International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 5 Issue 4, April-2016

An investigation of the effect of welding parameters and cooling state on the characteristics of austenitic stainless steel parts welded by pulsed/non-pulsed TIG welding.

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ABSTRACT

The aim of this work is to investigate the influence of the welding process parameters on the mechanical and metallographical properties of weldments curried out using TIG welding with pulsed/non pulsed current processes. The cooling state was introduces as an input parameter to investigate the main effects on the structure morphology and thereby the mechanical property. In this work the selected pulse frequency levels were 5-500 Hz in order to show the effect of low and high frequencies on the weldment characteristics of AISI 304L plates using filler metal of ER 308LSi. In this work, three levels four factors Taguchi L9 orthogonal array was used to analyze the ultimate tensile strength and micro-hardness of the welded specimens. Taguchi analysis was performed for the main effects plot to optimize the process parameters. Furthermore, the microstructure evolution has been investigated. The key findings of this work clarified that the pulse frequency has significant effect on the breaking of the dendrite arms during welding process and so strongly affects on the tensile strength. The cooling state also affects on the microstructure texture and thereby, the mechanical properties.

Keywords: TIG welding; Microstructure; Mechanical properties; Pulse frequency; Austenitic stainless steel.

1. INTRODUCTION

Tungsten inert gas (TIG) welding is the most widely used process for joining the stainless steel components with thickness less 10 mm [1]. It is very suitable for thin sheets due to its easier applicability, flexibility, and better economy [2]. The improving in the weld quality depends on the improvement in process parameters which requires the use of improved welding techniques and materials. Pulsed current TIG welding (PCTW) is a variation of continuous current TIG welding (CCTW) where involves cycling the welding current at a given regular frequency from a high level to low level [3]. In PCTW process, the peak current (I_p) is selected to melt the filler and base metal and to generate adequate penetration, whereas the base current (I_b) is set at a level sufficient to maintain a stable arc [4]. By contrast, in CCTW, the heat required to melt the filler and base metals is supplied only during Ip pulses allowing the heat to dissipate into the base material [5]. Devendranath Ramkumar et al. [6] used the pulsed and conventional TIG welding to study the weldability of AISI 904L stainless steel. They demonstrated that the PCTW generally offers better tensile properties as compared to CCTW weldments. Prasad et al. [7] used pulsed current in micro plasma arc welding process to study the quality of different types of stainless steels. They concluded that the AISI 304L achieved the better quality characteristics as comparison of AISI 316L, AISI 316Ti, and AISI 321. Dinesh Kumar et al. [8] used Taguchi method to analysis and optimize the process parameters for pulsed TIG welding process of AISI 304L stainless steels. They showed that travel speed and current are the most important parameters which affect the response variables.

From the observation made on the above online literature, various properties of austenitic stainless steel weldments were investigation. The present work is an experimental investigation performed on the application of PCTW and CCTW processes for welding of similar AISI 304L stainless steel sheets using filler metal of ER308LSi solid wire. This study focused on studying the effect of low and high levels of pulse frequency and other factors on the microstructure and mechanical characteristics. Additionally, new cooling system was introducing for investigating the effects of cooling states on the obtained microstructure and hence the mechanical properties

2. MATERIALS AND RESEARCH METHOD

The AISI 304L stainless steel is used in some of important industries such as containers of transporting chemicals, oil refinery, nuclear reactor tanks, dairy industries, textile industries, etc. In this work a 3.8 mm thick 304L sheet has been welded to similar 304L sheet by TIG technique. The filler metal selected for welding was ER 308LSi stainless steel solid wire with a diameter of 0.8 mm. The suggested shielding gas was Argon with 99.90% purity. The 304L stainless steel plate and the welding metal were chemically analyzed, and the results of the analysis were listed in Table 1. The plates were cut to the required dimensions (100 mm x 50 mm) using power hacksaw cutting machine. Square butt joint configuration was used to join these plates. The prepared parts were joined using CCTIG and PCTIG processes using LINCOLN TIG machine which can be used for continuous and pulsed currents. The pulsed current mode used in the used welding machine shown in Fig.1. The joining process were done with/without filler metal and with/without using cooling system. The travel speed and arc length were controlled using CNC machine, whereas the wire feed rate controlled using external wire feed machine. The water temperature was 20 ^{o}C with sufficient flow rate. Figure 2 shows the different units used in this work. In case of using cooling system, the 304L plates were placed on the copper backing plate, which was designed with internal water passages to increase the cooling rate of the melting pool zone (see Fig. 2b). To have defect free samples for testing, large number of trial runs were carried out with different combination of the process parameters. Some of process parameters were kept as constant during all experiments such as welding current of 175 A, arc length of4 mm, wire feed angle of ^{o}40, and stick out of 15 mm.

