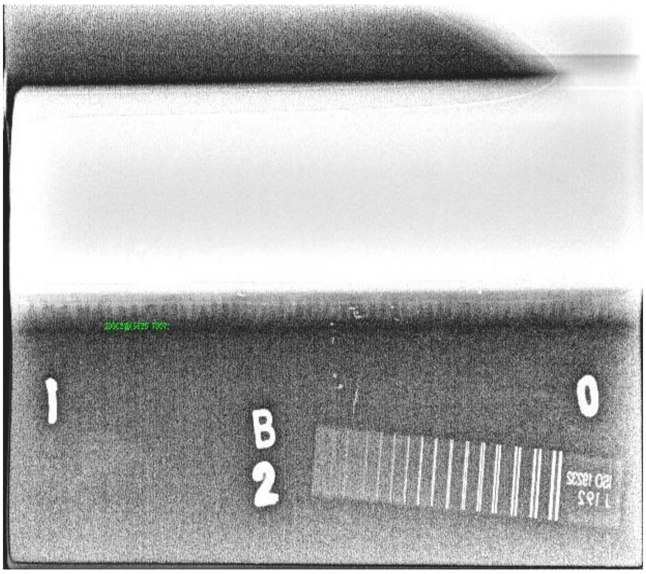


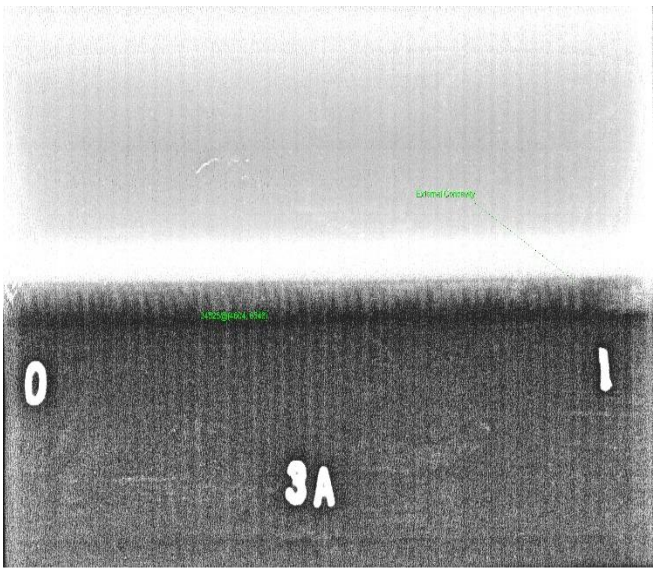
(b)

Fig. 10. Radiography test on specimen 2

Table 8. Radiography test results of specimen 2

Imperfection Designation	Radiography Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	-	Accepted
Slag Inclusions	-	Accepted
Lack of Fusion	-	Accepted
Lack of Penetration	-	Accepted

In specimen 2, no defects were found, as shown in Fig. 7 and Table 8. This means that the welding parameters used for specimen 2 were correct, resulting in no defects after radiography testing.



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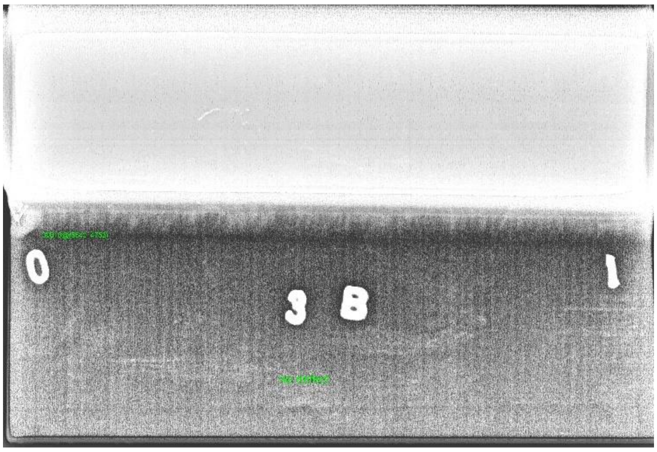


(b)

Fig. 11. Radiography test on specimen 3

Table 9. Radiography test results of specimen 3

Imperfection Designation	Radiography Interpretation	Result
Crack	-	Accepted
Gas Pore/Porosity	-	Accepted
Slag Inclusions	-	Accepted
Lack of Fusion	-	Accepted
Lack of Penetration	-	Accepted

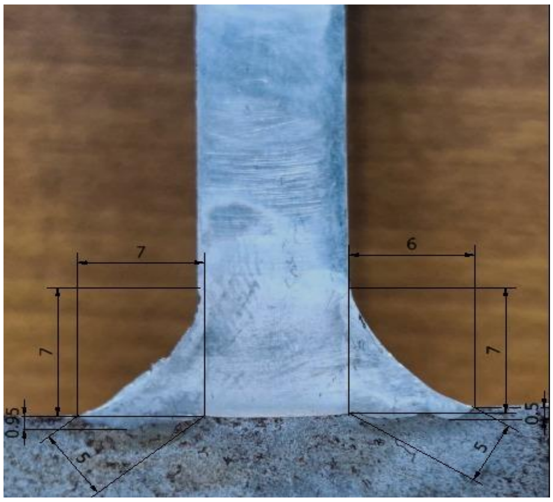
In specimen 3, there are also no defects, as shown in Fig 8 and Table 9. This indicates that the parameters used for specimen 3 are correct and do not cause defects.

