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# Weld Strength and Cracking Susceptibility Analysis of Pulsed TIG Welded Al-Mg-Si Alloy by Experimental Approach

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ABSTRACT

*Aluminium is a non ferrous corrosive resistance metal mainly used in automotive coolers, inter coolers and radiators. They are the part of automobile vehicles and made from aluminium alloys. The joints in this application are created by fusion welding process specifically Tungsten Inert Gas (TIG) and Pulsed current TIG (PCTIG) welding process. The working temperature range of different coolers, radiators are 20° C to 300° C and pressure ranges from 2.5 bar to 3.5 bar. During actual working of coolers, the weld joint experiences sudden high level and low level temperature changes. These will create high thermal stresses in the joints. It leads to cracking in the weld region and create failure of the weld joints. Various factors such as mechanical, metallurgical and thermal are responsible for cracking in the weld joints. Range of solidification temperature is one of metallurgical factor, stress generation is mechanical factor and cooling rate of weld metal is thermal factor for cracking. Houldcroft weldability test is employed to identify the cracking susceptibility (CS) of the weld. The current investigation is intended to discover the effect of pulse TIG welding process parameters on the mechanical properties and cracking susceptibility of precipitated aluminium Al-Mg-Si alloy. Diverse pulsed TIG welding process parameters such as peak current (Ip), base current (Ib) and frequency (f) were investigated with the objective of identify the tensile strength, yield strength and cracking susceptibility. The corresponding findings of optimum parameters are 180 peak current (Ip), 60 A base current (Ib) and at 6 Hz frequency (f) with tensile strength of 185.55 MP, yield strength 156.62 MPa. The significant of each parameter for tensile strength are Ip, Ib, Ip*Ib, Ip*f and Ib*f. The corresponding contributions in % are 14.56, 49.49, 12.26, 5.44, 12.15, 5.04, and 1.05 respectively. The statistical method such as Taguchi was employed for experiment design. Weldability test (Fishbone test) was performed on standard specimen and the cracking susceptibility index was identified. The cracking susceptibility index 5.26 % were observed with the value of 180 A of Ip, 80 A of Ib & 2 Hz of frequency (f).The results give an idea about the effect of pulsed TIG welding parameters on mechanical properties and cracking susceptibility.*

*Keywords: PCTIG welding; Houldcroft weldability test; cracking susceptibility; tensile strength; yield Strength*

## INTRODUCTION

One of richest element in the shell of earth available is aluminium having 8 % wt. which is second after ferrous alloy like steel between inexpensively significant metal. Some other non ferrous elements like copper, tin, lead were used from many years. In 1808, Sir Humphrey Davy (Britain) has identified metal called Aluminium (Coniglio 2008)(Mathers 2002; Lumley 2011). Aluminium is high corrosive resistant metal. Some alloying elements are added like silicon, copper, zinc, Magnesium, Manganese to improve its properties. Aluminium (Al) is low density metal utilized in many industries such as automobile, transportation, aerospace, civil constructions, packaging, storage, bridges etc. (Lakshminarayanan, Balasubramanian and Elangovan 2009) (Abdul Latif, Sajuri and Syarif, 2014). Aluminium & Aluminium alloys have wide use because of many technological developments in it that provides quality product & high productivity. (Rambabu, Prasad and Kutumbarao, 2017)The total consumption of Aluminium alloys by various industries are tabulated Table 1(The Office of Industrial Economics 2017). Designers and engineers confront hurdles when it comes to welding aluminium alloy. Oxide layer formations, high thermal conductivity, and high coefficients of thermal expansion and solidification shrinkages are a few of them.

The working of coolers' welds joint experiences sudden high level and low level temperature changes. These will create high thermal stresses in the joints. Because of fact that in intercoolers or radiator the coolants are continuously flowing in the coolers or radiators, the function of the coolant is to absorb heat from the source and release heat in the cooler, so coolants are continuously heated and cooled down. Heated and cooled coolants are in physical contact with the joint.so they experience the high and low level temperature. It leads to cracking in the weld region and create failure of the weld joints (Kikani and Thakkar 2017). Aluminium is a tricky material to work with since it has a proclivity to remain colorless at high temperatures. Researchers and specialist fabrication sectors are emphasizing on testing data to get the optimum process parameters for analysis. Currently center of attention of many researchers and industries are on sustainable manufacturing process. Sustainability covers three aspects which are economical, environmental & social. For economical point of view, one should go for simulation of manufacturing process. At present, many scholars and companies are focusing their attention on the sustainable manufacturing process. Sustainability encompasses three aspects: economic, environmental, and social. From an economic standpoint, modeling of the production process is preferable. Welding simulation allows you to execute multiple virtual experiments to evaluate different weld factors and save costly trials of actual welding experiments. It also gives various material behaviors throughout the welding process (Anca et al. 2011; Nateghi and Volukola, 2016; Su et al. 2017).