In this study, a four experimental factors three levels array was used. The range of each process parameter levels were selected based on trial welds and process parameters such as travel speed (TS), wire feed speed (WFS), pulse frequency (F), and introducing the cooling state (Cs) as a new factor as summarized in Table 2.

For the purpose of optimization and obtaining the best possible results with the test number of experiments, the experiments were designed in the 'Minitab 17' software. Taguchi's L9 orthogonal array was used to design the experiments in the research work. In the L9 orthogonal array, nine experiments were prepared to study the effects of the main parameters. The nine experiments were carried out based on the L9 array. The effects of the main input parameters on the weld parts were analyzed.

The tensile strength and micro-hardness of all specimens were measured carefully and the ooobserved values for strength with their S/N ratios summarized in Table 4. In Taguchi method, the optimum value is obtained by calculating the signal to noise ratio. Te term "signal" represents the desirable mean value, and the "noise" represents the undesirable value. Hence, the S/N ratio represents the amount of variation. S/N is the performance characterisitic having three types such as (1) Higher the better, (2) lower the better, and (3) nominal the better.

In the present study, hardness and ultimate tensile strength of the tested weld specimens were identified as the response, therefore, : higher the better (HB) is used for maximaizing both tensile strength and hardness of the welded parts. The higher the better performance is expressed

S/NHB= -10 log $[\frac{1}{n}\sum_{i=1}^{n} y_i^{-2}]$
where n is the number of repetition of output response in the same trial and y is the response.

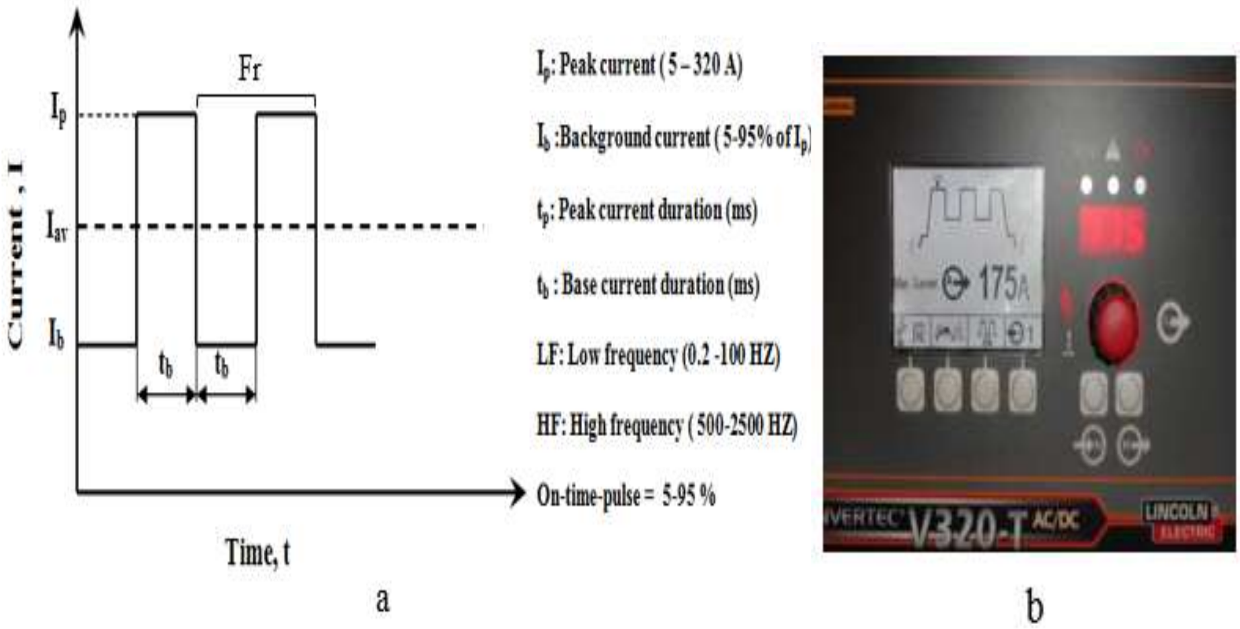

Fig. 1 (a) Schematic diagram of a standard pulse current-time wave form in present PCSMD process and (b) picture illustrates the welding machine screen when it setup on the pulsed current state

