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Technical Report

Optimization of pulsed TIG welding process parameters on mechanical properties of AA 5456 Aluminum alloy weldments

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ABSTRACT

The present work pertains to the improvement of mechanical properties of AA 5456 Aluminum alloy welds through pulsed tungsten inert gas (TIG) welding process. Taguchi method was employed to optimize the pulsed TIG welding process parameters of AA 5456 Aluminum alloy welds for increasing the mechanical properties. Regression models were developed. Analysis of variance was employed to check the adequacy of the developed models. The effect of planishing on mechanical properties was also studied and observed that there was improvement in mechanical properties. Microstructures of all the welds were studied and correlated with the mechanical properties.

1. Introduction

Al–Mg alloys are extensively used in defence and aerospace applications. Tungsten inert gas (TIG) welding is an arc welding process that produces coalescence of metals by heating them with an arc between a non-consumable electrode and the base metal. TIG welding process [1] is generally used for welding of Al–Mg alloys. The initial strength of the non-heat treatable aluminum alloys depends primarily upon the hardening effect of alloying elements such as silicon, iron, manganese and magnesium [2]. These elements increase the strength either as dispersed phase or by solid solution strengthening. The welding of non-heat treatable aluminum alloys typically have distinct effects when the heat input is increased, i.e. the width of the heat affected zone (HAZ) is increased and the minimum reduction in the mechanical properties are observed. Alloys 5XXX series with more than 3.0% magnesium are not recommended for elevated temperatures above 150 °F because of their potential for sensitization and subject susceptibility to stress corrosion cracking [3]. The minimum HAZ strength approximates to that of the annealed parent metal regardless of the starting temperature.

During welding, vaporization of alloying elements like magnesium can occur and this vaporization loss of any alloying elements can influence the mechanical properties of the welded joints by affecting the chemistry of the weld pool. The gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) welding processes are very often used for welding of these alloys. However, GTAW process is generally preferred because it produces a very high quality welds. Distortion is the major problem in welding of thin sections. However, the distortion is controlled in pulsed and magnetic arc oscillation GTAW process. Metallurgical advantages of pulsed and magnetic arc oscillation welds that are frequently reported in the literature includes grain refinement in the fusion zone, reduced width of HAZ, less distortion, control of segregation, reduced hot cracking sensitivity and reduced residual stresses [4–6].

The purpose of the present investigation is to optimize the pulsed TIG welding process parameters for increasing the mechanical properties using Taguchi method. Taguchi method is a systematic approach to design and analyze experiments for improving the quality characteristics. Taguchi method [7–10] permits evaluation of the effects of individual parameters independent of other parameters and interactions on the identified quality characteristics, i.e. ultimate tensile strength, yield strength, hardness, etc. Nowadays, Taguchi method has become a practical tool for improving the quality of the output without increasing the cost of experimentation by reducing the number of experiments.

Welds are made with the use of obtained optimum condition, and these welds are subjected to cold planishing process. The roll planishing is an effective process in which weld is passed between two steel rollers. During the planishing operation, the internal stresses which are induced during welding are relived and the grains are deformed. Hence, the mechanical properties of the welds have been improved.

2. Scheme of investigation

In order to maximize the quality characteristics, the present investigation has been made in the following sequence.

- Selection of base material and filler material.
- Identify the important pulsed welding process parameters.

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- Find the upper and lower limits (i.e. range) of the identified process parameters.
- Select the orthogonal array (design of matrix).
- Conduct the experiments as per the selected orthogonal array.
- Record the quality characteristics (i.e. mechanical properties).
- Find the optimum condition for maximizing the mechanical properties.
- Conduct the confirmation test.
- Develop the regression models to predict the mechanical properties within the selected range.
- Identify the significant factors.
- Check the adequacy of the developed models.

2.1. Selection of base material and filler material

The base material employed in this study is 2.14 mm thick Al–Mg Aluminum alloy welded with 5356 filler material. The chemical composition of the base material and filler material are shown in Table 1. The selection of the filler material is based on the mechanical properties and resistance to cracking in the weld [2].

2.2. Identify the important pulsed welding process parameters

From the literature [5,11] and previous work done [10,12,13], the most important process parameters which are having greater influence on the weld bead geometry and fusion zone grain refinement of pulsed welding process have been identified. They are: peak current, base current and pulse frequency.

2.3. The working range of the process parameters

A large number of trials have been conducted by varying one of the process parameters and keeping the others constant. The working range of peak current, base current, welding speed, pulse frequency has been explored by inspecting bead appearance and the full penetration. The working range of the process parameters selected under the present study and the constant process parameters are shown in Tables 2 and 3, respectively.

2.4. Selection of orthogonal array

Number of process parameters considered under this study is four, and the level of each parameter is two. The degrees of freedom of all the four parameters and their interactions are seven. Hence, L8(2^7) orthogonal array is selected. Each condition of the experiment was repeated twice to reduce the noise/error effects. The selected orthogonal array was presented in Table 4.

