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ORIGINAL ARTICLE

Effect of welding parameters on mechanical properties and optimization of pulsed TIG welding of Al-Mg-Si alloy

A. Kumar · S. Sundarrajan

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Abstract An attempt has been made to study the effect of pulsed TIG welding process parameters on dilution and mechanical properties such as notch tensile strength, hardness, and impact toughness in as-welded condition. Pulsed TIG welds exhibited lower notch tensile strength and impact toughness than the parent metal due to interdendritic network microstructure features. Taguchi method was used to optimize the pulsed TIG welding process parameters of heat-treatable (Al-Mg-Si) aluminum alloy weldments for maximizing the mechanical properties. An inverse relationship has been observed between the notch tensile strength and impact toughness.

Keywords Pulsed TIG welding · Aluminum alloy · Notch tensile strength · Hardness · Impact toughness · Microstructure · Taguchi method

1 Introduction

Al-Mg-Si 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. The TIG welding process [1] is generally used for welding of these alloys. The various techniques in the TIG welding process are pulsing and magnetic arc oscillation. By using the materials in solution, heat-treated and artificial ageing condition the complete weld, heat-affected zone, and parent metal can be aged in a single post weld heat treatment. However, difficulties have been reported in obtaining satisfactory properties in as-welded condition particularly strength and toughness due to low dilution of the base metal into the weld [2]. There are various methods such as inoculation with heterogeneous nucleants, surface nucleation, and dilution to improve the grain refinement in the weld zone. The use of inoculation for refining the fusion zone is successful in casting but not in welding [3]. Surface nucleation technique was also not much popular because of the complicated setups and procedures associated with its use.

The purpose of the present investigation is to improve the dilution of the base metal into the weld in pulsed TIG welding process by using the Taguchi method. Metallurgical advantages of pulsed current that are frequently reported in the literature include grain refinement in the fusion zone, reduced width of heat-affected zone (HAZ), less distortion, control of segregation, reduced hot cracking sensitivity, and reduced residual stresses [4, 5]. Grain refinement reduces hot cracking sensitivity in heat-treatable alloys by using pulsing and magnetic arc oscillation [6]. Dilution of the base metal into the fusion zone that provides sufficient amount of grain refinement is more effective than the filler metal containing refining elements [7, 8]. Hence dilution is more important in heat-treatable alloys because it reduces hot cracking sensitivity and improves mechanical properties.

2 Experimental procedure

The base material employed in this study is 3.14-mm-thick Al-Mg-Si aluminum alloy welded with 4043 filler material.

A. Kumar (✉)
Department of Mechanical Engineering,
National Institute of Technology,
Warangal 506 004, India
e-mail: adepu_kumar7@yahoo.co.in

S. Sundarrajan
Scientist 'G', Defence Research and Development Laboratory,
Hyderabad, India

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

	Mg	Si	Cu	Cr	Mn	Zn	Ti	Al
Al-Mg-Si alloy (base material)	0.85	0.68	0.22	0.06	0.32	0.07	0.05	Balance
4043 alloy (filler material)	0.05	4.8	0.17	0.05	0.24	0.05	0.05	Balance

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 [9].

A 350-W capacity AC welding machine (Make: Keppi) was employed for the welding experiments. The main process parameters in pulsed TIG welding are peak current, base current, pulse frequency, and welding speed, which are generally considered for controlling quality. In the present study, the effect of peak current, base current, and pulse frequency on dilution and mechanical properties have been studied. The other process parameters such as shielding gas flow rate and backup plate also influence the weld-quality characteristics and were optimized in the previous investigation [10]. Trial runs were conducted by varying one of the process parameters and keeping the others constant. The working range of peak current, base current, and pulse frequency were explored by inspecting bead appearance and the full penetration.

The range of the process parameters selected under the present study and the constant process parameters are shown in Tables 2 and 3, respectively. In the present investigation, the Taguchi method was employed to optimize the process parameters for maximizing the mechanical properties. The 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 is seven. Hence, L8(2^7) orthogonal array is selected. Each condition of the experiment was repeated twice to reduce the noise/error effects. The detail of the selected orthogonal array is presented in Table 4.

The quality characteristics, i.e.. notch tensile strength, hardness, impact toughness, and dilution of the base metal into the weld were evaluated for all the trials and then 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 verified.