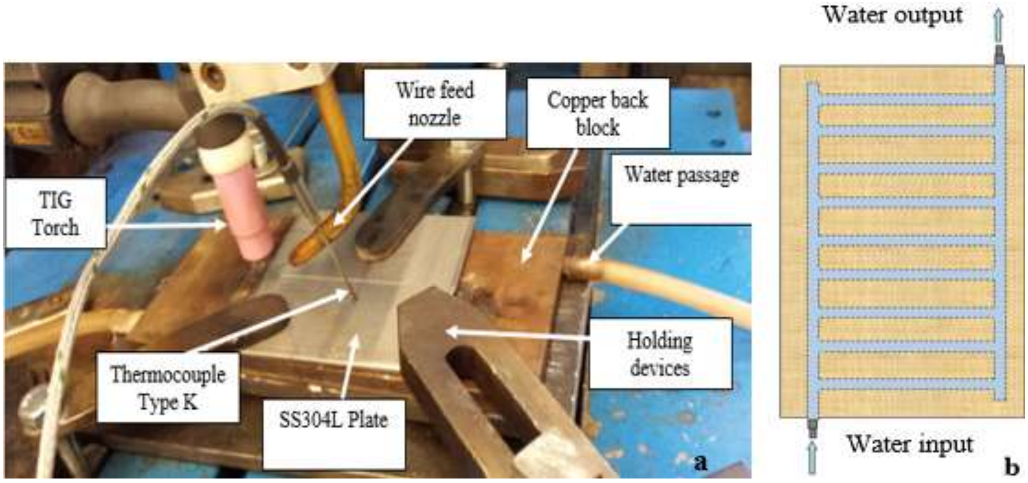

Fig. 2 (a) TIG welding experimental setup and (b) schematic illustrates the water cooling system

Table 1: The chemical composition of the base and the filler materials (in wt.%)

Element	%C	%Si	%Mn	%S	%P	%Mo	%Ni	%Cr	% Fe	Others
SS304 actual composition	0.015	0.528	1.011	0.0107	0.02	0.053	8.202	18.164	Rem.	V = 0.10, Cu = 0.031 Ti =0.01
ER308LSi as deposited composition	0.018	0.56	1.358	0.0331	0.033	0.115	9.412	19.557	Rem.	Co=0.941; Cu= 0.181 Ti=0.057

Table 2: Identified factors with levels

Symbol	Factor	Unit	Levels		
			1	2	3
TS	Travel speed	mm/s	1	2	3
WFS	Wire feed speed	m/min	0	2	4
F	Pulse frequency	Hz	0	5	500
Cs	Cooling state	-----	0*	1**	2***

*No copper back strip; ** With copper back strip; *** With continuous water cooling system

3. RESULTS AND DISCUSSIONS

3.1 Taguchi Analysis

The S/N ratio analysis of the results was carried out to determine theoptimized responses. The individual S/N ratio values of all the responses for each trial for both micro-hardness (MH) and ultimate tensile strength (UTS) are listed in Table 3. The level of a factor with highest S/N value was chosen as the optimum level of the parameters.

3.1.1 Tensile Strength

The UTS was calculated expaerimentally and taguchi method was used for analysis together with aid of analysis of variance. The main effects plots for the S/N ratios are shown in Fig. 2. The optimal process parameters have been established by analyzing response curves of S/N ratio. From Fig. 2, it is concluded that the first level of travel speed (1 mm/s), second level of wire feed rate (2 m/min), second level of frequency (5 Hz) and third level of cooling state (continuous water coolng system) give the optimal ultimate tensile strength. Analysis of variance of S/N ratio is summarized in Table 4. It is obvious that the frequency is the most important factor affects UTS with maximum percent attribution of 49.55 % followed by cooling state with percent attribution of 30.77%. The response values for S/N ratio for each level of identified factors have been listed in Table 5, whichshows the factor level values of each factor and their ranking.

