The Effect of Activating Fluxes on 316L Stainless Steel Weld Joint Characteristic in TIG Welding Using the Taguchi Method

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ABSTRACT

Gas tungsten arc welding is fundamental in those industries where it is important to control the weld bead shape and its metallurgical characteristics. However, compared to the other arc welding process, the shallow penetration of the TIG welding restricts its ability to weld thick structures in a single pass (~ 2 mm for stainless steels), thus its productivity is relativity low. This is why there have been several trials to improve the productivity of the TIG welding. The use of activating flux in TIG welding process is one of such attempts. In this study, first, the effect of each TIG welding parameters on the weld's penetration depth was shown and then, the optimal parameters were determined using the Taguchi method with L_9 (3^4) orthogonal array. SiO_2 and TiO_2 oxide powders were used to investigate the effect of activating flux on the TIG weld penetration depth and mechanical properties of 316L austenitic stainless steel. A camera was used to observe and record images of the welding arc, and analyze the relationship between increasing the penetration depth and arc profile. The experimental results showed that activating flux aided TIG welding has increased the weld penetration, tending to reduce the width of the weld bead. The SiO_2 flux produced the most noticeable effect. Furthermore, the welded joint presented better tensile strength and hardness.

Introduction

TIG welding is a process that uses a shielding gas (argon or helium) in which a non-consumable tungsten electrode is used for establishing an electric arc. It is commonly used for welding hard-to-weld metals such as stainless steels, magnesium, aluminium, and titanium [1-3].High quality metallurgical weld and good mechanical properties are the benefits of the TIG process. In contrast, low penetration depth and low productivity are its limitations. Therefore, it has limited economic justification when compared to consumable electrode arc welding processes in sections thicker than 10mm (0.375 in.). On the other hand, the tendency towards higher quality products and more productivity in recent years has led to the development of various provisions in TIG welding process. One of the

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most striking provisions is the use of activating fluxes in TIG welding process, which was coined in the early 1960s, and now is known as Active TIG (A-TIG) method. In this method, a thin layer of activating flux is applied on the surface of base metal. During welding, certain conditions in the arc and the weld zone lead to an increased penetration depth, and increased productivity in joining thick parts [4-7].

In addition, TIG welding parameters are not only the main factors in determining the depth of weld penetration and productivity of the process, but also they affect the performance of the activating fluxes. But there is not yet any analytical relationship between these parameters and welding geometry. However, knowledge of the relationship between welding parameters and weld quality is essential for controlling the process. Quality of welds can be analyzed through weld geometry (depth and width). However, weld geometry affects its shape and plays an important role in determining the mechanical properties of weld [8,9]. In general, for determining the optimal parameters, time consuming and costly tests should be used due to the complexity and non-linearity of welding process. Taguchi method, which is an effective method for estimating optimal parameters of welding process, has been used in this study.

Taguchi method is a powerful tool for designing high quality systems. It provides a simple, efficient, and systematic approach to optimize designs for performance, quality, and cost.

Experiments planned by statistical methods are the key tools of Taguchi method for designing the parameters. In statistical methods, the process is optimized through determining the optimal operating conditions, investigating the effect of each factor on the outcome, and estimating the outcome under optimal conditions [10].This method was used in this study to determine the optimal welding parameters for a weld with the maximum penetration depth and minimum width. Creating a weld with high penetration depth and low width will increases productivity and decreases the welding part distortion.

The effect of the activating fluxes on weld geometry and mechanical properties of joint has been studied comparatively. Information extracted from the experiments conducted in this study can be useful for the application in various industries.

