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OPTIMIZATION OF DISSIMILAR WELDING PROCESSES BETWEEN Ti-4V-6Al TITANIUM ALLOYS WITH SS304 STAINLESS STEEL BY GAS TUNGSTEN ARC WELDING PROCESS

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Abstract: This study investigated the ultimate tensile strength (UTS) of dissimilar welding processes between Ti-4V-6Al titanium alloys with SS304 stainless steel by gas tungsten arc welding (GTAW) process. The intermetallic compounds of the welds were investigated by X-ray diffraction, and the Taguchi method was used in the experimental design. The welding process parameters are welding current (A), welding speeds (B), and Wire feeds (C). ANOVA analysed the S/N ratio of ultimate tensile strength to determine the optimal parameters for statistically significant factors. Analyse for process parameters on the response and the level of the indispensability factor, as well as predict and regression model for optimal tensile strength. The investigation revealed that the optimum parameters were $A_1B_2C_2$, and the ultimate tensile strength was 285MPa. The ANOVA analysis found that welding current and welding speeds had significance on the ultimate tensile strength of the workpiece at a 95% confidence level. The investigation of intermetallic compounds of the welds with X-ray diffraction technical found that increased welding current tended to cause Ti_3Cu and Fe_4Cu_3 compounds and affected the tensile strength of the weld to decrease.

Keywords: Gas Tungsten Arc Welding; SS304; Ti-4V-6Al.

1. INTRODUCTION

The titanium alloy to carbon steel structure combines the advantages of each material. Currently used in various aerospace, chemical, and nuclear industries [1,2]. However, joining these materials through the fusion welding process also confronts a problem with the strength of the joints. In addition, due to the different specifications of the two materials, the welding process could have been more successful. For this reason, dissimilar materials cause phases or intermetallic compounds (IMC) to each other after cooling these materials.
In most cases, the resulting compounds have high hardness and low ductility when formed in the weld, causing the joint to have insufficient strength that could not be used in structural applications. Therefore, the joining of titanium to steel is usually a friction welding process [3-5], diffusion welding [6-9], explosion welding process [10-12], laser welding [13,14], electron beam welding [15], or other fusion welding processes. However, intermetallic compounds resulting from the thermal differences between the two materials often result in unsuccessful fusion welding. However, the fusion welding process is also popular due to its high flexibility and easy preparation. The challenge in welding titanium to steel with the fusion welding process is the formation of hard and brittle IMCs such as TiFe, $TiFe_2$, and $TiCr_2$ [3, 16]. Of which is significantly susceptible to weld cracking. Recently, it was reported that welding titanium to stainless steel by the laser welding process. The laser welding process can increase the UTS of the weld line [8-9]. Various studies discuss the enhancement of the junctions by inhibiting the formation of titanium-iron compounds with copper, vanadium, magnesium, cobalt, and nickel. These additions can effectively prevent the diffusion of titanium into the steel and inhibit the formation of compounds and other compounds [10-12]. Among the fillers mentioned above, copper filler rods are the most popular to protect titanium-iron compounds. For several reasons, such as (1) the melting temperature of copper is low and can adjust a wide range of welding parameters. (2) Copper is cheaper than magnesium and nickel, which can significantly reduce production costs. (3) Copper does not form compounds with iron, chromium, nickel, and

carbon [13-14]. However, the copper-titanium phase equilibrium diagram indicates that higher copper distribution often leads to the formation of Cu_2Ti, Cu_3Ti, CuTi, and $CuTi_2$ compounds [15]. However, the copper filler can also reduce the complex compounds in steel and titanium welding. Wang et al. [8] found that using copper filler in the welding joint of titanium alloy TA15 with SS304 stainless steel can increase the UTS of 310 MPa. Similarly, Tomashchuket et al. [9] welding titanium alloys with stainless steel by laser welding using copper fillers can increase the weld strength by more than 350 MPa. Yan Zhang et al. [15] examined the welds of titanium alloys with stainless steel by laser welding using vanadium-filled metal for a weld strength of 599 MPa. Y Zhang et al. [16] studied the welding joint of TC4 titanium to SS301L stainless steel by laser welding using copper filler metal. Solid solutions and iron-titanium compounds were found to have a mean maximum tensile strength (UTS) of 350 MPa. As mentioned above, it is found that the welding process of titanium alloy with carbon steel is preferable to laser welding, which is a welding process that is costly to weld and difficult for large structural applications. Therefore, the researcher proposes using a gas tungsten arc welding process (GTAW) with $ERCuSi_3$ copper filler for welding Ti-4V-6Al titanium alloy to SS304 austenitic stainless steel. The welding parameters were welding current, welding speed, and wire feeds. Furthermore, in an investigation of the optimum welding conditions, the Taguchi technique [17,18] was used as an analytical aid to determine the weld's UTS. Because the Taguchi method can reduce the number of experimental variables and obtain a response to approach the mean response of the target [19,20], The difference between this study is that there is no report on the use of the Taguchi method to examine the appropriate factors of the welding process of dissimilar materials. Between Ti-4V-6Al titanium alloy with SS304 stainless steel joint by GTAW process. The Taguchi method can design an efficient welding process.