2.5. Conduct the experiments as per the selected orthogonal array

The base metal sheets of dimension 250 mm × 150 mm × 2.14 mm have been prepared and butt joints were made using the experimental layout shown in Table 4. An automatic TIG welding machine has been employed for conducting the welding experiments. Prior to welding, the base metal sheets were pickled with a solution of NaOH and HNO_3, wire brushed, and degreased using acetone and finally preheated to 100 °C. The sheets to be welded were kept on steel backing bar and ends were clamped to maintain the alignment and gap. Purging is provided at the bottom of the sheets. The same argon gas is used for shielding as well as purging. The weld joint is completed in single pass.

Table 2
Working range of the process parameters

Symbol	Process parameter	Units	Lower level (1)	Higher level (2)
P	Peak current	Amps	70	80
B	Base current	Amps	40	50
S	Welding speed	mm/min	210	230
F	Pulse frequency	Hz	2	4

Table 3
Constant process parameters

Process parameter	Constant value
Shielding gas flow rate, l/min	10
Purging gas flow rate, l/min	5
Filler rod diameter, mm	1.6
Electrode material	98% W + 2% Zr
Electrode diameter, mm	3.15
Pulse ratio, %	50
Pulse on time, %	50

Table 4
Experimental lay out L8(2^7) orthogonal array

Exp. no.	P	B	P × B	S	P × S	B × S	F
Pm1	1	1	1	1	1	1	1
Pm2	1	1	1	2	2	2	2
Pm3	1	2	2	1	1	2	2
Pm4	1	2	2	2	2	1	1
Pm5	2	1	2	1	2	1	2
Pm6	2	1	2	2	1	2	1
Pm7	2	2	1	1	2	2	1
Pm8	2	2	1	2	1	1	2

2.6. Record the quality characteristics (i.e. mechanical properties)

Specimens for tensile testing were taken at the middle of all the joints and machined to ASTM E8 standards [14]. The configuration of specimen used under tensile testing is shown in Fig. 1. Tensile test was conducted using a computer-controlled universal testing machine with a cross head speed of 0.5 mm/min. All the welded specimens were failed in the weld region. The ultimate tensile strength of the weld joint is the strength of the weld.

Specimens for metallographic observation and microhardness tests (15 mm width) were considered at the middle of all the joints. The specimens were suitably sectioned, mounted in transverse direction of the welding, mechanically polished according to standard metallographic procedures and etched using modified Keller's reagent (2 ml HF, 3 ml HCl, 20 ml HNO_3 and 175 ml H_2O). Microstructures were observed and recorded using an optical microscope. Microhardness tests were carried out on the welded samples with a load of 15 g and a duration of 15 s using a Vickers digital microhardness tester. The microhardness was measured at an interval of 0.5 mm across the weld, 1 mm across the heat affected zone and 1.5 mm across the unaffected base metal. The schematic sketch of the hardness survey is shown in Fig. 2. The hardness distribution across the weld is shown in Fig. 3.

Table 1
Chemical composition of the base material and filler material (wt%)

	Mg	Si	Cu	Cr	Mn	Zn	Ti	Fe	Al
Al–Mg (AA 5456 Aluminum alloy) (base material)	5.3	0.3	0.1	0.35	0.65	0.10	0.20	0.40	Balance
5356 Alloy (filler material)	5.0	–	–	0.12	0.12	–	0.13	–	Balance

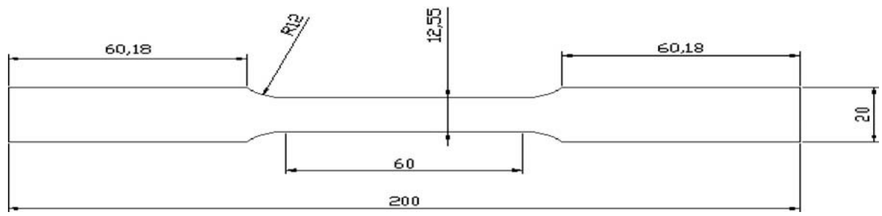

Fig. 1. Configuration of plain tensile test specimen.

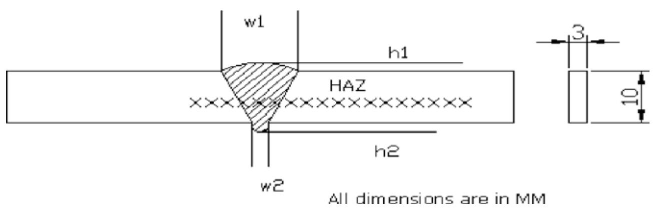

Fig. 2. Schematic sketch of hardness measurement in transverse across the joint.

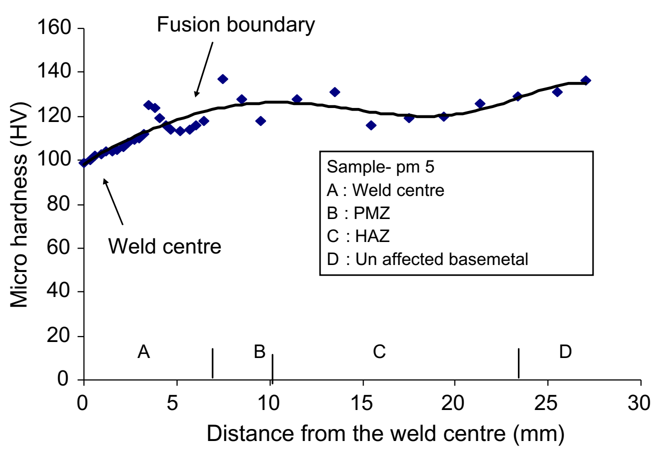

Fig. 3. Microhardness survey in transverse to the weld direction of Al–Mg (AA 5456) weld (sample – Pm5).