TABLE 1. Use of Aluminium in different markets

| Major Market | 2016 (millions of pound) | % of total |
|---|---|---|
| Building & construction | 3234 | 12.2 |
| Transportation | 9311 | 35.2 |
| Consumer durables | 1750 | 6.6 |
| Electrical | 1843 | 7.0 |
| Machinery & equipment | 1728 | 6.5 |
| Containers & packaging | 4758 | 18.0 |
| Other | 687 | 2.6 |
| Domestic total | 23311 | 88.2 |
| Exports | 3117 | 11.8 |
| Total shipment | 26428 | 100 |

The weldability of aluminium alloys is influenced by the service circumstances, the welding technique employed, and the surroundings in which the welding process is carried out. When welded with a typical arc welding technique, aluminium alloys have very poor weldability. Welding of aluminium alloys experienced several glitches in the form of fractures.

During welding, there are two sorts of cracks that might form. There is both hot and cold cracking. (JOHN C. LIPPOLD, 2015) Hot cracking is also referred as solidification cracking, whilst cold cracking is referred as liquation cracking. Solidification cracking can occur in the fusion zone, whereas liquation cracking occurs in the partially melted zone (PMZ) of heat-affected zone (HAZ). Hot cracking is typically caused by a combination of metallurgical and mechanical factors.

A metallurgical factor is an incorrect filler or base alloy composition, whereas a mechanical factor involves stresses. Many weldability tests are employed to determine cracking susceptibility. Such tests are the Varestraint Test, Transvarestraint Test, Cast Pin Tear Test, Hot Ductility Test, Strain-To-Fracture Test, Reheat Cracking Test, and Houldcroft (Fishbone) Test (Lippold 2015). The current study focuses on the comparison of experimental and simulation weld results for aluminium alloys and evaluate the cracking susceptibility value of aluminium alloy performing weldability test.

## DESIGNATION OF ALUMINIUM ALLOYS

The primary categorization of aluminium alloys is heat treated and non-heat treated. To accomplish the ideal mechanical properties, many alloying elements are combined with aluminium. Different aluminium alloy designations are depending on the alloying element that has been added to it (Mathers 2002). Table 2 illustrates the categorization of it. The Al-Mg- Si alloys come under AA 6XXX series.

TABLE 2. Classification of alloy series

| Sr No | Alloy Series | Principle Alloying Element |
|---|---|---|
| 1 | 1XXX | 99.0% min. Aluminium (Al) |
| 2 | 2 XXX | Copper (Cu) |
| 3 | 3 XXX | Manganese (Mn) |
| 4 | 4 XXX | Silicon (Si) |
| 5 | 5 XXX | Magnesium (Mg) |
| 6 | 6 XXX | Magnesium (Mg) & Silicon (Si) |
| 7 | 7 XXX | Zinc (Zn) |
| 8 | 8 XXX | Other alloying element |

## EXPERIMENTAL WORK

For performing excellent welding of aluminium alloys, many fusion welding techniques such as shielded metal arc welding (SMAW), tungsten inert gas welding (TIG), metal inert gas welding (MIG), and many are used. In the present study, Al-Mg-Si alloy was welded employing pulsed TIG (PCTIG) (Singh, Dey and Rai, 2017) on 3.2 mm thickness using ER 4043 as a filler material without any edge preparation. The modified version of conventional TIG welding is pulsed TIG (PCTIG) welding process.

It requires the cycling of the welding current at a selected standard frequency from a high value to a low value. In order to acquire adequate penetration, bead contour usually the peak current and while to maintain steady arc, base current sufficient values are chosen (Singh, Dey and Rai 2007; Stevens 2007; U and Wu, 2002; T.Senthil Kumar, 2005; Giridharan and Murugan, 2009; Lakshminarayanan, Balasubramanian et al. 2009; Karunakaran and Balasubramanian 2011). The PCTIG welding process has been used, with the essential process parameters: pulsed current or peak current (Ip), base current or background current (Ib), and frequency (f). Alternate Current was the mode of current employed in the experiment (AC). The welding was performed with Fronius PCTIG welding equipment.

