SMAW: The Effects of Currents and Welding Rod Diameters on Welded Joint Ultimate Tensile Strength Using the Full Factorial DOE

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Abstract. This research was significant as it extensively studies the effects of current and rod diameter on SMAW welded joint. The Mild Steel (AISI 1018) was used as the base material to be welded using the E-6013 welding rod. The experiment was constructed according to the full factorial design of experiment (DOE). This project found that the current and rod diameter are the significant factors in affecting the ultimate tensile strength (UTS). New contribution from this research was that the rod diameter is more significant than the current in affecting the UTS of a welded joint. In addition, this research also contributed new finding by showing that the interaction between current and rod diameter as significant in affecting the UTS. This interaction was also found to be more significant that current but less significant than rod diameter in affecting the UTS of welded joint. In addition, this research showed that the tensile strength increases when the current is increased from 80A to 100A. However, the tensile strength decreased as the current is set between 110A to 130A. At the same time, the welding rod diameter of 2.5mm produced the highest tensile strength compared to 3.2mm and 4.0mm rod diameter. This research also optimised the experiment and found that the highest tensile strength obtained is 342.39 MPa, which is produced using 80A of welding current with 2.5mm rod diameter.

1. Introduction
Welding process is the joining technique predominantly used in the production of metallic structures applied in various areas such as railway construction and shipbuilding. Welding technologies are substantial in the Oil and Gas Industries. For example, the underwater parts such as tubes and vessels are typically prone to the welding faults and gaps. These faults and gaps are responsible for the nucleation and spread of cracks that might damage their function [1]. The Shielded Metal Arc Welding (SMAW) is an arc welding that used electrode. This process is known as the oldest, most versatile and simplest joining process that uses coated electrode to complete the process. The electrode with thin and long round shape is held manually by the welder. The electric arc is generated by touching and quickly withdrawing the tip of the coated electrode against the workpiece. The distance between the coated electrode and the workpiece need to be sufficient enough to maintain the arc [2].

Current researches in SMAW single pass welding are such as by Nassar et al. [3]. They performed an experimental study on the effect of electrode types on tensile properties of low carbon steel. In this study, the different welding electrodes; E6013 and E7018, acts as the welding parameter. The carbon
steel plates were joined by using electrode type E6013 and E7018 with 3.25mm diameter. The welded specimens were tested for tensile strength. The outcomes showed that, the mechanical properties; such as the UTS, yield strength and elongation percentage of the welded specimens, were remarkably influenced by different welding electrodes. They concluded that the fracture toughness of welded specimen in E6013 join was found to be better compared to the welded specimen in E7018 join and the specimens that welded using the E6013 electrode displays better UTS [3].

Mattoo et al. [4] investigated the effect of different filler rods on welded mild steel using SMAW. The experiment was carried out by using three different types of electrode, which are Austenitic stainless steel (308L), Ferritic stainless steel (430) and Mild steel (E7018). Their dependent variables for this research were tensile strength, hardness, microstructure and heat affected zone. They confirmed that, the tensile strength for the welded specimens reach the highest value when welded using the E7018, while the hardness reach the highest value when welded using the Ferritic stainless steel 430 filler rod. At the same time, the microstructure and heat affected zone were determined by optical microscope. They found that the ferrite structure and pearlite are present in dendritic form. They also concluded that the smaller grains are coagulated to form new grains, thus grain growth is present [4].

Jha and Jha [5] focused on the effect of welding current on the tensile strength properties. In this paper, the mild steel alloy specimens were welded using the SMAW with welding current as the varying parameter. The current used were 100 amp, 110 amp, 120 amp, 130 amp and 140 amp. They found that, specimen that was welded using 120 amp produced maximum tensile strength. It was also observed that the tensile strength increases with increased in current only up to 120 amp. Comparison of weld carried out across 100 amp, 110 amp, 130 amp and 140 amp, they concluded that the maximum tensile strength recorded was 515.185 MPa achieved at 120 amp [5].