The quality characteristics, i.e. ultimate tensile strength, yield strength, percent elongation and hardness of the weldments were evaluated for all the conditions and presented in Table 5.

2.7. Find the optimum condition for maximizing the mechanical properties and conduct the confirmation test

The optimization of process parameters using Taguchi method [9,10] permits evaluation of the effects of individual parameters independent of other parameters, and also of their interactions on the identified quality characteristics, i.e. ultimate tensile strength (UTS), yield strength, percent elongation and hardness. The statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each process parameter and their interaction in influencing the quality characteristic is evaluated. The ANOVA also provides an indication of which process parameters are statistically significant. The optimum process parameter combination is predicted and the optimum results are presented in Table 6. The same optimum combination is observed in all the quality characteristics. For validations of the optimum results, experiments are conducted as per the optimum conditions and mechanical properties are evaluated and the average results are presented in Table 7. It is observed that, experimental values were closer to the optimum values.

2.8. Develop the regression models

The responses *Y* such as ultimate tensile strength, yield strength, percent elongation and hardness are the function of peak current, base current, welding speed and pulse frequency. The response function can be expressed as

Table 6
Optimum values of the quality characteristics

Quality characteristics	Optimum condition	Optimum value
UTS (MPa)	$P_2B_1S_2F_2$, i.e. peak current at level 2 (80 A),	290
Yield strength (MPa)	Base current at level 1 (40 A) welding speed	183
Percent elongation	at level 2 (230 mm/min), and frequency at	12
Hardness (HV)	level 2 (4 Hz)	118

Table 7
Validation of the optimum results

Quality characteristics	Optimum condition	Optimum value	Experimental value[a]
UTS (MPa)	$P_2B_1S_2F_2$	290	289.85
Yield strength (MPa)		183	182.35
Percent elongation		12	11.58
Hardness (HV)		118	117.56

[a] Average of three values.

Table 5
Mechanical properties of pulsed AA 5456 Aluminum alloy weldments

Specimen ID	UTS (MPa)		Yield strength (MPa)		Percent elongation		Microhardness (HV)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Pm1	265	260	165	168	10	11	100	98
Pm2	275	260	175	169	12	11	110	108
Pm3	245	250	155	160	9	10	98	94
Pm4	260	255	168	164	11	12	100	94
Pm5	280	285	180	185	14	13	114	102
Pm6	260	265	175	170	12	11	102	115
Pm7	250	258	160	165	10	10	99	104
Pm8	275	270	178	175	12	12	106	104
Base material	325	320	228	218	18	17.5	125	120

$$Y = f(\text{Peak current, base current, welding speed, pulse frequency})$$
$$Y = f(\text{P, B, S, F})$$

The regression model selected includes the effects of main factors and first-order interactions of all the factors. It is the part of power series of polynomial and expressed as

$$Y = b_0 + b_1(\text{P}) + b_2(\text{B}) + b_3(\text{S}) + b_4(\text{F}) + b_{12}((\text{PB}) + b_{13}(\text{PS}) + b_{23}(\text{BS})$$

where b_0 is the average of responses, $b_1, b_2, \ldots, b_{23}$ are the regression coefficients (i.e. b_k) that depend on respective main and interaction factors which are calculated by using the following expression [15,16].

$$b_k = \frac{\sum_{i=1}^{N} X_{ik} Y_k}{N}, \quad k = 0, 1, 2, \ldots, n \tag{1}$$

where X_{ik} is the value of factor or interaction in coded form, Y_k is the output response (ultimate tensile strength, yield strength, percent elongation and microhardness), N is the number of observations and n is the number of coefficients of the model. The coefficients of the variables and their interactions are computed using the above relationship.

2.9. Identify the significant factors

Analysis of variance (ANOVA) is applied to find out the significance of main factors and their interactions. In addition the *F*-test can also be used to determine which welding process parameter has significant effect on the response (i.e. ultimate tensile strength, yield strength, percent elongation and hardness). Usually, the change of the welding process parameter has significant effect on the response when the *F*-ratio is large. It is found that the coefficients of the variables and their interactions are significant.

2.10. Check the adequacy of the developed models

Coefficient of correlation '*r*' is used to find how close the predicted and experimental values lie and it is calculated using the following expression

$$r^2 = \sum(Y_\text{p} - Y_\text{a})^2 \Big/ \sum(Y_\text{e} - Y_\text{a})^2 \tag{2}$$

where Y_p is the predicted (using the above model); Y_e is the experimental value; Y_a is the average of experimental values. The developed regression equations and the corresponding coefficients of correlation are presented in Table 8. It is observed that, the coefficients of correlation of the entire developed model are found to be higher values. Hence the developed models are significant.