TABLE 3. Chemistry of Al-Mg-Si T6 alloy

| Content | Si | Cu | Mg | Zn | Fe | Ti | Mn | Cr | Al |
|---|---|---|---|---|---|---|---|---|---|
| % element | 0.66 | 0.22 | 1.03 | 0.013 | 0.26 | 0.011 | 0.107 | 0.126 | 97.47 |
| Set value | 0.40-0.80 | 0.15-0.40 | 0.80-1.30 | 0.25 max | 0.70 max | 0.15 max | 0.15 max | 0.04-0.35 | Rem. |

The different consumables such as filler material was chosen as per the standard i.e. ER 4043. The chemistry for the same was taken by performing the spectroscopy using spectrometer results. The chemistry of weld material and filler material is collected from performing the spectroscopy test by optical emission spectrometer and is illustrated in Table 3 & Table 4. It is matched with the chemical composition given in American welding society (AWS) handbook (O'Brien and Carlos Guzman, 1997). The chemical composition for the same are specified in Table 3 (Davis 1993).

TABLE 4. Chemical Composition of ER 4043

| Content | Al | Si | Fe | Cu | Ti | Zn | Mn | Mg |
|---|---|---|---|---|---|---|---|---|
| Alloy 4043 | Bal. | 4.5-6.0 | 0.60 max | 0.30 max | 0.15 max | 0.10 max | 0.15 max | 0.20 max |

The parameters and its range were identified and selected based on the pilot experimental work, industries data and standard literature. The selection of correct consumables for PCTIG welding, such as shielding gas, gas flow rate, filler metal, type of tungsten electrode, welding speed, etc. are based on the AWS handbook and ASME sec. IX standards and is provided in Table 5.

Process Qualification record (PQR) and welding procedure specification (WPS) were prepared in accordance with ASME Sec. IX standard (ASM International Handbook Committee, 2001).The plates of aluminium alloy AA 6061 T6 were cut to a precise size of 200×100×3.2 mm. For the experiments, ER 4043 filler material with a 2.4 mm diameter and a 0.8 percent zirconium coated tungsten electrode were used. Cleaned components were welded manually by PCTIG welding process with different factors such as Peak current (Ip), base current or background current (Ib) and frequency (f). Alternating current was taken in welding process. The PC TIG welding was performed in standard operating conditions with qualified welder using Fronius made welding machine. Experimental values which are kept constant during experimentation are tabulated in table 5.

TABLE 5. Experimental constant Parameters' value

| Sr No | Parameter | value |
|---|---|---|
| 1 | voltage | 15-18 volts |
| 2 | Tungsten electrode & size | 98 % W, 0.8 % Zr, 3.2 mm dia. |
| 3 | Shielding Gas | Argon |
| 4 | Shielding gas flow rate | 5 lit./min. |
| 5 | Filler metal | ER 4043 |
| 6 | Welding position | 1G |
| 7 | Welding speed | 4-6 mm / sec. |
| 8 | Nozzlediameter | 9 mm ceramic cap |
| 9 | Cleaning cycle | 40 % |
| 10 | Welding cycle | 60% |
| 11 | Current wave | Square |

After welding the specimen were prepared in standard size for tensile test and yield test. It was cut and machined as per the standard size according to ASTM E8M-04.The experimental test results were examined and summarized in Table 6.

TABLE 6. Experimental Test Results

| Ex. No | Peak current (Ip) | Base current (Ib) | Frequency (f) | Tensile Strength (Mpa) | Yield Strength (Mpa) |
|---|---|---|---|---|---|
| 1 | 120 | 60 | 2 | 140.66 | 116.74 |
| 2 | 120 | 80 | 4 | 123.36 | 97.1 |
| 3 | 120 | 100 | 6 | 123.54 | 97.54 |
| 4 | 150 | 60 | 4 | 137.50 | 113.6 |
| 5 | 150 | 80 | 6 | 132.68 | 109.6 |
| 6 | 150 | 100 | 2 | 119.03 | 96.83 |
| 7 | 180 | 60 | 6 | 185.55 | 156.62 |
| 8 | 180 | 80 | 2 | 133.24 | 95.96 |
| 9 | 180 | 100 | 4 | 123 | 113.01 |