Ogbunnaofor et al. [6] used SMAW to study the effect of welding current and electrode types on the tensile properties. They used Mild steel plate (AISI 1018) as the base material. Their independent variables were welding current (65, 70, 75 and 80A) and electrode types (E6011 and E6013). The results showed that, the UTS and yield strength values increase with the increased in welding current, until it reaches an optimum value, which is at 75A (for E6011) and 80A (for E6013). Also, E6011 produced the maximum yield strength and UTS of 358.50 MPa and 421.70 MPa respectively. While, for E6013, the maximum yield strength is 319.37 MPa and gave a maximum UTS of 383.20 MPa. They concluded that, the strongest combination of tensile properties was found when the specimen welded with E6011 at welding current of 75A, while specimen that was welded using E6013 was maximum at welding current of 80A [6].

Jorge et al. [1] used SMAW to weld high strength low alloy (HSLA-80) steel materials. They used the E11018-G type of electrode and applied double “V” bevel profile of joint with the angle of 60° on multi-pass welding. Their independent and dependent variables were different heat conditions and UTS respectively. They found that heat treatments did not affect the UTS and microstructure of welded joint, UTS is high in the fusion zone (FZ) during post-heating and the UTS is below 110,000 psi [1].

Talabi et al. [7] carried out a research on the effect of welding variables on the mechanical properties of low carbon steel welded joint. The welding parameters that were investigated in this research were welding current, electrode diameter, arc voltage and welding speed. The plates were joined together using SMAW with the E7018 low hydrogen electrode rod. They found that the increased in the arc voltage and welding current resulted in increased hardness and decreased in yield strength, tensile strength and impact toughness. They concluded that increased in current and voltage implies an increase in heat input that can generate space for the creation of defects, thereby reducing the mechanical properties observed. They also concluded that, electrode with diameter of 2.5 mm provides the best combination of mechanical properties [7].

Mohd-Tahir et al. [8] performed an investigation on mechanical properties of welded material under different types of welding filler. The experiment was done by employing SMAW to weld the low carbon steel (AISI 1020). The types of welding filler (E6013, E7016 and E7018) and welding
current (80A & 90A) were taken as the independent variables, whereas the dependent variables were the mechanical properties of the welded joint, which include the tensile strength and the hardness of the welded joint. The results were analysed using the two-ways ANOVA. This research found that, when the heat input increase, the mechanical properties decreased. They also concluded that welding filler E7016 produced the optimum tensile strength, while the welding filler E7018 produced the optimum hardness test at welding current of 80A [8].

Soy et al. [9] used SMAW to determine the ideal welding parameters and their limits. In this paper, three different types of material; plain carbon steel, alloy steel and stainless steel, were used as the base materials. Their independent variables are arc length, welding speed, electrode diameter, welding current and electrode angle. Their results showed that the welding current changes according to the thickness of the work piece, where the optimum value of welding current intensity are between 60 amp to 150 amp. The 2.50, 3.25 and 4.00 mm diametric electrodes were selected as the most ideal for SMAW process applications. The results also showed that, in case of arc length moved away from the sample, the blowing, welding seam, sound of explosion and light intensity rose up, while, when the arc length comes nearer to the work piece, the welded joint become swollen [9].

Buchely et al. [10] studied the effect of parameters in SMAW process. They applied 60° of V-groove joint on the Austenitic Stainless steel. Their first independent variable is types of electrode coating, which are E308L-15, E308L-16 and E318L-16P coated electrode with 15, 16 and 16P level of deposits. Another independent variable that they used is heat input level and its applied by manipulate the current level of 70A, 85A and 100A. Their dependent variables are UTS, high cycle fatigue and hardness measurement. They design their experiment using the full factorial DOE. They found that the current level of 100A produces the greatest UTS compared to the other levels. Moreover, the greater is the heat input, the smaller will be the spacing of dendrite arm and the better is the resistance to fatigue. They also found that the higher is the deposits, the greater will be the fatigue life of welding and the lower is the hardness. They concluded that the E308L-15 electrode have better resistance to fatigue than the other electrodes [10].