Experimental Procedure

316L austenitic stainless steel with a chemical composition presented in **Table 1** was used to conduct the tests. For this purpose, sheets with the dimensions of 150×150×8 mm were prepared and tests were conducted in two steps. In the first step, optimal parameters of welding process were determined using Taguchi method with $L_9(3^4)$ orthogonal array. The $L_9(3^4)$ means that to investigate 4 factors on a qualitative index with 3 levels for each factor, all required tests will be (81) 3^4. Using Taguchi method, such study is applicable with only 9 tests. In this study, four main parameters of TIG process including welding current, arc length, welding speed, and the tungsten electrode angle were evaluated at three levels. The values of each A, B, C, and D parameters are shown in **Table 2**.Selecting values of the parameters levels were made in the light of theoretical and experimental standpoints at the three levels of low, medium, and high. Taguchi experimental layouts are shown in **Table 3**. In order to ensure results and minimize the effects of uncertainty, all tests were repeated three times, and the averaged results were evaluated. In all tests, bead shape welding has been done without the filler metal on the sheet in a single pass. It is noteworthy that the tungsten electrode diameter which contains 2% thorium (3.2mm), and high purity argon Debye (13L/min) were fixed in all welds.

In order to determine the parameters which significantly affect the depth to width ratio, investigation of the welding parameters was done using ANOVA analysis. The S/N ratio was selected based on the bigger-the better criterion in order to achieve the optimal parameters which are as follows[11]:

Table 1. Chemical composition (wt.%) of 316L stainless steel.

C	Si	Mn	Cr	Ni	Mo	P	S	UTS (MPa)	Elongation (%)
0.025	0.477	1.26	17.4	10.2	2.1	0.032	0.002	558	50

Table 2. Welding parameters with levels of Taguchi method.

Factor	Process parameter	Level 1	Level 2	Level 3
A	Welding Current (A)	150	180	210
B	Electrode angle (Degree)	60	75	90
C	Welding speed ($mm.s^{-1}$)	3.3	4.2	5
D	Arc length (mm)	2	3	4

Table 3. Experimental layout using the $L_9(3^4)$ orthogonal array.

Experiment No.	Experiments	Process variables level			
		Welding current	Electrode angle	Welding speed	Arc length
1	$A_1B_1C_1D_1$	150	60	3.3	2
2	$A_1B_2C_2D_2$	150	75	4.2	3
3	$A_1B_3C_3D_3$	150	90	5	4
4	$A_2B_1C_2D_3$	180	60	4.2	4
5	$A_2B_2C_3D_1$	180	75	5	2
6	$A_2B_3C_1D_2$	180	90	3.3	3
7	$A_3B_1C_3D_2$	210	60	5	3
8	$A_3B_2C_1D_3$	210	75	3.3	4
9	$A_3B_3C_2D_1$	210	90	4.2	2

$$(S/N)_i = -10log\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{Y_{ij}^2}\right] \quad (1)$$

In this equation, i is the number of the experiment, Y_{ij} is the qualitative index, and n is the total number of experiments. To evaluate the effect of parameters variations on qualitative index, participation percentage was also used.

Taguchi S/N ratio defines the ratio of signal factors (fixed factors) to turbulence factors (uncontrollable factors). Analysis of the S/N ratio is used to determine the best test performance or the best composition of various factors in order to reach the optimal result.

The ANOVA analysis is another powerful tool of Taguchi process which is done after S/N ratio analysis. Error variance and relative importance of the factors are determined in this analysis.

In the second step, the effect of activating fluxes on TIG weld was studied according to the optimal parameters of the first step experiments. SiO_2 and TiO_2 powders with particle size of 30-60 µm have been used as the activating fluxes. A suspension of oxide powders and acetone was prepared and set aside to transform to pulp; after that, some of it was applied on the surface of the jointby a brush. Then all samples were put under the equal welding conditions. After welding, cross sections of the welded specimens were prepared, and after grinding, polishing, and etching with Marbel solution (10gr$CuSO_4$ + 50ml HCL + 50ml H_2O), weld penetration depth and width of the samples were measured by optical microscope. Then Vickers hardness test was done on the melting zone with 200 gr·f load for 15 s. Tensile test specimens were prepared in small size according to ASTM E8 standard. To ensure the accuracy of tensile test results, three tensile specimens of each weld have been tested, the average result of which was the tensile properties criterion. Fracture surface of the tensile specimens was analyzed by SEM. Arc welding was photographed in order to investigate the reasons for increasing penetration depth by activating fluxes.