There are several analytic approaches available to optimize the welding process parameters. Regression analysis was used to evaluate the results. Regression analysis is used to determine the relationship between a single response variable and a variety of predictor variables. The regression equations were developed and are used to estimate the value of tensile strength within the factorial space that was utilized. The regression equation illustrates the interaction effects of Ip, Ib, and f on mechanical characteristics.

$$\textit{Tensile strength} = -35.6 + 1.957\,Ip + 3.982\,Ib - 79.0\,f - 0.03630\,Ip*Ib + 0.3599\,Ip*f + 0.2960\,Ib*f \quad (1)$$

Statistical approaches are used to maximize experimental outcomes. Several strategies are used to examine and optimize the data. In this experiment, the Taguchi technique was used. "ANNOVA is a statistical methodology that is used to examine each process parameter in order to establish a level of confidence." (Ibrahim *et al.* 2011). ANNOVA was used to determine the contribution of each parameter to tensile strength and yield strength. Table 7 demonstrates studies where the most important process parameters or combinations of parameters for tensile strength are Ip, Ib, Ip*Ib, Ip*f, and Ib*f. 14.56, 49.49, 12.26, 5.44, 12.15, 5.04, and 1.05 are the equivalent contributions. The p values for corresponding parameters are also mentioned. It shows each parameter is significant.

TABLE 7. ANNOVA results for Tensile strength

| Source | DF | Sum of square | Contribution (%) | Adj SS | Adj MS | F-value | P-Value |
|---|---|---|---|---|---|---|---|
| Regression | 6 | 3209.18 | 98.95 | 3209.18 | 534.86 | 31.32 | 0.031 |
| Ip | 1 | 472.24 | 14.56 | 362.02 | 362.02 | 21.20 | 0.044 |
| Ib | 1 | 1605.24 | 49.49 | 408.59 | 408.59 | 23.92 | 0.039 |
| f | 1 | 397.56 | 12.26 | 393.34 | 393.34 | 23.03 | 0.041 |
| Ip*Ib | 1 | 176.57 | 5.44 | 553.28 | 553.28 | 32.40 | 0.030 |
| Ip*f | 1 | 393.98 | 12.15 | 543.89 | 543.89 | 31.85 | 0.030 |
| Ib*f | 1 | 163.59 | 5.04 | 163.59 | 163.59 | 9.58 | 0.090 |
| Error | 2 | 34.16 | 1.05 | 34.16 | 17.08 | | |
| Total | 8 | 3243.34 | 100 | | | | |

According to AWS the weldability is defined as "The capacity of a material to be welded under fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service." Different test are used to evaluate the weldability of weld joint. Cracking susceptibility index gives an idea about the weldability of the joints. Typically different weldability tests are practically performed and houldcroft weldability test for checking the cracking susceptibility was chosen (Lippold 2015).

## HOULDCROFT WELDABILITY TEST

The houldcroft weldability test is a specific test in which special test specimens resembling fishbone must be arranged. Such a test should be suitable for determining the solidification cracking of a welding component. Figure 1 depicts this. Several slots of varying widths were cut into the specimen on both sides of the work piece. The rigidity of the weld joint is decreased by the slots having higher length of slot. The lower length of slots is provided at the starting of the bead on plate weld and progressively decreases the length of the slots. Lower weld rigidity would be observed with higher slot length and vice versa. By diminishing the slot span diminish the stiffness of the tests that will cease to end of cracks at a few points. Crack length is deliberated and helpful for recognizing cracking susceptibility of weld sample.

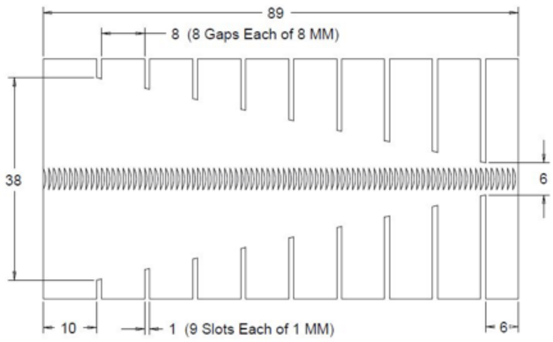


FIGURE 1. Standard Houldcroft Weldability test specimen for cracking susceptibility

Different essential , supplementary essential PCTIG welding parameters such as peak current (Ip), base current (Ib) and frequency (f) are taken as input parameters (Lakshminarayanan, Balasubramanian and Elangovan 2009; T.Senthil Kumar 2005) and the effect of these parameters on cracking susceptibility were investigated.