Table 3: Taguchi L9 orthogonal array and experimental results of the responses

Exp. No	Input parameters				Responses			
	TS	WFS	F	Cs	HV	S/N ratio	UTS	S/N ratio
1	1	0	0	0	207	46.319	671.73	56.547
2	1	2	5	1	310.675	49.846	697.315	56.868
3	1	4	500	2	295.625	49.414	684.79	56.711
4	2	0	5	2	234.45	47.401	738.1	57.362
5	2	2	500	0	263.55	48.417	531.7	54.513
6	2	4	0	1	240.18	47.61	581.8	55.295
7	3	0	500	1	228.15	47.164	560	54.963
8	3	2	0	2	302.52	49.615	701	56.914
9	3	4	5	0	212.75	46.557	530	54.485

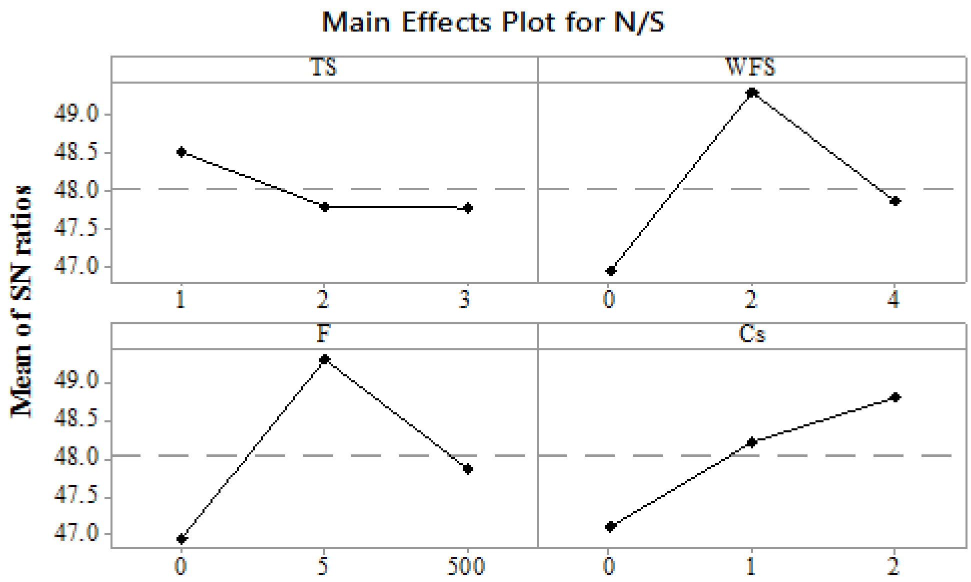

Fig. 2 Effects of process parameters on tensile strength S/N ratio

Table 4: ANOVA for means of UTS

Source	DOF	Seq. SS	Adj. MS	F-value	P-value	Percent contribution
TS	1	0.8385	0.8385	4.4	0.104	5.87 %
WFS	1	1.2123	8.1708	42.87	0.003	8.48 %
F	1	7.0826	7.0826	37.16	0.004	49.55 %
Cs	1	4.3981	4.3981	23.07	0.009	30.77 %
Error	4	0.7624	0.1906			5.33 %
Total	8	14.294				100 %
R-Sq. = 94.33				R-Sq. (adj.) = 89.33		

Table 5: Response table for S/N ratios of UTS for larger the better characteristics

level	TS	WFS	F	Cs
1	48.55	46.95	46.95	47.15
2	47.8	49.3	49.3	48.15

3	47.7	47.9	47.9	48.8
delta	0.85	2.35	2.35	1.65
Rank	1	2	2	3

3.1.2 Micro-Hardness (MH)

The main effects plots for the S/N ratios are shown in Fig. 3. The mean of the S/N values is shown in Table 3. The From the Fig. 3 and Table 3, combination of optimum level of the parameters was interpreted. The most significant factors were Cs and TS which significantly affect on the micro-hardness. From Fig 3, the S/N values were inversely proportional to TS, WFS, and F from level 1 to 3, whereas S/N value was found to increase with increasing the levels 1 to 3 of cooling states. From Fig. 3, it is concluded that the first level of travel speed (1 mm/s), first level of wire feed rate (0 m/min), first level of frequency (0 Hz) and third level of cooling state (continuous water coolng system) give the optimal micro-hardness. Analysis of variance of S/N ratio is summarized in Table 6. It is obvious that the cooling state is the most important factor affects MH with maximum percent attribution of 47.85% followed by travel speed with percent attribution of 22.89% .