Results and Discussion

Determining TIG welding process optimal parameters

Taguchi experimental results of weld penetration depth are shown in **Table 4**.For more accurate results, each test was repeated three times, and its average result was considered as the penetration depth criterion. Sum of squares and S/N ratio was calculated for each factor separately in order to determine the effect of different factors on the result. S/N ratio calculated values of Taguchi layout are shown in **Fig. 1**. The purpose is to increase the penetration depth, and decrease the TIG weld width. So S/N ratio was selected on the basis of bigger-the better criterion. ANOVA analysis and used to determine the relative contribution of each factor. According to its results, optimal parameters were selected as $A_3B_2C_1D_1$ to achieve maximum penetration depth and minimum weld width. So the optimal parameters of the process are welding current 210 A, electrode angle 75^o, welding speed 3.3 mm.s^{-1}, and arc length 2mm.

Effect of activating fluxes on weld morphology

Following Taguchi experiments and determining the optimal parameters, activating fluxes were used. Cross section of the welds, using optimal parameters, and at different states of using and not using the activating fluxes,are shown in **Fig. 2**.

As can be seen, the use of flux leads to the major changes in penetration depth and weld width. According to **Fig. 2**, the percentages of increased penetration depth in the use of TiO_2 and SiO_2 are 260% and 300%respectively, as compared to the case with no flux. Increased penetration depth can be due to the mechanisms which occur because of the flux decomposition [12-14]. High temperature of the area beneath the arc welding (about 6000 K) leads to the decomposition and evaporation of flux from the surface of the weld. Thermodynamic equations related to TiO_2 and SiO_2 are given below (**Eq. 2** and **3**).

$$SiO_{2(s)} = Si_{(s)} + O_{2(g)}$$
$$\Delta G^0 = 902000 - 174T \tag{2}$$

$$TiO_{2(s)} = Ti_{(s)} + O_{2(g)}$$
$$\Delta G^0 = 910000 - 173T \tag{3}$$

Oxide molecules resulting from the decomposition of the flux will join to the free electrons around the arc plasma. Electron absorption by these oxide molecules willbring about the formation of negative ions ($2e + O_2 \rightarrow O_2^{2-}$) with low mobility which surround the arc. The presence of this oxide layer around the arc leads to the arccontraction and the prevention of the heat lossby the electrons. Front view of the arc plasma column images are shown in **Fig. 3** at the presence and absence of flux. Along with the arc contraction, input current density at theanode center (anode spot) is increased and is followed by increasing weld penetration depth. It was shown by the Qing-ming and Xin-hong that the decomposition of activating flux will lead to the increase in arc voltage [15]. It can be said that further increase in penetration depth by SiO_2 is due to the further increase of arc voltage. This is because of the