The base metal sheets of dimension 250×150×3.14 mm have been prepared and butt joints were made using the experimental layout shown in Table 4. 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 a copper backing bar and the ends were clamped to maintain the alignment and gap. Purging is provided at the bottom of the sheets. The same argon gas has been used for shielding as well as purging. The weld joint is completed in a single pass.

Specimens for tensile testing (both plain and notched specimens) were taken at the middle of all the joints and machined to ASTM E8 standards [11]. The configuration of the specimens used for plain tensile test and notch tensile test are shown in Fig. 1a and b, respectively. Tensile test was conducted using a computer-controlled universal testing machine (make: Shimadzu, model: AUTOGRAPH) with a cross head speed of 0.5 mm/min. All the welded specimens failed in the base metal region and the properties related to the base metal are obtained but not the weld metal. Hence, notch tensile test is conducted to reveal the weld metal properties.

The specimen for impact test was made as per ASTM A370 standards (sub size) [11] and the test was conducted on a Charpy impact test machine. The configuration of the impact test specimen is shown in Fig. 1c.

Specimens for metallographic observation and micro-hardness tests (15-mm width) were taken at the middle of

Table 2 Working range of the process parameters

Symbol	Process parameter	Units	Lower level (1)	Higher level (2)
A	Peak current	Amps	180	200
B	Base current	Amps	60	72
C	Welding speed	mm/min	120	150
D	Pulse frequency	Hz	2	6

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	3.15
Electrode material	98% W + 2% Zr
Electrode diameter, mm	3.15
Pulse ratio, %	50
Pulse on time, %	50

Table 4 Experimental lay out L_8 (2^7) orthogonal array

Exp.no.	A	B	A x B	C	A x C	B x C	D
P1	1	1	1	1	1	1	1
P2	1	1	1	2	2	2	2
P3	1	2	2	1	1	2	2
P4	1	2	2	2	2	1	1
P5	2	1	2	1	2	1	2
P6	2	1	2	2	1	2	1
P7	2	2	1	1	2	2	1
P8	2	2	1	2	1	1	2

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. Micro-hardness tests were carried out on the welded samples with a load of 15 g and a duration of 15 s using a Vickers digital micro-hardness tester (make: Shimadzu, model: HMV-2000). The micro-hardness was measured at an interval of 0.15 mm across the weld, 0.5 mm across the heat-affected zone, and 1 mm across the unaffected base metal. The schematic sketch of the hardness survey is shown in Fig. 2.

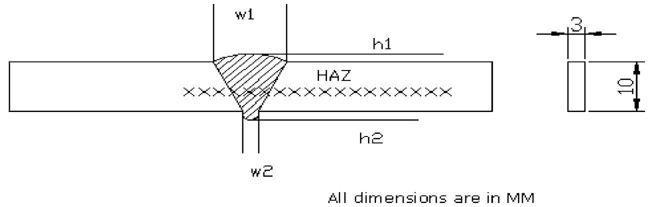

Fig. 2 Schematic sketch of hardness measurement in transverse to the weld

Weld metal dilution (i.e., volume fraction of the base metal into the weld bead) was evaluated in terms of area fraction (assumed to represent volume fraction) as follows [6, 8]

Weld metal dilution (%) $= \frac{Ab}{Aw} \times 100$

Ab = The cross section area of the base metal melted

Aw = Cross-sectional area of the weld bead including reinforcement.

Fig. 1 Configuration of **a** plain tensile test specimen, **b** notch tensile test specimen, and **c** Charpy V-notch impact test specimen