2.11. Validations of the developed models

A few numbers of observations are taken under different set of parameters within the limits investigated and the corresponding estimated values are determined by the use of developed model.

Table 8
Regression equations for the mechanical properties of the weldments

S. no.	Response	Regression equation	Coefficient of correlation
1	Ultimate tensile strength	Y = 263.33 + 4.56P − 5.44B + 1.69S + 4.19F + 0.81PB − 2.06PS + 5.44BS	0.88
2	Yield strength	Y = 169.50 + 4.0P − 3.88B + 2.25S + 2.63F − 0.13PB − 1.25PS − 3.38BS	0.91
3	Percent elongation	Y = 11.63 + 0.63P + 0.25B + 0.13S−0.25F + 0.25PB − 0.88PS + 0.25BS	0.82
4	Hardness	Y = 101.38 + 3.63P − 3.38B + 0.88S + 0.63F + 1.13PB − 3.63PS + 1.88BS	0.93

Where P, peak current; B, base current; S, welding speed; and F, pulse frequency.

Table 9
Validation of the process models of pulsed TIG welds of AA 5456 Aluminum alloy: (a) UTS (MPa); (b) yield strength (MPa); (c) percent elongation; (d) microhardness (HV)

S. no.	Experimental condition				Process model value	Experimental value	Percentage deviation
	Peak current	Base current	Welding speed	Pulse frequency			
(a)							
1	70	40	210	4	267.50	282.00	5.45
2	70	45	210	4	264.28	275.00	4.05
3	70	45	210	2	260.59	262.00	0.54
4	75	40	210	2	265.59	275.00	1.64
5	80	40	210	2	267.87	280.00	4.52
(b)							
1	70	40	210	4	172.13	175.00	1.66
2	70	45	210	4	170.19	171.00	0.01
3	70	45	210	2	167.56	166.00	0.90
4	75	40	210	2	171.50	175.00	2.04
5	80	40	210	2	173.50	182.00	4.89
(c)							
1	70	40	210	4	10.25	12.00	17.05
2	70	45	210	4	10.94	11.00	0.52
3	70	45	210	2	11.13	10.50	5.66
4	75	40	210	2	11.32	12.00	6.05
5	80	40	210	2	11.51	13.00	12.53
(d)							
1	70	40	210	4	109.01	112.00	2.74
2	70	45	210	4	108.26	109.00	0.68
3	70	45	210	2	107.51	105.00	2.30
4	75	40	210	2	106.76	110.00	3.03
5	80	40	210	2	106.01	115.00	8.48

The predicted and experimental values are shown in Table 9. It is observed that, the percentage error is found to be very small. Hence the developed model is so adequate within the selected variables.

3. Planishing

The roll planishing is an effective process in which weld is passed between two steel rollers. The optimum pressure is applied between the rollers is about 2 bar and the optimum speed of 30 mm/min so that weld bead is pressed and there is no top and bottom reinforcement. During the planishing operation, the internal stresses which are induced during the welding are relived and the grains are deformed [17]. Hence, mechanical properties are improved. The schematic sketch of roll planishing process is shown in Fig. 4.

Welds are made with the use of obtained optimum condition and these welds are subjected to cold planishing process. Mechanical properties are evaluated and compared with these results to unplanished condition. Mechanical properties of weldments before and after planishing are presented in Table 10.

4. Discussion

During tensile tests, all the welded specimens were failed within the weld region. Hence, ultimate tensile strength is equal to the strength of the weld. Pulsed welds have shown fine grain structure compared to the continuous welds is due to thermal disturbances and decrease in heat input.

Table 10
Comparison of mechanical properties of pulsed TIG AA 5456 aluminum alloy weldments before and after planishing

Quality characteristics	Optimum condition	Before planishing	After planishing
UTS (MPa)	$P_2B_1S_2F_2$	289.85	290.35
Yield strength (MPa)		182.35	195.24
Percent elongation		11.58	13.26
Hardness (HV)		117.56	118.52

In general, hardness in the fusion zone is lowest due to the as-cast nature of the microstructure, which is characterized by the coarse dendrite grains, interdendritic segregate phases, and the lack of strengthening phase. Hardness is higher compared to the continuous welds and this could be due to refinement of grain structure and low segregation of phases [18].

The portion of the HAZ close to the weld is harder than the rest of the HAZ, but still softer than the base metal [19]. It is due to the fact that, weldment was subjected to sufficient heat for a reasonable amount of solutionizing (i.e. all the elements are dissolved in single solid solution) and fast enough cooling rate to be quenched and produce a somewhat super saturated solid solution. Very fine precipitates (i.e. Mg_2Al_3) could have formed during cool-