Statistical tool MINITAB software was used to prepare design of experiment and for the analysis purpose. The cracking susceptibility index were evaluated by mention equation (Lippold 2015).

$$\textbf{Cracking Susceptibility} = \frac{\textbf{LC}}{\textbf{Lt}} \times \textbf{100} \quad (2)$$

CS= Cracking susceptibility
Lc= Length of crack
Lt=Total length of weld

The Figure 2 shows the dye Penetrant testing of welded component for cracking susceptibility.

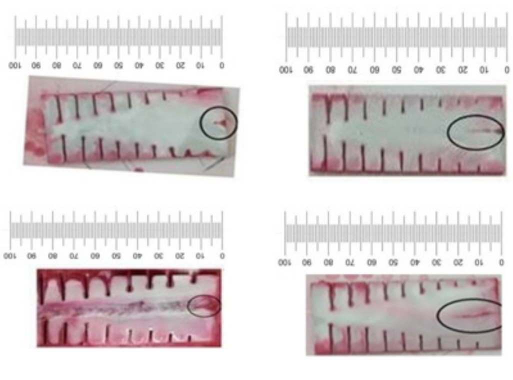

FIGURE 2. Dye penetrant testing of weld samples

## RESULT & DISCUSSION

The Dye Penetrant method was applied for inspect the surface cracks for welded specimen. By using steel rule total length of cracks on bead on plate weld was measured. Table 8 illustrates the subsequent cracking susceptibility values.

TABLE 8. Cracking Susceptibility

| Ex. No | Ip A | Ib A | f Hz | Cracking Susceptibility (%) |
|---|---|---|---|---|
| 1 | 120 | 60 | 2 | 5.26 |
| 2 | 120 | 80 | 4 | 13.16 |
| 3 | 120 | 100 | 6 | 7.89 |
| 4 | 150 | 60 | 4 | 9.21 |
| 5 | 150 | 80 | 6 | 10.53 |
| 6 | 150 | 100 | 2 | 39.47 |
| 7 | 180 | 60 | 6 | 26.32 |
| 8 | 180 | 80 | 2 | 5.26 |
| 9 | 180 | 100 | 4 | 28.95 |

## CONCLUSIONS

The current investigation has been carried out to assess the influences of pulsed current parameters and optimize the parameters to attain optimum mechanical properties and cracking susceptibility of Pulsed TIG welded Al-Mg-Si aluminium alloy. From this investigation, following conclusions have been obtained:

1. Design of experiment concept is more economical method for predicting the outcome of pulsed TIG parameters on tensile properties. The pulsed TIG welding process succefully performed on Al-Mg-Si aluminium alloy. The predominant parameters like Ip, Ib and f are optimized to accomplish maximum tensile and yield strength. Though the soundness of the process is restricted to the investigated considered parameters.
2. The suitable pulsed TIG process parameters for current experimentation is at 180 A peak current (Ip), 60 A base current (Ib) and at 6 Hz frequency (f). The corresponding values for tensile strength and yield strength are 185.55 MPa &156.62 MPa respectively. Higher the peak current the amount of heat generated is more and weldment trying to convert into equiaxed dendrite. Analysis also proves the significant of each parameters for tensile strength are Ip, Ib, Ip*Ib, Ip*f and Ib*f. The corresponding contributions in % are 14.56, 49.49, 12.26, 5.44, 12.15, 5.04, and 1.05 respectively.
3. From the experimental investigation the result shows that the cracking susceptibility (CS) index for different value of Ip, Ib and f. The higher value of CS i.e. 28.95 % was observed in case of 180 A Ip, 100 A of Ib and 4 Hz f.The lowest value of Cracking Susceptibility i.e.

5.26 % were observed with the value of 180 A of Ip, 80 A of Ib & 2 Hz of frequency (f).the higher the Peak current (Ip) i.e. 180 A will lead to high heat generation. High heat will slow down the cooling rate throughout solidification. Weldment has longer time available for grain coarsening. So the cracking susceptibility index is higher with higher value of Peak current (Ip).aluminium alloy having high possibility of generate cracks because is also depend upon the alloying elements available in filler metal.

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## DECLARATION OF COMPETING INTEREST

None

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