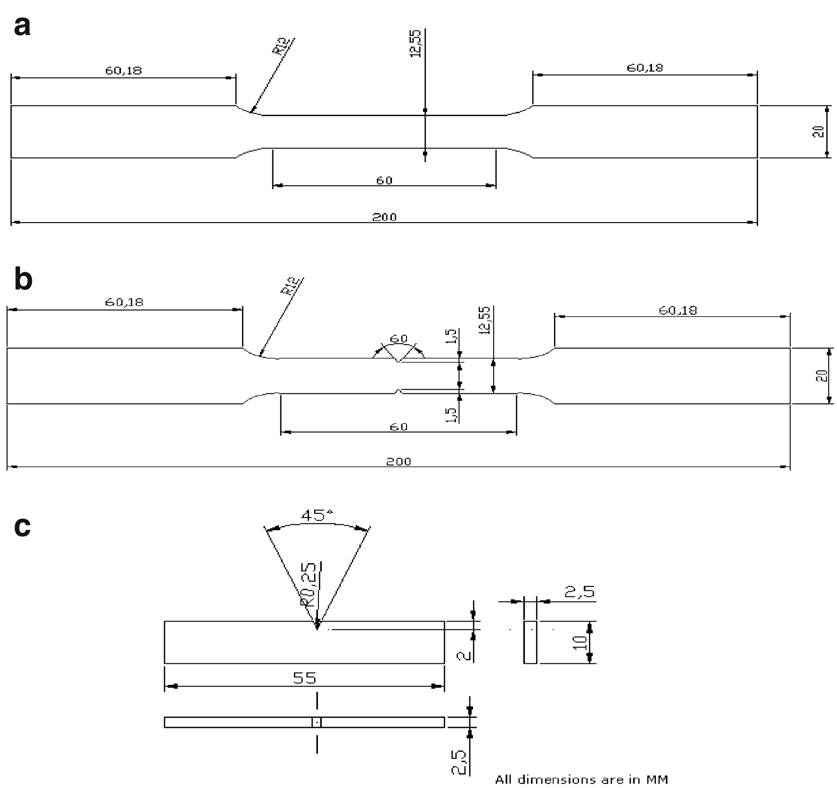

Table 5 Mechanical properties of Al-Mg-Si alloy welds

Specimen ID	Notch tensile strength (MPa)		Micro-hardness at the weld center (HV)		Impact toughness (J)		Dilution (%)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
P1	174	169	70	65	2.0	3.0	74.45	60.33
P2	185	180	81	90	2.5	2.0	75.35	74.25
P3	166	169	80	96	1.0	1.5	67.14	65.45
P4	173	170	84	80	4.0	3.0	70.26	69.54
P5	185	190	110	105	1.0	2.0	84.22	85.14
P6	180	180	89	95	2.0	2.0	72.43	73.52
P7	173	165	92	94	3.0	3.0	62.38	70.15
P8	183	180	86	82	4.0	4.0	68.20	70.35
Base metal	321	324	110	108	10	11	—	—

3 Results and discussions

3.1 Mechanical properties

Notch tensile strength, impact toughness, hardness, and dilution of pulsed TIG welds are presented in Table 5. The data on all the properties and dilution have been subjected to regression analysis. These developed regression equations are used to predicting the notch tensile strength, impact toughness, hardness, and dilution within the factorial space exploited. Regression equations showing the interaction effects of parameters on properties, and correlation coefficients for the observed properties are summarized in Table 6. High correlation coefficients indicate a good relationship between the parameters and the observed property data. Maximum notch tensile strength was observed when the pulse frequency and pulse current are on the higher side.

Micro-hardness survey in transverse to the weld direction of a typical weld (P5) revealed four different regions, such as weld center (WC), partially melted zone (PMZ), heat-affected zone (HAZ), and unaffected base metal are shown in Fig. 3. Hardness is highest in the partially melted zone (PMZ) because this zone has fine grains compared to the weld center. The hardness is lower in the HAZ portion because of deformed grains. Softening in the heat-affected zone (HAZ) of 6061-T6 aluminum alloy is due to dissolution of strengthening β'' (Mg_2Si) precipitates [12, 13]. The portion of the HAZ close to the weld is harder than the rest of the HAZ, but still softer than the base metal, which is due to fact that weldment was subjected to sufficient heat for a reasonable amount of solutionizing and fast enough cooling rate to be quenched and produce a somewhat super-saturated solid solution. Very fine precipitates (i.e., Mg_2Si) could have formed during cooling or

Table 6 Regression equations for the mechanical properties

S. no.	Response	Regression equation	Coefficient of correlation
1	Notch tensile strength	$Y=176.38+3.13x_1–4.00x_2+2.50$ $+3.38x_4–0.25x_1x_2–1.25x_1x_3+1.63x_2x_3$	$x_3$0.90
2	Hardness	$Y=87.44+6069x_1–0.69x_2–1.56\ x_3$ $+3.81x_4–4.94x_1x_2–4.56x_1x_3–2.19x_2x_3$	0.89
3	Impact toughness	$Y=2.50+0.13x_1 + 0.44x_2 + 0.44\ x_3$ $-0.25x_4 + 0.44x_1x_2–0.06x_1x_3 + 0.38x_2x_3$	0.88
4	Dilution	$Y=71.45+1.85x_1–3.51x_2+0.29x_3+2.31\ x_4$ $-2.01x_1x_2–2.46x_1x_3 + 1.36x_2x_3$	0.80

where, x_1 = Peak current, x_2 = Base current, x_3 = Welding speed, and x_4 = Pulse frequency