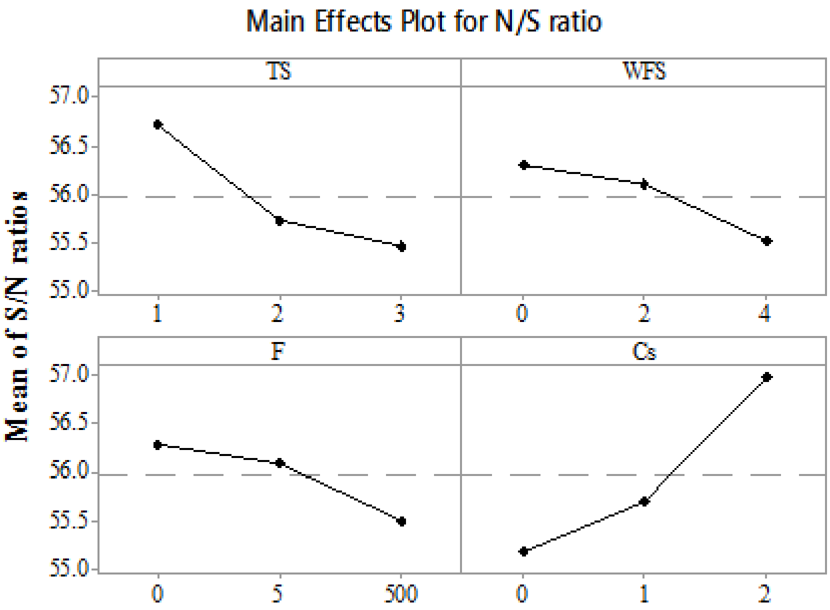

Fig. 3 Effects of process parameters on micro-hardness S/N ratio

Table 6: ANOVA for means of MH

Source	DOF	Seq. SS	Adj. MS	F-value	P-value	Percent contribution
TS	1	2.3613	2.36128	4.75	0.095	22.89%
WFS	1	0.9449	0.05151	0.10	0.764	9.16%
F	1	0.0836	0.08364	0.17	0.703	0.81%
Cs	1	4.9359	4.93589	9.93	0.034	47.85%
Error	4	1.9887	1.98871			19.28%
Total	8	10.3144				100 %
R-Sq. = 80.72%				R-Sq. (adj.) = 61.44%		

Table 7: Response table for S/N ratios of MH for larger the better characteristics

Level	TS	WFS	F	Cs
1	56.7	56.3	56.3	55.1
2	55.7	56.1	56.1	55.7
3	55.45	55.5	55.5	57
delta	1.25	0.8	0.8	1,9
Rank	1	1	1	3

3.2 Microstructure

It is clear that two differnet kinds of δ-ferrite, namely lathy and skeletal δ-ferrite are formed in the austenitic matrix. Fig. 4 shows the variation of δ-ferrite morphology in weld zone using CCTGA of experiments 1 and 8. Experiment 1 shows the microstructure of specimen prepared without using the copper strip and without adding filler metal, whereas experiment 8 shows the effects of using continuous water cooling system and with adding filler metal. Fig. 4a dipicts greater skeletal and vermicular δ-ferrite with high grain size, and Fig. 4b reveals that the grain size generally was finer and higher concentration ot total δ-ferrite contnt compared to experiment 1 (Fig.4a).

The amount of δ-ferrite exists in the weld metal depends on several factors, the most significant factors are chemical composition of the filler and base metal, welding procedure, and the amount of heat input to the melting pool during the welding process [9]. Furthermore, the process of rapid solidification with high temperature gradient, it is beneficial to obtain fine microstructure. Low heat input to the weld zone may result from high travel speed, using continuous cooling system, or using high pulse frequency. Fig. 5 shows the effects of pulse frequency on the microstructure texture. High frequency leads to break the dendritic arm of the austenitic stainless steels and produces uniform structure (see Fig.5b). Figure 6 describes the effects of the pulsed current on columnar grains as comparing to conventional current process. Mourad et al. [10] demonstrated that residual ferrite is strongly influnce by the heat input. At high cooling rates, which result from pulsed current process, high travel speed, or continuous water cooling system, the transformation of δ-ferrite to austenite is suppressed, and higher residual ferrite content in the welding metal is expected as shown in Figs. 4b and 5b.