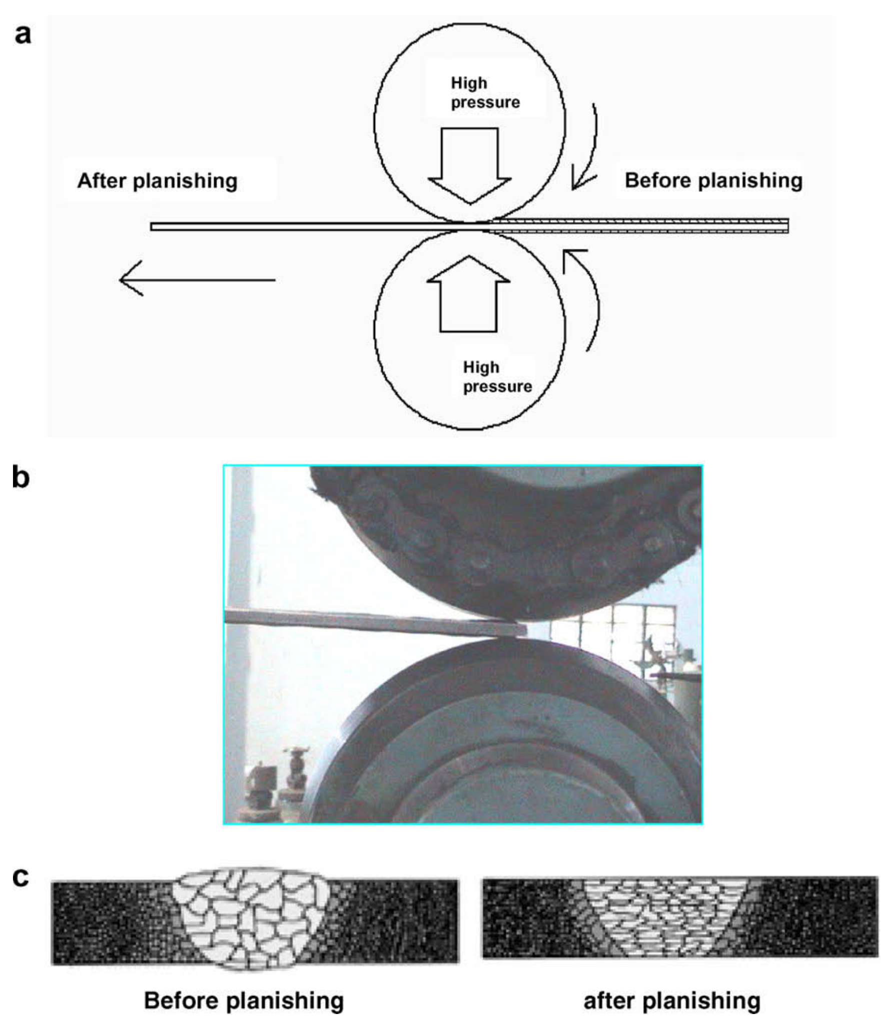

Fig. 4. Planshing process: (a) schematic sketch of roll planishing process; (b) closed view, during operation; and (c) comparison of microstructure before and after planishing.

ing or during natural ageing, resulting in a local hardness peak in close to the fusion boundary.

The microstructures at the weld centre of pulsed welds using the experimental layout are shown in Fig. 5. From these figures, it is evident that, the samples welded by using the condition i.e. Pm5 (peak current – 80 A, base current – 40 A, welding speed – 230 mm/min, and pulse frequency – 4 Hz) resulted in fine equiaxed grains compared to other conditions. It is also observed that a fine interdendritic network of aluminum with much of the Mg_2Al_3 eutectic (dark) precipitates near grain boundaries. It is evident that at higher frequency, the thermal and mechanical disturbances might be more which is due to fact that the weld pool resonant frequency is closer to the experimental frequency of operation, i.e. at 4 Hz. Similar trends have been observed in the literature [11,13].

The microstructure observation of the condition set i.e. Pm4 (peak current – 70 A, base current – 50 A, welding speed – 230 mm/min, and pulse frequency – 2 Hz) is resulted in coarse grain structure. It might be expected that the thermal and mechanical disturbances would be less at lower frequencies. From the observation of the weld microstructures, it is clear that, the combination of peak current, base current, welding speed and pulse frequency resulted in fine equiaxed grain structure.

The aim of this paper is to emphasize on the quality characteristic with minimum number of experiments for the process param-