Ahmed et al. [11] studied the effect of different time durations on the Post Weld Heat Treatments (PWHT). They used HSLA steel and applied E9018-B3 electrodes in their experimentation. They applied double V (60°) groove joint on their specimens. Their independent variables are duration of post weld heat treatments, which are 0.5, 2.0, 10 and 50 hours. Their dependent variables are UTS, and impact toughness. They concluded that 2 hours PWHT produces good mechanical properties such as UTS and yield strength (YS). There is another PWHT times in the range of 2 hours to 10 hours that improves the UTS properties. They also concluded that impact resistance decreased with the increased of PWHT more than 10 hours [11].

Olawale et al. [12] conducted studied on SMAW. They used E6013 electrodes, terminal voltage of 80V and low carbon steel. Their independent variables were the welding current of 100A, 120A and 140A, and the heat treatment at various temperatures. Their dependent variables were hardness, tensile and impact test. The results shown that 140A produces the highest UTS than 100A and 120A. They found that increased in current enhances the hardness and strength but reduces the impact strength. They concluded that the increased in normalising temperature increases the hardness and strength but decreases in the impact strength [12].

Singh et al. [13] focused on SMAW process and studied the effect of mechanical vibration on the mechanical properties of the welded metal. They used the Mild Steel with thickness of 6 mm and E6013 type of electrode. They applied the butt joint during welding of their specimens. They setup the vibratory by using 9V battery. Their independent variables are ranges of frequencies (250 Hz, 100 Hz and 80Hz), welding currents (90A, 100A and 110A), and welding speed (8 cm/min, 10 cm/min and 12cm/min). They designed their experiment by using the Taguchi’s DOE. Their dependent variables are UTS properties and micro-hardness. They concluded that the mechanical vibration increases the UTS and hardness properties of the welded joints [13].

Widodo et al. [14] focused on mechanical properties of SMAW. They used 2.6 mm diameter of AWS A5.4 E308-16 electrode and 3 mm thickness of AISI 304 stainless steel. They applied the V-
groove (60°) joint in their experiment. They set their independent variables as welding currents (70A, 80A and 90A). Their dependent variable was UTS. They concluded that the 90A level of current producing the highest UTS compared to 70A and 80A [14]. Evans [15] used SMAW with the electrode ISO 2560 with various diameters which were 3.25mm, 4.0mm, 5.0mm and 6.0mm. They found that both YS and UTS decreased with the diameter of the electrode [15].

Talabi et al. [7] focused on SMAW. They used low carbon steel as their base material. The parameters that they studied were welding current, arc voltage, welding speed and electrode diameter. The machine that they used are grinding machine and Impact Testing machine. They found that the selected welding parameters had significant effects on the mechanical properties of the specimens [7].

Ye et al. [16] focused on the effect of the groove types in welding. The base material that they used is the SUS304 austenitic stainless steel. Their independent variable was types of groove; which is V-groove, K-groove and X-groove. Meanwhile, their dependent variables are residual stress (longitudinal stress and transverse stress) and YS. They found that the V-groove join is good in predicting the residual stress, angular distortion and its longitudinal tensile stress is wider than the others joint. They also found that the peak value of transverse tensile stress for V-groove is greater than the K-groove and X-groove and the sensitization region on the top surface is greater in V-groove join than the other joins. They concluded that the V-groove is recommended in order to avoid the Stress Corrosion Cracking (SCC) [16].