2. RESEARCH METHODOLOGY

2.1 Materials and Methods

The experiment used the GTAW process to join Ti-4V-6Al titanium alloy with SS304 stainless steel, a thickness of 3 mm, dimension 75x200 mm (width x length). The welding pool was added with a copper ERCuSi3 filler rod, and the chemical composition of the experimental material is illustrated in Table 1. Welding was used on the copper backing plate, with a thickness of 10 mm. a hemispherical groove of 3 mm. for penetration, use of pure argon gas (99.99%), and 10 l/min of flow rate. The workpiece has a groove angle of 30 degrees, and the root opening is 2 mm. The arc length of the electrode tip and the workpiece is 6 mm. Electrode diameter 2 mm. The total groove angle is 60 degrees. In welding electrodes and filler rod slants angled towards stainless steel, the demonstrates the welding process of GTAW is shown in Fig 1.

Table 1. The chemical composition of the materials

Element (wt), %	Material		
	SS304	Ti-4V-6A1	CuSi3
C	0.02	0.009	-
Si	0.44	-	2.84
Mn	1.32	-	0.82
P	0.045	-	-
S	0.002	-	-
Cr	18.67	-	-
Ni	8.04	-	-
Mo	0.02	-	-
Fe	bal	0.001	-
V	-	4.20	-
N	-	0.01	-
Al	-	6.13	-
H	-	0.001	-
Ti	-	bal	-
Cu	-	-	bal
Other	-	-	0.50

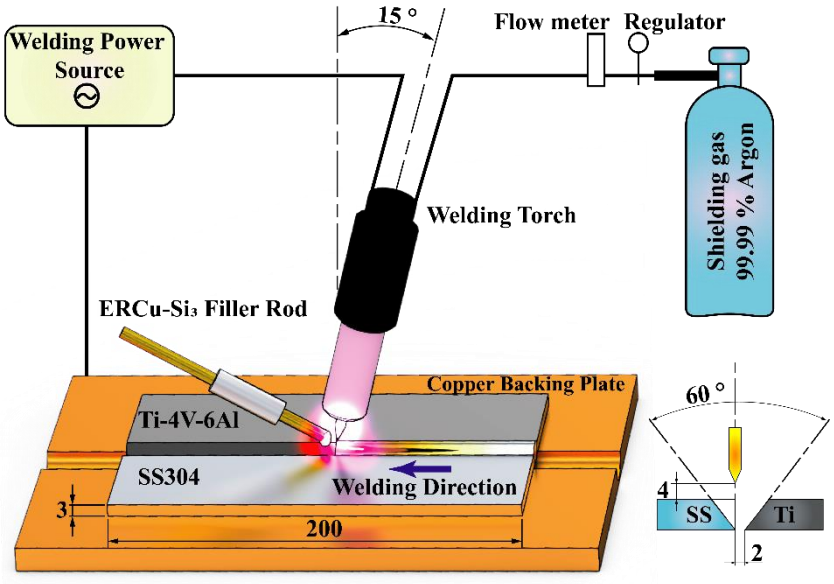

Fig. 1. The welding process

2.2. Weld investigation

The mechanical properties investigation was the UTS and weld hardness. The UTS of the welds is investigated according to ASTM-E8 with a universal testing machine. (HD-B616-2-60T, NAKON PHANOM UNIVERSITY, Thailand) The tensile test sample is shown in Fig 2. In an investigation of the weld hardness, the test samples were polished with emery papers from 180-2000. Next, the sample was polished with 1-3 µm alumina powder. Finally, the sample is cleaned with acetone and dried with hot air. Hardness was performed with Vickers's microhardness tester (IQUALITROL: model: MHV-2000Z Series; Dongguan, China) at 9.81 N. Hardness is investigated transversely to welds across SZ, HAZ, TMAZ, and BM. The inspection distance is 0.2 mm and the dwell time is 10s. X-ray diffraction analysis (Model: XRD 6100-2kw Shimadzu diffraction analysis machine) for investigation of intermetallic compounds of welded.