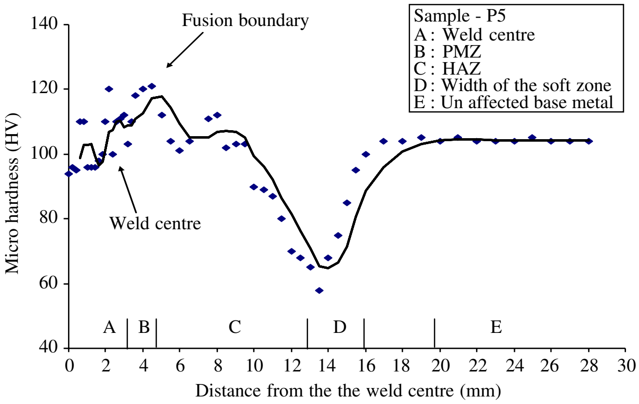

Fig. 3 Micro-hardness survey in transverse to the weld direction of Al-Mg-Si weld

during natural ageing, resulting in a local hardness peak in close to the fusion boundary [7]. Width of the soft zone is calculated based on the hardness of less than 60% of the base metal hardness and observed that width of the soft zone is minimum (i.e., 3 mm).

3.2 Optimization of process parameters

The optimization of process parameters using the Taguchi method [10, 14–16] permits evaluation of the effects of individual parameters independent of other parameters, and also of their interactions on the identified quality characteristics, i.e., notch tensile strength (NTS), hardness, impact toughness, and dilution. The optimum results are presented in Table 7. 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 8. It is observed that experimental values are closer to the optimum values.

Results of ANOVA indicate that pulse frequency, base current, and peak current are significant 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 in Fig. 4. From Fig. 4a to c, it is observed that percent contribution of base current followed by pulse frequency has more of an influence on dilution and mechanical properties. The same optimum combination is observed in NTS and dilution, hence, the dilution of the base metal into the weld is the key factor to refining the grain structure.

3.3 Microstructures

The effect of pulsed TIG welding process parameters on weld metal properties has been studied. This is a heat-treatable aluminum alloy, hence, degradation of mechanical properties in the HAZ portion during welding can be improved after post-weld heat treatment, hence the observations of microstructures at the weld center are considered for comparison in different welding conditions. The microstructures at the central region of pulsed TIG welds using the experimental layout are shown in Fig. 5. It is observed that microstructures consists of dendrites and assume the dendrite arm spacing equal to the grain size. From these figures, it is evident that the samples welded by using the condition, i.e., P5 (peak current of 200 A, base current of 60 A, welding speed of 150 mm/min, and pulse frequency of 6 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_2Si eutectic (dark) precipitates near the dendrite boundaries. The phase volume fraction of Mg_2Si eutectic was estimated according to ASTM E 562 [11] using image analyzer software and was found to be more in the weld condition P5 (i.e., 28.27%). 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 6 Hz. Similar trends have been observed in the literature [17].

The micro-structure observation of the condition set, i.e., P4 (peak current of 180 A, base current of 72 A, welding speed of 150 mm/min, and pulse frequency of 2 Hz) resulted

Table 7 Optimum values of the quality characteristics

Quality characteristics	Optimum condition	Optimum value
NTS (MPa)	$A_2B_1C_2D_2$	195
Hardness (HV)	$A_2B_1C_2D_2$	110
Impact toughness (J)	$A_1B_2C_2D_1$	2.5
Dilution (%)	$A_2B_1C_2D_2$	80.25

Table 8 Validation of the optimum results

Quality characteristics	Optimum condition	Optimum value	*Experimental value
NTS (MPa)	$A_2B_1C_2D_2$	195	192.56
Hardness (HV)	$A_2B_1C_2D_2$	110	108.25
Impact toughness (J)	$A_1B_2C_2D_1$	2.5	3.25
Dilution (%)	$A_2B_1C_2D_2$	80.25	78.56