These researches demonstrated trends in experiment carried out. The experiment trends changes from single variable (or factor) or multi-variables with single level to multi-variables with multi-levels. This change is due to the need to compare between multiple variables/factors simultaneously in one experiment rather than just evaluating the performance of individual variable. In fact, in actual welding process, these multi-variables will need to be considered or set properly together and not individually. This scenario encouraged research in the direction of multi-variables with multi-levels. However, this multi-variables with multi-levels research is not simple. The existence of multiple variables, which require to be manipulated at various levels, leads towards huge number of variable-level combinations. A proper way of handling this complex experiment is required. This required researcher to revolutionise the experimental design. As a result, the Design of Experiment (DOE), which promises optimum number of specimens per experiment, becomes the handy tool or technique to handle the huge experiment [17]. At the same time, the huge number of variable-level combinations leads to experiment with lots of output data or results to be handled. A systematic way of handling these huge number of output data is a necessity. Luckily, the DOE, which is equipped with statistical analysis, provides a systematic way to handle the huge experiment and analyses the huge number of output data extensively [17]. Concurrent with this research direction, this paper presented an extensive study on the effects of currents and rod diameters on the UTS of the welded metal using the full factorial DOE.

2. Research Methodology

In this research, the Mild Steel (AISI 1018) was used and prepared according to the ASTM E-8 standard whereby the width, thickness, and gauge length for each specimen were 12.5mm, 4mm and 50mm respectively. More than 72 flat bars of the Mild Steel (AISI 1018) were machined by using milling and grinder machines in order to produce the 60°V-groove and root face. Next, these flat bars were welded by using the WIM AC200 welding machine and E6013 welding rod. The current levels were set at 80A, 90A, 100A, 110A, 120A and 130A. Meanwhile, the rod diameters that were applied are 2.5, 3.2 and 4 mm. Using the combination of parameters, a Full Factorial DOE table was developed. The welding experiment was then conducted following the sequences as outlined by the DOE table. Then, the excess metal and rusty surface were removed by using milling machine and grinding machine until the dimension as specified in the standard ASTM E-8 for all specimens. Finally, the tensile test was then conducted on every specimen by using the GOTECH AI-7000M tensile machine, which have 1020kN capacity, minimum 0.001mm/min test speed and power of 3300watts. The tensile tests were carried out as outlined by the American Society for Metals (ASM)
International, which includes several steps such as sample selection, sample preparation, test set-up, test procedure and data recording [18].

3. Results Discussions

The results from the tensile test were then collected. ANOVA was then carried out on the tensile test data as summarized in table 1. Based on the table, the ANOVA indicated that the current is a significant factor in affecting the UTS (with p-value =0.011). This result is parallel with the findings from Buchely et al. [10], Bodude et al. [19], Singh et al. [13], Widodo et al. [14] and Olawale et al. [12]. These researchers found that different current levels will produce different mechanical properties including the tensile strength. This is also parallel with Talabi et al. [7], who found that the welding current had significant effect on the mechanical properties of the specimens. In this research, the result showed that the tensile strength increases when the current increased from 80A to 100A. However, the tensile strength decreases as the current was set between 110A to 130A. According to Talabi et al. [7], this scenario occurred due to the present of void and defect when the current increased. Moreover, this scenario might also happen because of the excessive grain growth due to the current increased.

In addition, the rod diameter is also found to be a significant factor in affecting the tensile strength (with p-value =0.000). This is parallel with the Evans [15], who found that the welding rod diameter had significant effect to the UTS of the specimens. According to Evans [15], this result happened because of the present of manganese as one of the chemical composition that influenced the mechanical properties of the welded mild steel. The manganese contents slightly decrease as the welding rod diameter increased. Therefore, increases in the welding rod diameter will decreases in UTS of the welded mild steel.