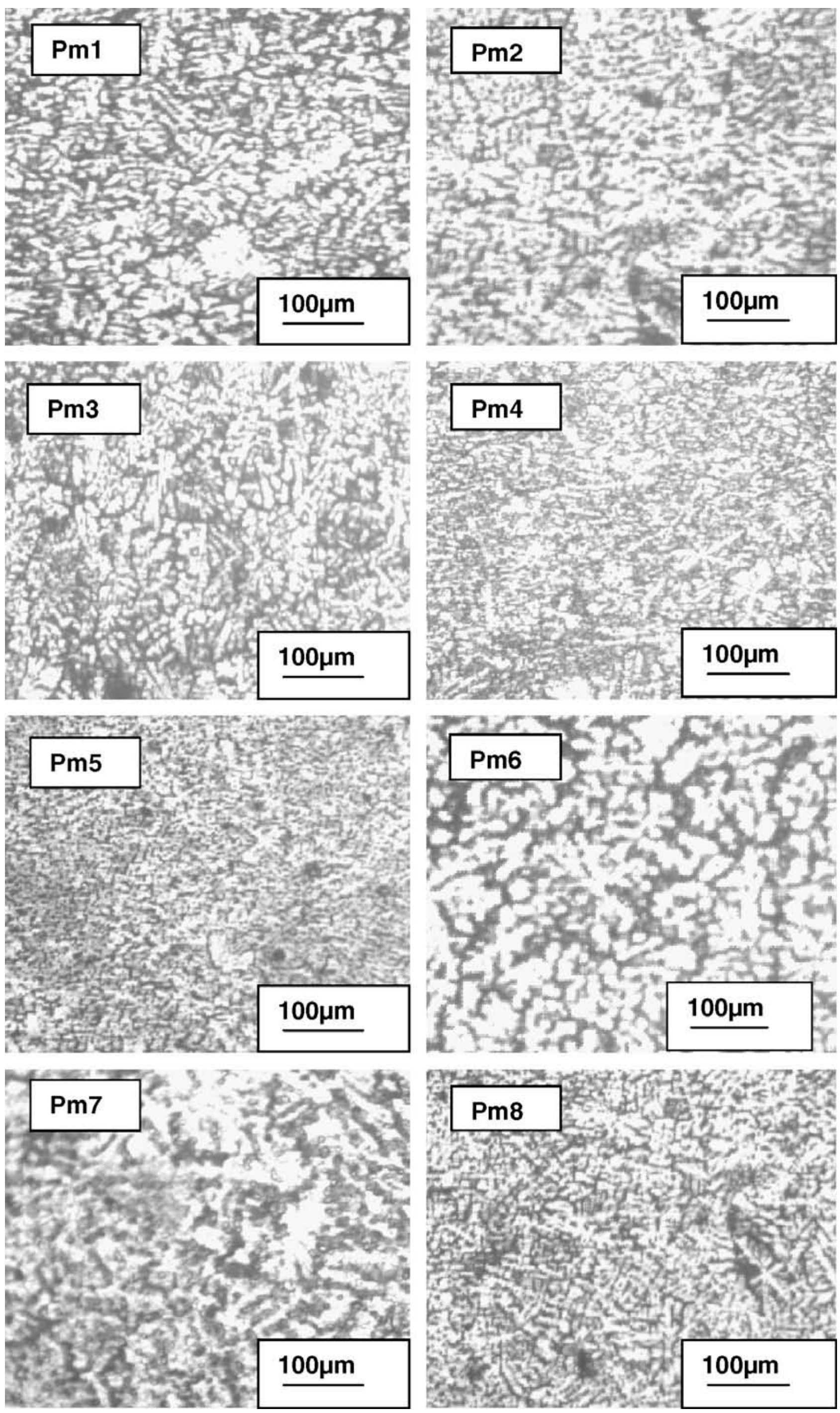

Fig. 5. Microstructures at the weld centre of pulsed TIG welds.