* Average of three values

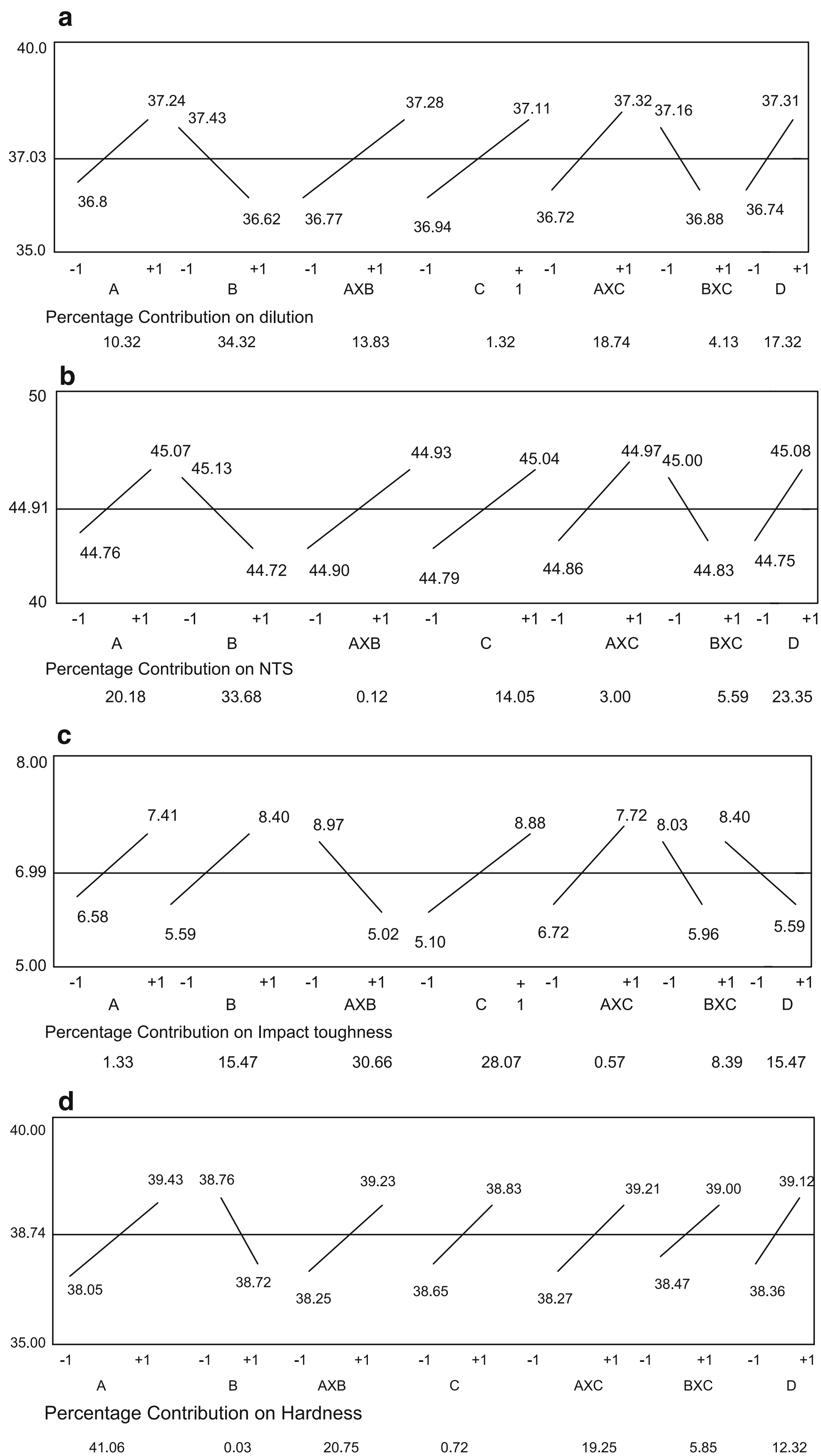

Fig. 4 Graphical representation of S/N ratio and percent contribution of parameters and their interactions. **a** Dilution, **b** NTS, **c** Impact toughness, and **d** micro-hardness

in a coarse grain structure. The phase volume fraction of Mg_2Si eutectic was estimated and found to be less in the condition P4 (i.e., 10.28%). 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, and pulse frequency resulted in a fine equiaxed grain structure.