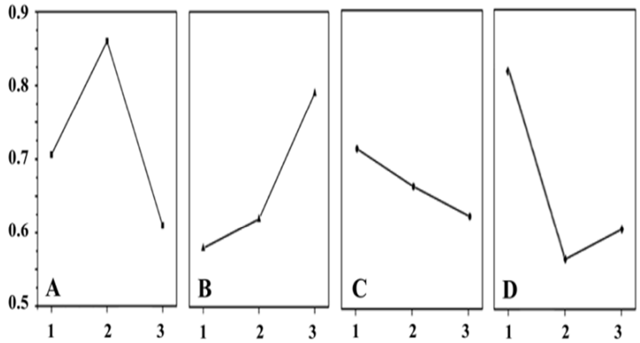
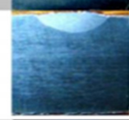
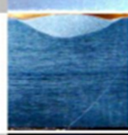
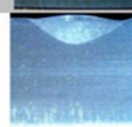
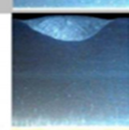
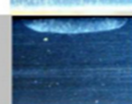
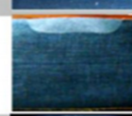
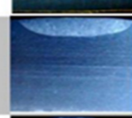
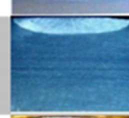
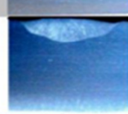
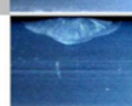
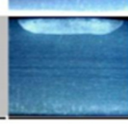
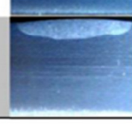
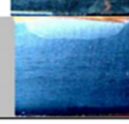
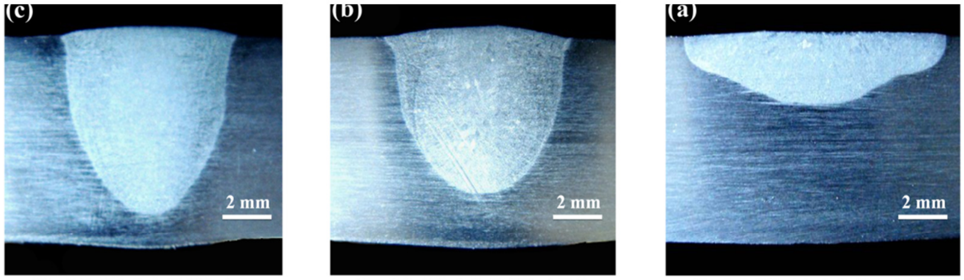


Fig. 1. S/N graph for highest weld depth to bead-width ratio.

Table 4. Experimental results of weld penetration and D/W ratio.

Experiment number	Test 1	Test 2	Test 3	Penetration (mm)	Weld depth to width ratio (D/W)
1				1.15 1.22 1.31	0.21 0.19 0.25
2				1.66 1.59 1.61	0.34 0.38 0.35
3				1.38 1.41 1.5	0.32 0.29 0.25
4				1. 58 1.79 1.63	0.27 0.29 0.34
5				1.45 1.35 1.67	0.23 0.17 0.23
6				1.33 1.41 1.29	0.18 0.22 0.19
7				1.37 1.47 1.42	0.17 0.24 0.23
8				1.98 2.11 1.84	0.26 0.34 0.25
9				1.37 1.42 1.39	0.16 0.19 0.22



(D=7.2, W=7.9, D/W=0.9) (D=6.2, W=8.2, D/W=0.76) (D=2.4, W=10.6, D/W=0.23)

Fig. 2. The effect of oxide fluxes on weld morphology a)without flux b)TiO_2 flux c)SiO_2 flux.

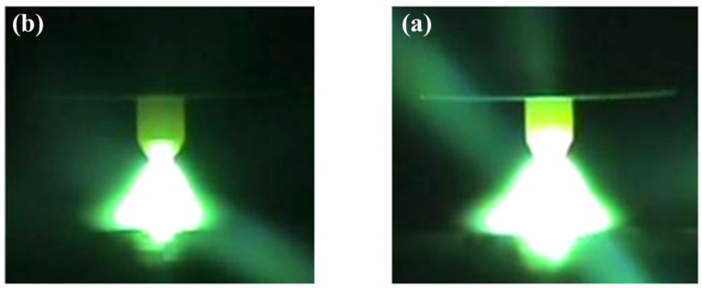


Fig. 3. Arc plasma column images of a) without flux and b) SiO_2 Flux.

Table 5. The effect of activated flux on arc voltage.

Weldment	Arc voltage (V)
Without flux	13.2
TiO_2 Flux	14.6
SiO_2 Flux	15.4

fact that the silicon oxide is a ceramic oxide and forming a conductive channel between the tungsten electrode and work piece is harder than the titanium oxide, which is a metal oxide.