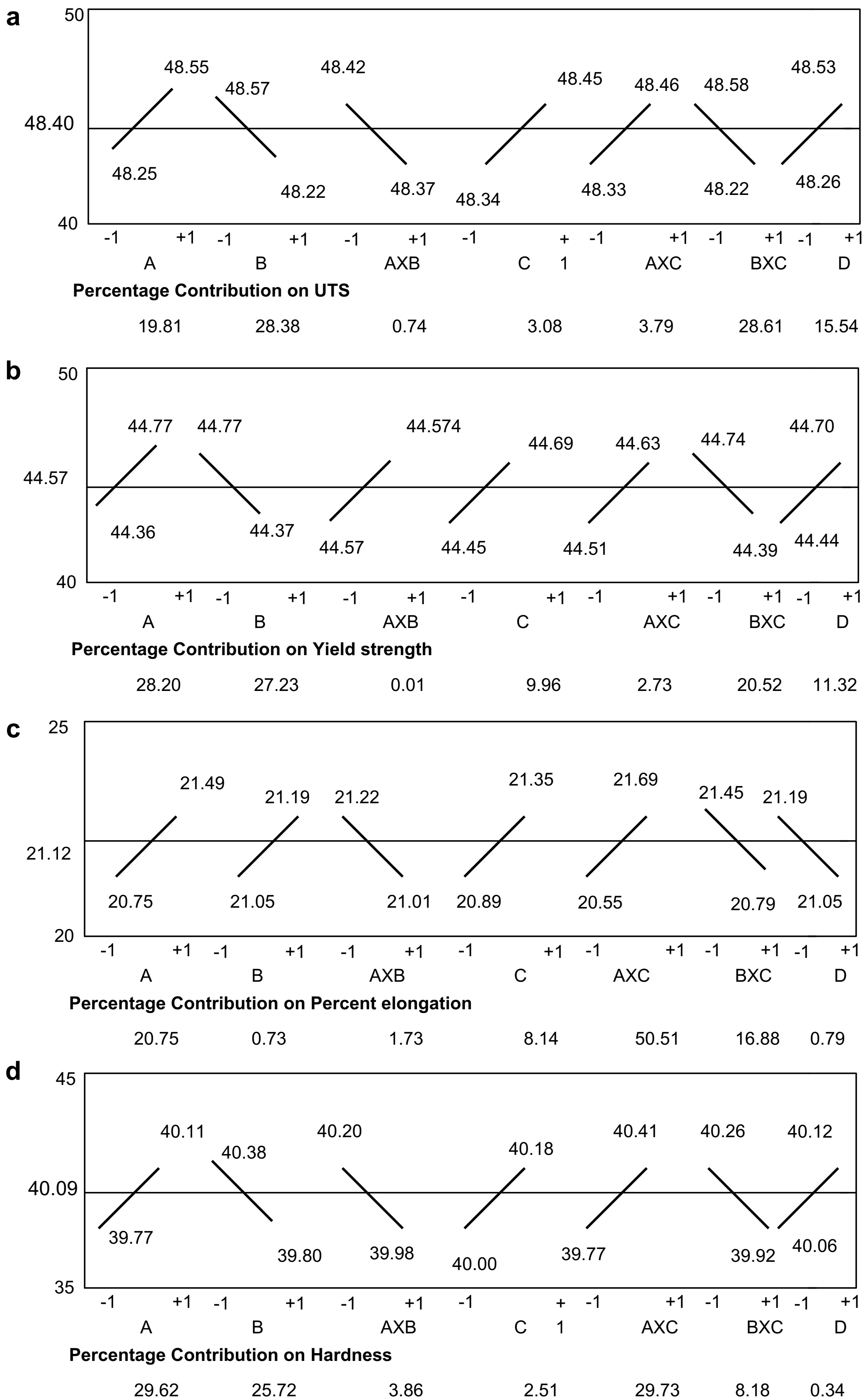

Fig. 6. Graphical representation of S/N ratio and percent contribution of parameters and their interactions: (a) ultimate tensile strength; (b) yield strength; (c) percent elongation; (d) hardness.

eters carried out for which Taguchi method is adopted. The same optimum condition was observed for all the quality characteristics. The percentage contribution for the process parameters and of their interactions on the quality characteristics are presented in graphical form (Fig. 6). From the Fig. 6a–d, it is evident that, percent contribution of pulse frequency is shown higher values in all

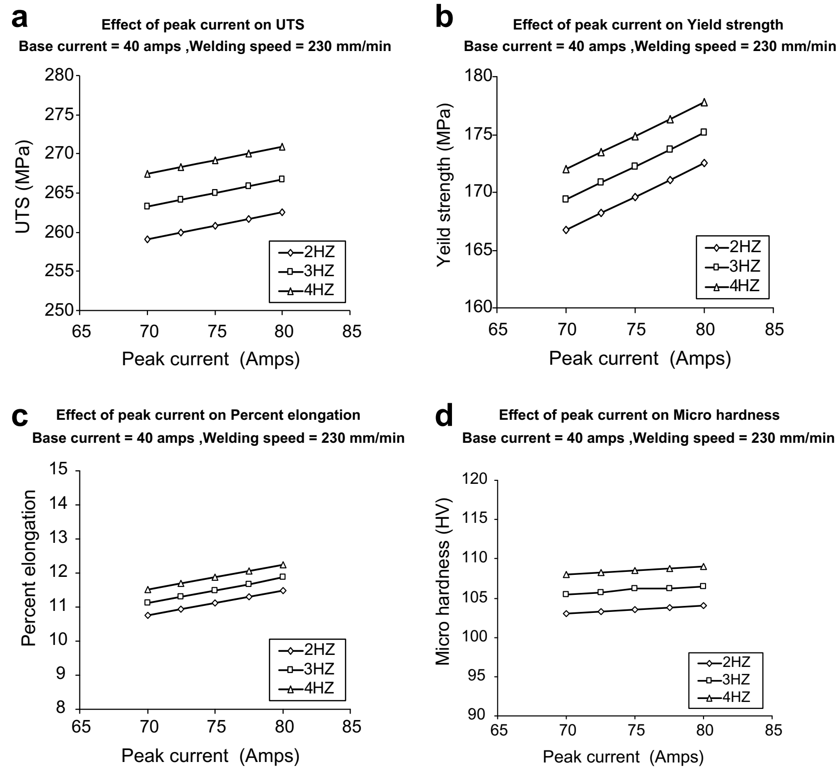

Fig. 7. Effect of peak current on the responses of pulsed TIG welds of AA 5456 Aluminum alloy: (a) UTS; (b) yield strength; (c) percent elongation; (d) microhardness.