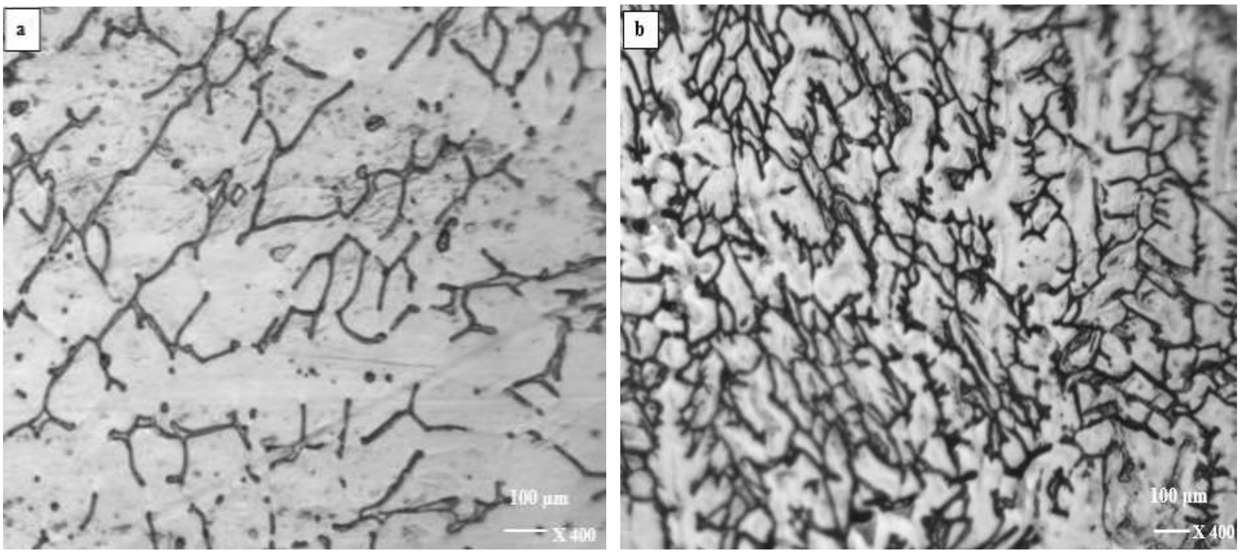

Fig. 4 CCTIG (a) exp.1 (TS 1mm/s, WFS 0, Cs 0) and (b) exp.8 (TS3mm/s, WFS 4m/min, Cs2)