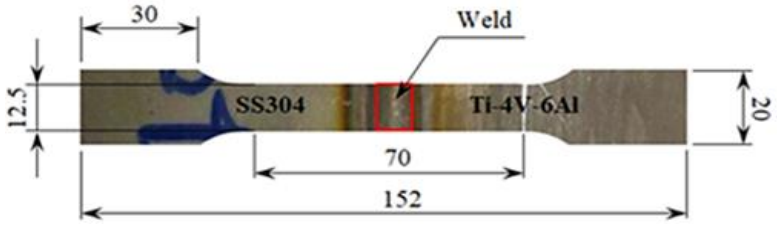

Fig.2. Dimension of the tensile sample
(Unit: mm) ASTM-E8

2.3 Experimental Design

The experiment investigation welding current is (70-90)A, and welding speeds are 90-110 mm/min. Furthermore, Wire feeds are 100-120 mm/min. Taguchi was used in designing experiments to analyze the optimal response of welded. This study used the L9 (3^3) Orthogonal Array (OAS). The experimental factors are shown in Table 2. The larger-is-better equation of UTS illustrates equation (1) for the target value selection experiment. S/N_s is the signal-to-noise ratio, n is the number of datasets, and y_i is the dependent variable or response.

Table 2. Factors and parameters of the experimental

Experimental factor	**Experimental levels**		
	-1	**0**	**1**
Welding Current (A): A	70	80	90
Welding Speeds (mm/min): B	90	100	110
Wire feeds (mm/min): C	100	110	120

$$S/N_L = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

Taguchi is a technique for designing, experimenting, and finding the results of experimental factors. The Taguchi method is a final design that determines optimal performance under specified conditions. The tool used for the Taguchi method is the Orthogonal array (OA), a matrix system of several specifications at the row and column level. The Taguchi method uses a signal-to-noise (S/N) ratio to find the number of available variables. The S/N-Ratio is the mean measure of the effect of noise factors on the performance characteristics of the variables. It will measure the S/N of the number of variables in the response data and bring it closer to the mean of the desired target response.

The efficiency test procedure is shown in Fig. 3.

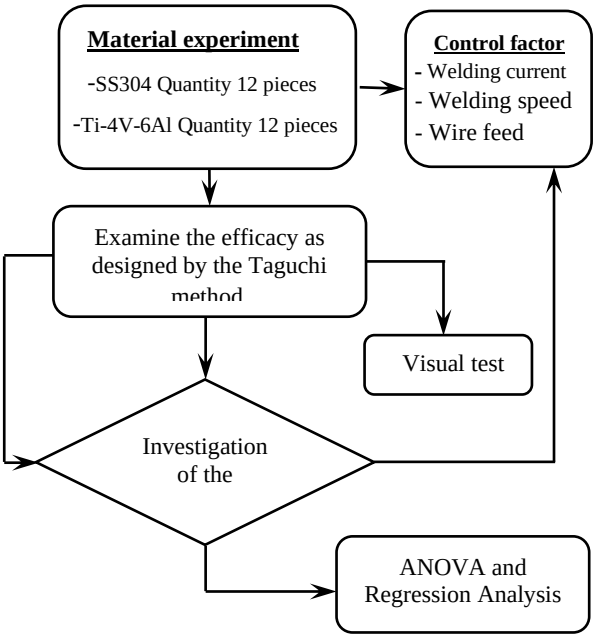

Fig. 3. The experimental procedure of the welding process to determine the optimization by the Taguchi method

3. EXPERIMENTAL RESULTS

3.1. Signal to Noise Ratio *(S/N Ratio)*

Optimal parameters of the welding process with the Taguchi method were analyzed by signal-to-noise ratio analysis; S/N analyzed the main effect of the factor and S/N Ratio values on the UTS values. Larger-the-better [21-25] values were determined. The results of the analysis are as follows.