4 Conclusions

The same optimum combination (i.e., $A_2B_1C_2D_2$) is observed in notch tensile strength (NTS) and dilution. The behavior of the welded joints at the optimum condition (i.e., $A_2B_1C_2D_2$) of process parameters is attributed to the higher dilution of the base metal into the weld, resulting in an increased amount of Mg_2Si precipitates that are formed in the

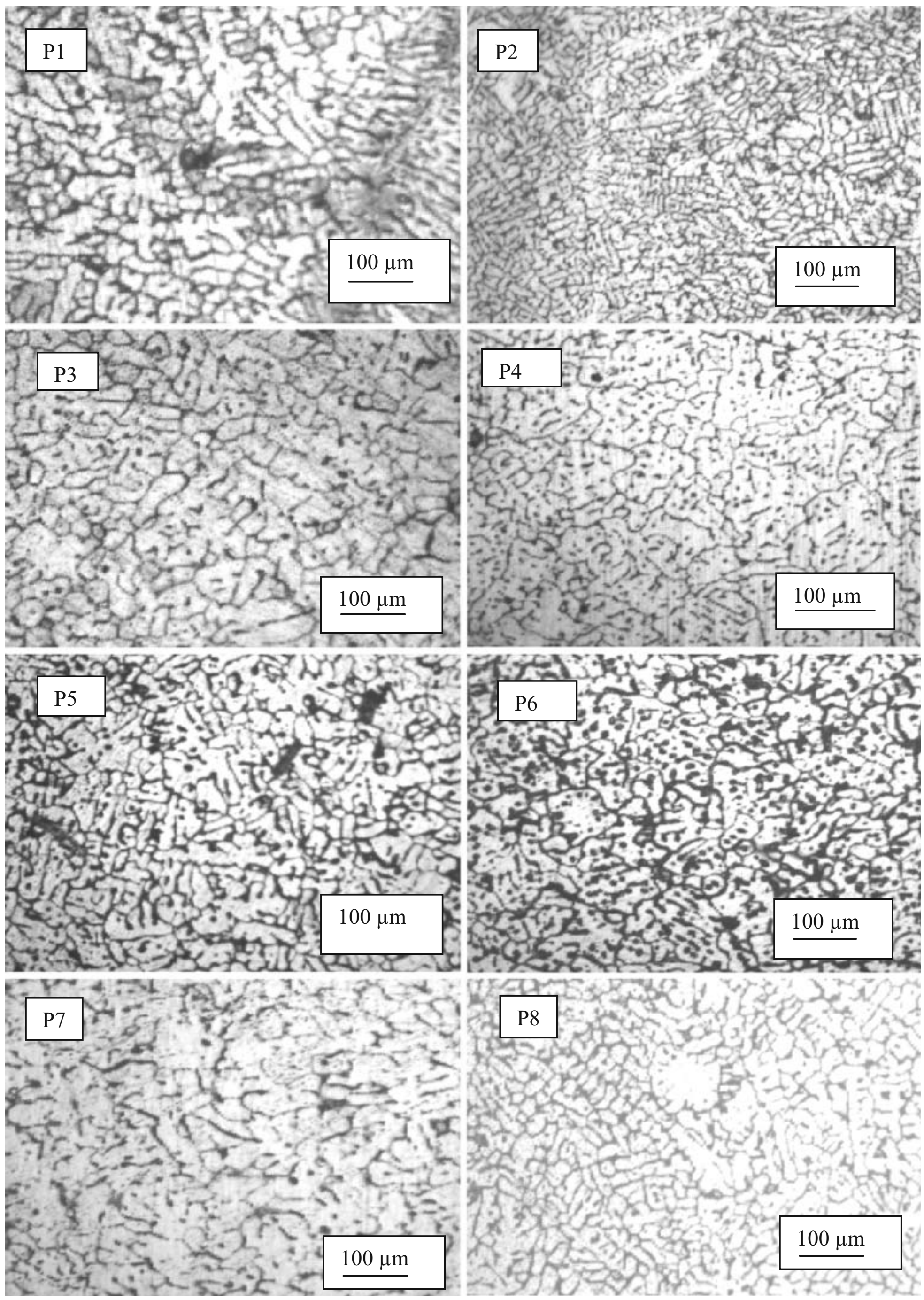

Fig. 5 Micro-structures at the weld center of pulsed TIG welds

aluminum matrix. In addition, the metallographic analysis reveals a fine grain structure at the weld center, which results in higher mechanical properties. However, the different optimum combination (i.e., $A_1B_2C_2D_1$) observed for the impact toughness is due to a coarse grain structure.

The width of the soft zone (i.e., portion D in Fig. 3, which is less than 60% of the base material hardness) is low in the parameter combination P5. This is due to fact that different thermal cycle during welding, cooling rate, dissolution, and/or growth of precipitates and formation of stable phases. Regression equations were developed to predict the quality characteristics within the selected range of parameters.

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