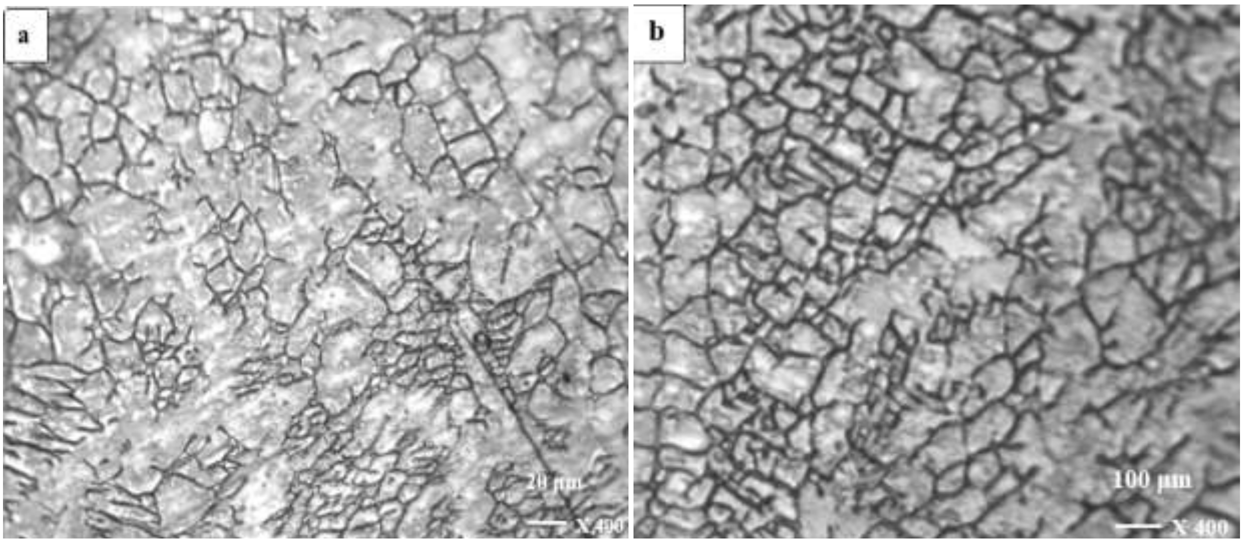

Fig.5 PCTIG (a)exp. 3 (TS 1 mm/s, WFS 4 m/min, Cs 2, F 5 Hz), (b) exp. 7 (TS 3 mm/s, WFS 0 m/min, Cs 1, F 500 Hz)

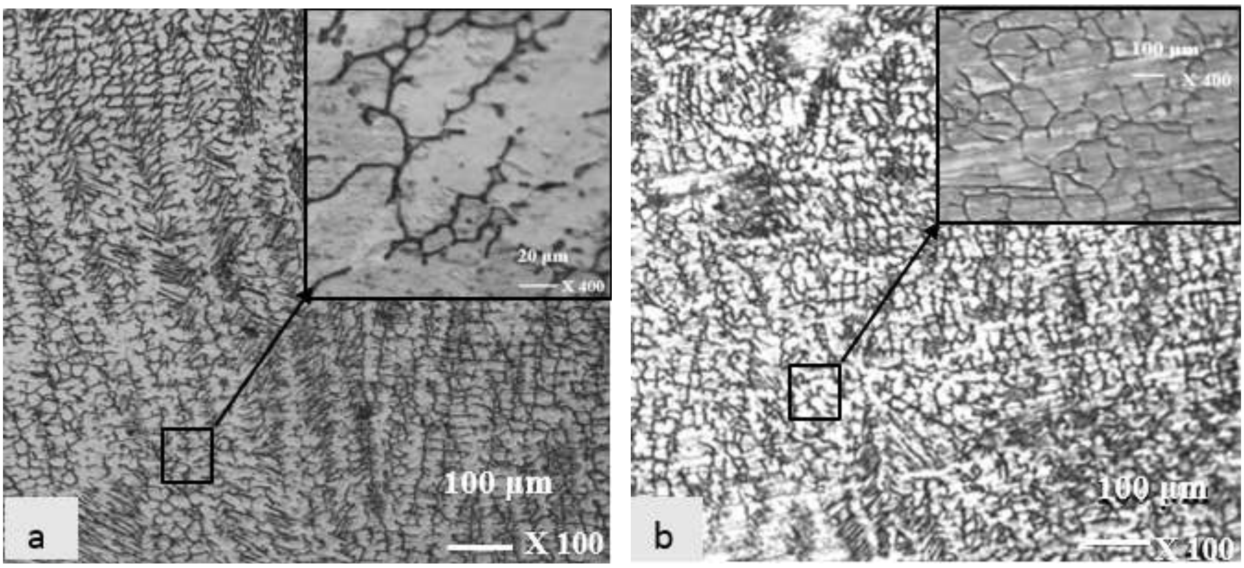

Fig. 6 Micrographs illustrate the effects of frequency on the dendritic arms (a) continuous current (exp. 1) and (b) pulsed current (exp.5).

CONCLUSION

This paper has presented the optimization of process parameters of welding of 3.8 mm sheets of AISI 304L stainless steel material through experimental study for non-pulsed & pulsed current TIG welding. The L9 orthogonala array has been used to assign the selected parameters and using the analysis of variance to analize the resuls. The results show that the pulse frequency is the most significant factor influences the ultiate tensile strength since it significantly affects the grain size through breakingthe dendrite arms as well as the amount of δ-ferrite is relatively higher. Whereas, the cooling state factor is most significant parameter affects on the micro-hardness, since it creates a fine structure with high residual δ-ferrite content which leads to increasing the hardness of the weldments. The highest tensile strength achieved during this research is 738 MPa at frequency of 5 Hz and using continuous water coo ling system. While highest hardness obtained is 310 HV at frequency of 5 Hz and using the copper strip with air cooling. High pulse frequency affects on the morphology of the welded parts and hence improves the mechanical properties. Additionally, there is no evidence of any sensitization of the welded parts can be seen for all specimens also no other defects can be observed in all cases during macro- and microstructure tests.

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