| Source         | DF  | Seq SS | Contribution | Adj SS | Adj MS | F- Value | P- Value |
|----------------|-----|--------|--------------|--------|--------|----------|----------|
| Model          | 20  | 373627 | 73.85%       | 373627 | 18681  | 7.06     | 0.000    |
| Blocks         | 3   | 24375  | 4.82%        | 21548  | 7183   | 2.71     | 0.055    |
| Linear         | 7   | 220014 | 43.49%       | 217325 | 31046  | 11.73    | 0.000    |
| Current        | 5   | 43815  | 8.66%        | 44192  | 8838   | 3.34     | 0.011    |
| Rod Diameter   | 2   | 176198 | 34.83%       | 173515 | 86758  | 32.79    | 0.000    |
| 2-Way Interactions | 10 | 129239 | 25.54%       | 129239 | 12924  | 4.88     | 0.000    |
| Current*Rod Diameter | 10 | 129239 | 25.54%       | 129239 | 12924  | 4.88     | 0.000    |
| Error          | 50  | 132311 | 26.15%       | 132311 | 2646   |          |          |
| Total          | 70  | 505938 | 100.00%      |        |        |          |          |

Model Summary

| S          | R-sq | R-sq(adj) | PRESS | R-sq(pred) | AICc | BIC  |
|------------|------|-----------|-------|------------|-----|------|
| 51.4414    | 73.85% | 63.39% | 266076 | 47.41% | 801.22 | 829.91 |

New finding from this research is that the ranking of each factor in affecting the UTS as shown on Figure 1. Specifically, the pareto chart shows that the rod diameter is a more significant factor than the current in affecting the tensile strength of a welded joint. Additional new finding from this research, the interaction between current and rod diameter is also found to be more significant than the current but less significant than rod diameter. This demonstrates that proper selection of rod diameter is more significant for the welder than the current.
Figure 1. The Pareto chart ranking the parameter current and rod diameter along with their interaction.

The Figure 2 shows the main effects plot that is used to identify the maximum and minimum values of the tensile strength corresponding to the current and rod diameter. According to the pattern of the main effects plot, the tensile strength is increased when the current is in the range of 80A to 100A but decreased in the range of 110A to 130A. Therefore, by comparing these current ranges, the highest tensile strength is produced by 100A. This result is closed to Buchely et al. [10], Bodude et al. [19], Singh et al. [13], and Widodo et al. [14] findings. They also found that the optimum current to produce the greatest UTS is in the range of 90A to 110A.

Meanwhile, the main effect plot also shows that the welding rod diameter of 2.5mm produces the highest tensile strength compared to 3.2mm rod diameter. At the same time, the 3.2mm rod diameter produces the highest tensile strength compared to 4.0mm rod diameter. At the same time, the Fig 2 shows that the tensile strength decreases with the increased in the diameter of the welding rod. This scenario is parallel with the Evans [15], they found that the tensile strength decreases with the increased in the diameter of the electrode. Moreover, they also found that the greater UTS is produced using smaller diameter of welding rod. According to Evans [15], this scenario happened because smaller rod diameter produces the highest contents of manganese, which resulted in the greater tensile strength in comparison to the larger rod diameters.

Figure 2. The Main Effects Plot for Tensile Strength (MPa) versus Current (A) and Rod Diameter (mm).
Using the results collected during experiment, a regression equation was developed as shown in Equation (1). Using the regression equation, the optimum parameter setting of was estimated. Basically, the values for welding current (C) and rod diameter (R) identified as producing the highest tensile strength are 80A and 2.5mm respectively, which resulted in tensile strength of 342.39 MPa. This result is parallel with Mohd-Tahir et al. [8], Ogbunnaoffor et al. [6] and Talabi et al. [7]. Specifically, the experiment conducted by Mohd-Tahir et al. [8], and Ogbunnaoffor et al. [6] found that the greater UTS was produced using current of 80A. At the same time, Talabi et al. [7] found that the greater UTS was produced by using welding rod of 2.5mm rod diameter. In conclusion, this project proves using regression equation in optimization that the best combination of current and rod diameter is 80A and 2.5mm respectively that produced the maximum UTS of 342.39 MPa.