Table 3. Experimental design: L9, mean UTS values, and signal-to-noise ratio values

Run	A	B	C	UTS (MPa)	S/N Ratio
1	70	90	100	248	47.89
2	**70**	**100**	**110**	**285**	**49.10**
3	70	110	120	205	46.24
4	80	90	110	186	45.39
5	80	100	120	166	44.40
6	80	110	100	172	44.71
7	**90**	**90**	**120**	**122**	**41.73**
8	90	100	100	145	43.23
9	90	110	110	130	42.28

This research is to study the weld factor on UTS, experimental model, experimental results, and S/N ratio for weld UTS and mean S/N of UTS response, as shown in Table 3. The effect of welding factors analysis revealed that

the mean UTS and S/N ratio was appropriate: $A_1B_2C_2$, welding current is 70A, welding speed is 100 mm/min, and wire feeds are 110 mm/min.
Fig. 4 illustrates and analyzes the main effect plot of the factors for the signal-to-noise ratio (S/N Ratio) of the mean UTS for the welded. The maximum level values for each factor are as follows: welding current level 1 is 70A, welding speed level 2 is 100 mm/min, and wire feed level 2 is 110 mm/min.

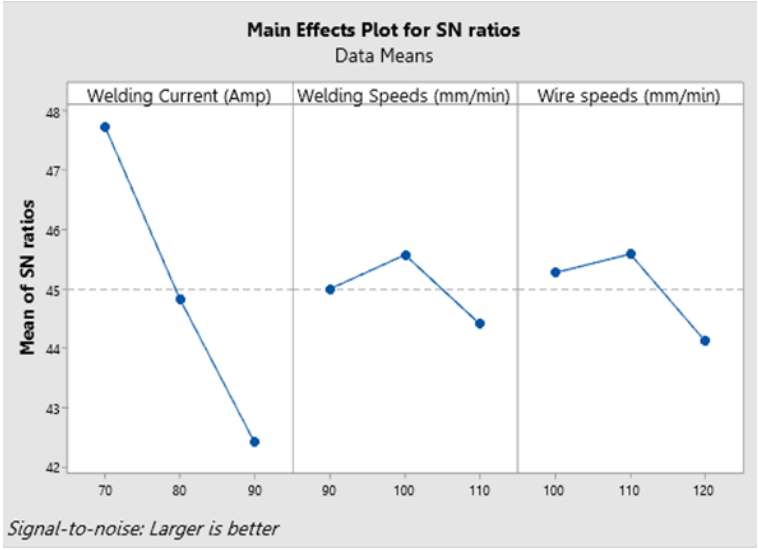

Fig. 4. Main effects plot for the Signal Noise Ratio of UTS

Table 4 illustrates the S/N ratio of the mean factors for UTS at each level. The results exhibited that for the first level of welding current (A), the maximum response was 47.74; for the second level of welding speed (B), the maximum response was 45.58; and for the second level of wire feeds (C), the maximum response was 45.59.

Table 4. Response table for signal-to-noise ratios of UTS

Level	A	B	C
1	47.74	45.00	45.28
2	44.83	45.58	45.59
3	42.41	44.41	44.12
Delta	5.33	1.17	1.47
Rank	1	3	2

The optimal parameter analysis results of UTS using signal-to-noise ratio values. The suitable parameters for welding Ti-4V-6Al alloy with SS304 stainless steel by GTAW welding process are as follows: Optimal factor A is welding current of level 1 is 70A, Optimal factor B is welding speed of level 1 is 100 mm/min, and Optimal factor C is wire feeds, Level 2 is 110 mm/min. Therefore, the optimal UTS parameter for this welding is $A_1B_2C_2$

3.2. Analysis of Variance *(ANOVA)*

Table 5 shows the ANOVA analysis of the mean UTS of the weld. In general, the probability distribution of the data considers DF, where DF=2 was used for specifying the number of variables in ANOVA calculations. An analysis of the process coefficient of determination (R-square) of 99.66% indicates that welding factors such as welding current, welding speed, and wire feeds were significant for the process. Additionally, for the parameters of the Seq SS, the Adj SS, and Adj MS, a high F-value indicates the importance of the factor. However, this experiment found that welding current and wire feeds significantly affected the UTS since both factors had a P-value of less than 0.05 ($p \leq 0.05$). Therefore, welding current and wire feed parameters are the most critical parameters in the process at a 95% confidence level. On the other hand, an investigation of welding speed demonstrates an insignificant UTS of the weld due to a P-value above 0.05 ($p \geq 0.05$).