Effect of activating fluxes on mechanical properties

Tensile and hardness test results of the welds are shown in **Fig. 4**. As can be seen, welds containing flux have a relatively higher hardness and yield strength than those of noflux. The obtained results are in agreement with findings of previous research [16]. Considering that the fracture area of all specimens has been in the heat affected zone (HAZ), microstructure examination was applied tothis area. According to theobserv-ations, the HAZ of the welded specimens in the presence of activating flux, has a smaller grain size than those with no flux. Welding arc contraction via flux, resulting in less heat entering the area around the weld, can be considered as the reducing factor of grain size in this area. So, the tensile properties of weld are increased due to the decrease in grain size using TiO_2 and SiO_2 activating fluxes.

SEM examination of fracture surface of the ruptured specimens revealed a porous structure in all specimens, which is created due to the joining of micropores. The fracture mode in both cases (with or without the flux) is similarly soft dimple. According to **Fig. 5**, it is obvious that the welded specimen fracture surface, using SiO_2 activating flux, has a lot of tiny and shallow dimples, indicating atensile strength higher than that

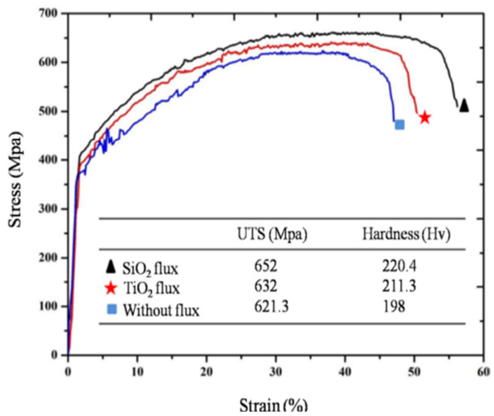


Fig. 4. The effect of activating flux on mechanical properties.

of the welded specimen without activating flux.

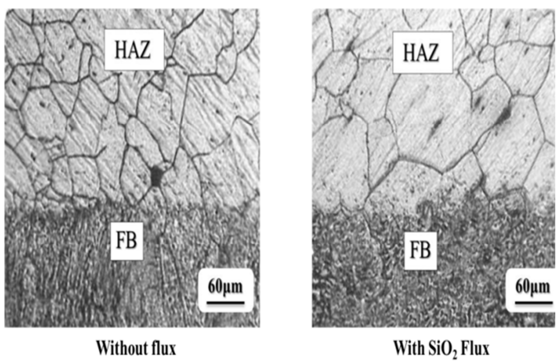


Fig. 5. Optical micrographs of fusion boundary and heat affected zone.

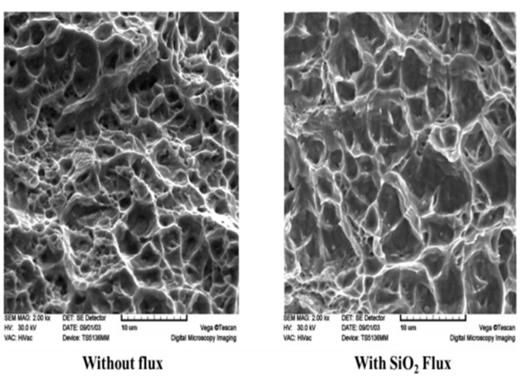


Fig. 6. Scanning electron microscopy of fracture surface.

Conclusions

Taguchi experimental results showed that among four major parameters of welding, i.e. welding current (A), electrode angle (B), welding speed (C), and arc length (D), the welding current and speed are the most effective ones and increase the penetration depth to width (D/W) ratio. Weld penetration depth is increased due to the increase in the current and the decrease in the welding speed. It was determined that the use of activating fluxes not only increases the weld penetration depth, but also decreases the weld width, which is important in terms of welding distortion. Activating fluxes improve the joint mechanical properties by decreasing the grain size of heat affected zone.

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