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Tensile\,\,Strength = 230.31 - 51.5\, C_{80} - 3.7\, C_{90} + 22.8\, C_{100} + 5.5\, C_{110} + 20.8\, C_{120} + 6.1\, C_{130} + 66.89\, R_{2.5} - 13.81\, R_{3.2} - 53.08\, R_{4.0} \\
+ 96.7\, C^*R_{80\,2.5} - 56.7\, C^*R_{80\,3.2} - 40.0\, C^*R_{80\,4.0} + 38.2\, C^*R_{90\,2.5} \\
+ 3.4\, C^*R_{90\,3.2} - 41.5\, C^*R_{90\,4.0} - 10.9\, C^*R_{100\,2.5} + 42.4\, C^*R_{100\,3.2} \\
- 31.5\, C^*R_{100\,4.0} - 11.2\, C^*R_{110\,2.5} - 0.4\, C^*R_{110\,3.2} + 11.6\, C^*R_{110\,4.0} \\
-62.6\, C^*R_{120\,2.5} + 14.5\, C^*R_{120\,3.2} + 58.1\, C^*R_{120\,4.0} - 50.2\, C^*R_{130\,2.5} \\
- 3.2\, C^*R_{130\,3.2} + 53.3\, C^*R_{130\,4.0} \\
\]  

(1)

4. Conclusion
This project investigated the effects of currents and rod diameters on the tensile strength of a SMAW welded joint. Specifically, this research found that both current and rod diameter are significant factors in affecting the tensile strength of a welded joint. New finding from this research is that the rod diameter is found to be a more significant factor than the current in affecting the tensile strength of a welded joint. This research emphasized further the need to select proper rod diameter for the welder more than the current. At the same time, this research also contributes new finding by showing that the interaction between current and rod diameter as significant in affecting the UTS. This interaction is also found to be more significant than current but less significant than rod diameter in affecting the UTS. This project also shows that the tensile strength increases when the current is increased from 80A to 100A. However, the tensile strength decreases as the current was set between 110A to 130A. In addition, the welding rod diameter of 2.5mm produces the highest tensile strength compared to 3.2mm. However, the 3.2mm rod diameter produced higher tensile compared to 4.0mm rod diameter. Finally, this project proved using regression equation in optimization that 80A of welding current and 2.5mm rod diameter is the best parameter combination that produced the maximum tensile strength of 342.39 MPa.

References
[1] Jorge L J, Candido V S, Silva A C R, Filho F C G, Pereira A C, F Luz S, Monteiro S N 2018 J. Mater. Res. Tech. 598-605.
[2] Kalpakjian S and Schmid S 2014 Manufacturing Engineering and Technology (Pearson Education South Asia Pte Ltd, Singapore).
[3] Nassar A A, Leflah R M, Abdulsada M J and Kufa 2018 J. Eng. 4 163-173.
[4] Mattao S, Kumar V, Ahmed S 2015 Int. J. Eng. Res. Tech. (IJERT). 4 193-197.
[5] Jha R and Jha A K 2014 Int. J. Eng. Res. Tech. (IJERT) 3 1304-1307.
[6] Ogbunnaoffor C K, Odo J U and Nnuka E E 2016 Int. J. Sci. Eng. Res. 7 1120-1123.
[7] Talabi S I, Owolabi O B, Adebisi J A and Yahya T 2014 Adv. Prod. Eng. Manag. 9 181-186.
[8] Mohd Tahir A, Mohd Hair N A and Wei F J 2018 AIP Conf. Proc. 1958 020003.
[9] Soy U, Iyibilgin O, Findik F, Oz C, Kiyat Y 2011 Sci. Res. Essays. 6 3153-3160.
[10] Buchely M F, Colorado H A, Jaramillo H E 2015 J. Manu. Process 181-189.
[11] Ahmed S R, Agarwal L A and Daniel B S S 2015 Mater. Today Proc. 2 1059-1066.
[12] Olawale J O, Ibitoye S A, Oluwasegum K M, Shittu M D, Ofoeze R C 2012 J. of Miner. Mat.
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