3.3 Macro Test

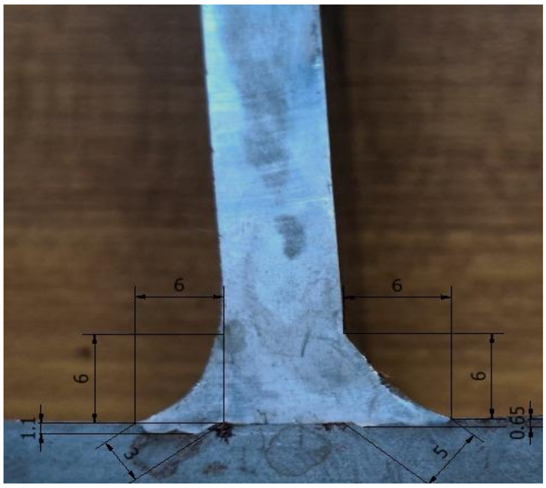
From the data in Table 10 and Fig. 12, it shows that in the three macro photos of the specimen, fusion occurred between the ASTM A36–SS316 materials, and there were no defects. The research of Fauzi et al. [22], concluded that heat input greatly influences the Heat Affected Zone (HAZ) and fusion line in SS400 carbon steel and AISI 304 stainless steel. This can be seen in Table 10.

In the three specimens, the macrophotography results in Fig. 12 show penetration in the ASTM A36 – SS 316 fillet joint, where specimen 1 with a welding speed of 93 mm/min is 0.95 mm on side 1, specimen 2 with a welding speed of 86 mm/min is 1.1 mm on side 1, and specimen 3 with a welding speed of 83 mm/min is 1.25 mm. This shows the deepest penetration at a welding speed of 83 mm/min. This occurs because the increase in heat input affects the increase in the height of the weld reinforcement, bead width, penetration depth, penetration and deposition area [23].

The deepest penetration occurred in specimen 3 due to the slower welding speed compared to the other specimens. Penetration increased by 31.6% when the welding speed decreased from 93 mm/min to 83 mm/min. A slower welding speed increases the heat input during welding. This is in line with Ericsson's research [24] which concluded that the lower the welding speed, the greater the heat input received by the material. This improves metal flow and enhances the effectiveness of welded joint formation.



(a)



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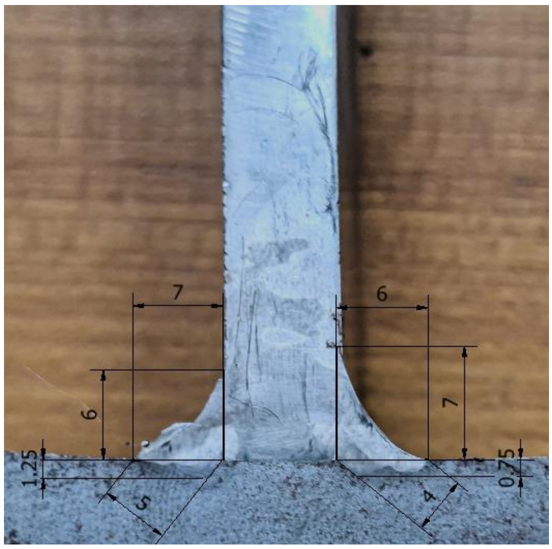

(c)

Fig. 12. Macro photo of welding speed variation (a) 83 mm/min, (b) 86 mm/min, (c) 93 mm/min. (all unit in mm)

The results of the macro etch test in Fig.12 can be seen in Table 10.

Table 10. Measurement results of specimens 1, 2, and 3

Spesimen	H (mm)		L (mm)		A (mm)		X (mm)	
	H1	H2	L1	L2	A1	A2	X1	X2
Spesimen 1	7	7	7	6	5	5	0.5	0.95
Spesimen 2	6	6	6	6	5	3	0.65	1.1
Spesimen 3	7	6	6	7	5	4	0.75	1.25

Table 11. Comparison of welding speed with heat input

Specimen	Welding Speed	Heat Input		Depth penetration (mm)	
		Fill	Cap	X1	X2
1	93	1.171	1.242	0.5	0.95
2	86	1.266	1.343	0.65	1.1
3	83	1.312	1.392	0.75	1.25

As can be seen in Table. 11 welding speed decreased from 93 mm/min to 83 mm/min, heat input increased, resulting in deeper weld penetration. The increase in heat input promoted a larger molten pool and improved fusion between ASTM A36 and SS316.

4. Conclusions.

In dissimilar metal welding between ASTM A36 and SS316 materials with welding speed variations of 83, 86, and 93 mm/min, the results of the three variations after being tested in non-destructive testing (Penetrant and Radiography Test) and destructive testing (Macro Test) showed no defects in the specimen, and the results were accepted, so the welding had good weld quality. However, of the three variations, the penetration of the welded joint was found to be the deepest, namely at the lowest welding speed of 1.25 mm at a welding speed of 83 mm/min (specimen 3). This was due to the optimum heat input, which caused deeper penetration.

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