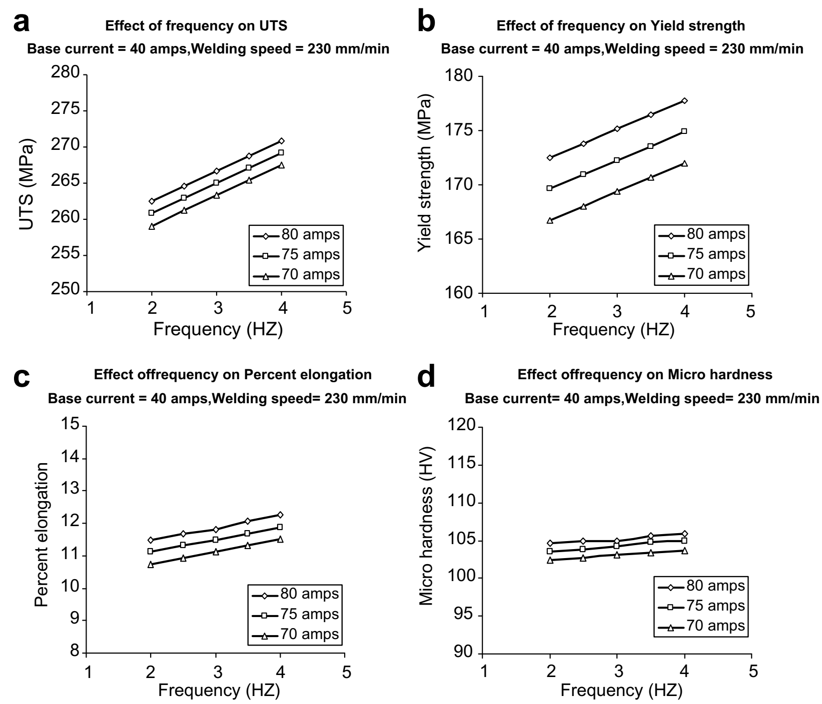

Fig. 8. Effect of frequency on the responses of pulsed TIG welds of AA 5456 Aluminum alloy: (a) UTS; (b) yield strength; (c) percent elongation; (d) microhardness.

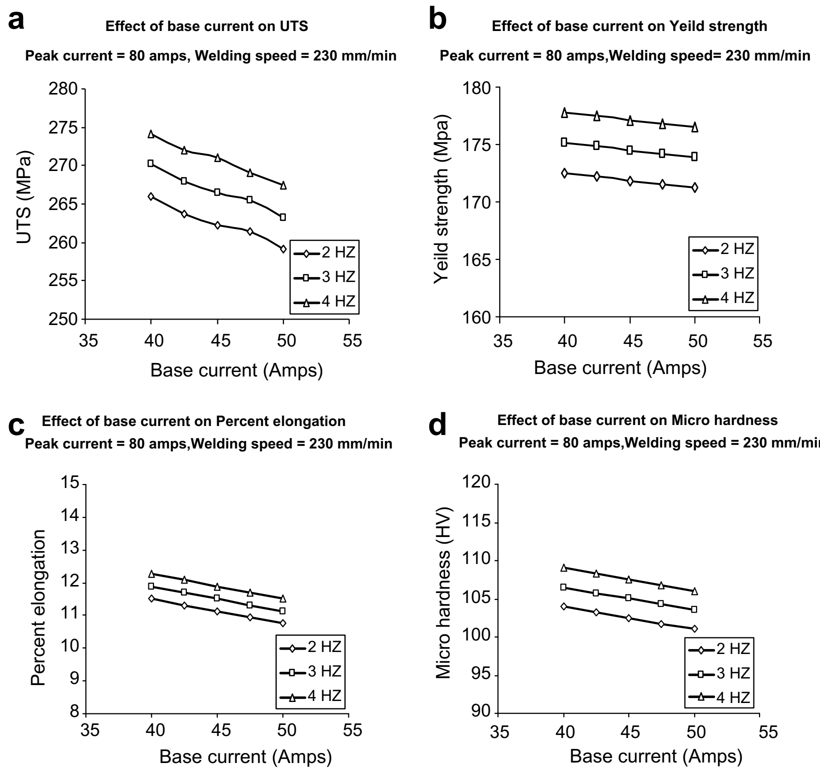

Fig. 9. Effect of base current on the responses of pulsed TIG welds of AA 5456 Aluminum alloy: (a) UTS; (b) yield strength; (c) percent elongation; (d) microhardness.

the properties. Hence, the effect of pulse frequency is more influence on the mechanical properties welds. And it is also observed that, frequency and interaction between welding current and welding speed were significant.

Mathematical models have been developed and written in MATLAB. The developed programs have been used to estimate the mechanical properties of AA 5456 Aluminum welds. Predicted values are plotted as graphs and presented in Figs. 7–9. The plotted graphs can be effectively used to understand the effect of peak current, base current, pulse frequency on mechanical properties of AA 5456 Aluminum alloy welds.

5. Conclusions

The influence of pulsed welding parameters such as peak current, base current, welding speed, and frequency on mechanical properties such as ultimate tensile strength (UTS), yield strength, percent elongation and hardness of AA 5456 Aluminum alloy weldments have been studied and the following conclusions are obtained.

The same optimum combination (i.e. $P_2B_1S_2F_2$) is observed in all the mechanical properties of welds. The behavior of the welded joints at the optimum condition (i.e. $P_2B_1S_2F_2$) of process parameters is attributed to increase an amount of Mg_2Al_3 precipitates that are formed in the aluminum matrix. In addition, the metallographic analysis reveals a fine grain structure at the weld centre, which results in higher mechanical properties.

It is observed that, there is 10–15% improvement in mechanical properties after planishing. This is due to fact that, internal stresses are relieved or redistributed in the weld.

Regression equations were developed to predict the quality characteristics, i.e. ultimate tensile strength, yield strength, percent elongation, and hardness within the selected range of parameters.

The practical benefit this study is that, with use of obtained optimum condition increases the mechanical properties and developed regression models are useful for the automation of the process.

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