Table 5. Response table for signal-to-noise ratios of UTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Welding Current	2	42.7170	42.7170	21.3585	260.57	0.004
Welding Speeds	2	2.0441	2.0441	1.0221	12.47	0.074
Wire feeds	2	3.5828	3.5828	1.7914	21.85	0.044
Residual Error	2	0.1639	0.1639	0.0820		
Total	8	48.5078				

R-Sq = 99.66 %; R-Sq (adj) = 98.65 %

3.3. Regression Analysis

The experiment obtained the optimum factor for welding on the UTS: a welding current of 70A, welding speed of 100mm/min, and wire feeds of 110mm/min. As a result, the Taguchi method's predicted UTS has 276.33 MPa. The regression equation analysis for the predicted UTS is exhibited in equation (2).

$$UTS = 853 - 5.683A - 0.817B - 1.200C \text{ (MPa)} \quad (2)$$

Predictive the UTS for regression equation is presented in equation (3).

$$UTS = 853 - 5.683(70) - 0.817(100) - 1.200(110) = 241.49\text{MPa} \quad (3)$$

The experimental comparison with statistical analysis found that the test confirmation of UTS averaged 285MPa. The prediction by Taguchi Method and the regression analysis were 276.33MPa and 241.49MPa, respectively.

Table 6. Confirmation of experimental results

Level	UTS (MPa)			Average UTS (MPa)
	No.1	No.2	No.3	
1	274	282	269	275.00
2	291	288	270	283.00
3	277	275	288	280.00
Total Average				**279.33**

3.4. Confirmation of experimental results

The confirmation of experimental results was the final setup of the optimal parameters obtained from the predicted UTS based on the Taguchi method ($A_1B_2C_2$). The experiment was repeated in three of these factors; nine tensile test samples were prepared each, and the mean UTS was obtained at 279. 33MPa. The results of the repeated experiments are exhibited in Table 6.

4. DISCUSSION RESULTS

4.1. Tensile and Vickers Hardness Test Analysis

The UTS analysis was verified in sample 2 *(*$A_1B_2C_2$*), which* is the UTS of welded. It found the sample fracture position in the transition zone on the Ti-4V-6Al side. Since the transition zone forms brittle intermetallic compounds between copper and Ti-4V-6Al, such as Ti_3Cu and Fe_4Cu_3 [26], it is easily fractured when subjected to tensile loads. As exhibited in Fig.5, the weld was damaged by brittleness.

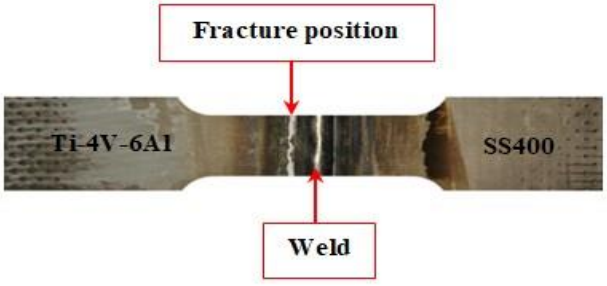

Fig. 5. Fracture sample of tensile test

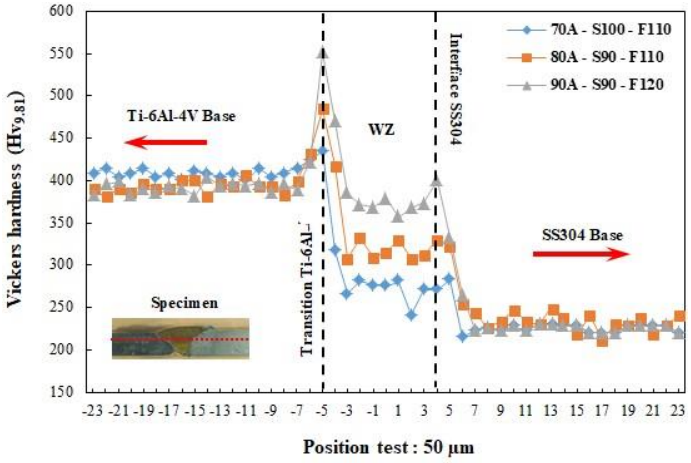

Fig. 6. The hardness test for welded

The weld hardness exhibited in sample 2 ($A_1B_2C_2$) is the lowest hardness, sample 4 ($A_2B_1C_2$) is the intermediate hardness, and sample 7 ($A_3B_1C_3$) is the maximum hardness. The average welded hardness is 283 HV, 330 HV, and 468 HV, respectively. Fig. 6 illustrates that hardness is investigated transversely to welds across SZ, HAZ, TMAZ, and BM. It was found that sample 7 is 90A-S90-F120 with the maximum welded hardness. According to an X-ray diffraction investigation, the increased welding current raised the brittle intermetallic compound.

4.2. Investigation of the morphology of the weld

The efficacy of the welding process by the Taguchi method exhibited that sample 2 had the maximum UTS, sample 4 had the intermediate UTS, and sample 7 had the lowest UTS. All three samples were then to investigate the weld morphology to describe the transference occurring within the weld. Fig. 7 illustrates XRD patterns of samples that intermetallic compounds between the base material and filler metals, such as Ti_3Cu and Fe_4Cu_3. It has been observed that the welding current on the formation of intermetallic compounds in the welded. For example, at the welding current of 90A, the peak concentration of the Ti_3Cu compound was highest. When the welding current was reduced, the concentration of Ti_3Cu and Fe_4Cu_3 compound was decreased at 80A and 70A, respectively.

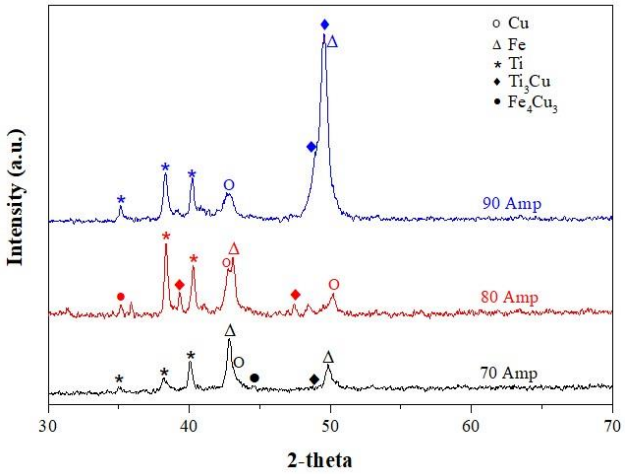

Fig. 7. The X-ray diffraction (XRD) pattern of welded

4.3. Comparison of Studies with Literature Review

Table 7 is a comparison of research studies with a literature review, finding that most of the research focused on the analysis of the chemical composition of the welds between titanium alloy and stainless steel. In addition, the research mentioned has yet to study the relevant factors in welding between both materials. As well as establish a model to predict experimental results. Therefore, for the advantage of practice and study, the authors investigated the optimum welding factor by designing an experiment with the Taguchi method. The Taguchi method has the advantage of reducing the sample size of the experiment. The Taguchi method could predict the results of the

experiment effectively; moreover, this research also studied the UTS of the workpiece after welding for information in further research and study.

Table 7. Comparison method of UTS based on dissimilar welding joint

Method	Welding process	Base metal	Filler metal	Weld analysis	UTS (MPa)	Ref.
N/A	FW	Ti6Al4V/ SUS321	N/A	SEM/EDS/XRD	560	[3]
N/A	Diffusion bonding	Ti6Al4V/ MDSS	N/A	SEM/EDS/XRD	520	[6]
N/A	laser/ELB	Ti6Al4V/ AISI 316L	Cu	SEM/EDS/XRD	N/A	[9]
N/A	laser	TC4/ SUS301L	Cu	SEM/TEM/XRD	350	[12]
N/A	GTAW	TC4/ SUS304	Cu	SEM/EDS	107	[13]
N/A	GTAW	TC4/ SUS304	$CuSi_3$	SEM/EDS	328	[14]
Taguchi	GTAW	Ti6Al4V / SUS304	$CuSi_3$	XRD	285	This work

5. CONCLUSIONS

Optimal parameters of dissimilar welding process between Ti-6Al-4V/SS304 with GTAW process affecting UTS using Taguchi method. It was found that the welding process parameters used mean UTS and S/N ratio where the most suitable level was $A_1B_2C_2$. The predicted UTS from the Taguchi model was 276.33MPa, and the regression analysis was 241.49MPa. The experimental confirmation of UTS tends to have a similar aspect. An analysis of variance (ANOVA) found that welding factors on UTS were welding current and Wire feeds, whereas welding speeds were insignificant on UTS of weld at a 95% confidence level. Therefore, welding current and wire feeds should be considered in the dissimilar welding process between Ti-6Al-4V/SS304 and the GTAW process. As welding current and wire feed on the formation of intermetallic compounds after welding, welding is unsuccessful. The weld's chemical composition and corrosion resistance should be examined in the following study.

6. ACKNOWLEDGMENT

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