Effects of Arc Voltage and Welding Current on the Arc Length of Tungsten Inert Gas Welding (TIG)

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Abstract- The effects of welding current and arc voltage on the arc length of Tungsten Inert Gas (TIG) welding was investigated in this study. Mild steel plates of 10mm thickness and 50mm x 100mm diameter were joined together through TIG welding process for four (4) different intervals and the welding arc lengths were measured consecutively. The measured arc length for each welding interval increased from 1.19mm, 1.93mm, 2.54mm and 3.12mm as the current increased from 50A, 100A, 150A to 190A while the voltage also maintained the same increasing trend from 200V, 240V, 280V to 320V. The minimum arc length values measured for each welding interval with the aforementioned current and voltage range also maintained an increasing trend, and that led to the conclusion that the higher the welding current and arc voltage, the longer and wider the arc length which is an influential factor to other welding attributes.

Keywords Welding, Arc voltage, Arc length, Welding current, Electrode, Mild Steel.

1. Introduction

Welding is the process of joining two or more metals together [1]. Welding processes can be classified into two major groups such as fusion welding and solid-phase welding. Fusion welding is based on the principles of heat application to join two or more materials together, and it is categorized into various types of welding operation which includes arc welding, resistance welding, oxy-fuel welding also referred to as oxyacetylene welding or oxy welding, electron beam welding and laser beam welding. Solid-phase welding which is the other group of welding classification is based on the application of pressure alone or combination of both heat and pressure to join two or more materials together, and it is categorized into diffusion welding, friction welding, forge welding and ultrasonic welding [2]. Arc is divided into four (4) major processes such as Shielded Metal Arc Welding (SMAW) also known as Manual Metal Arc Welding, Gas Metal Arc Welding (GMAW) also known as Metal Inert Gas or Active Gas Welding (MIG/MAG), Flux Core Arc Welding (FCAW) and Gas Tungsten Arc Welding or Tungsten Inert Gas (TIG) which is the centre of focus in this study [3]. The above mentioned welding processes has not always been widely used in the past but its application and relevance in many industries in recent times has increased tremendously due to cost and reliability. Among the aforementioned welding technologies, TIG welding is gradually emerging as the process of choice for joining thin material, dissimilar and particularly suitable for welding metals and metal alloys than any other arc welding process with little smoke or fumes, neat and slag free welds and appearance that may result in ease of finishing despite its slower travel speeds than other processes, lower filler metal deposition rates and the cost of equipment which can be higher than using other welding processes [4]. Tungsten inert gas (TIG) welding also referred to as Gas tungsten arc welding (GTAW) is an electric arc welding method that applies a non-consumable tungsten electrode in the process of joining two metals together.

Weld penetration is the rate at which the fusion line extends below the surface of the welded material. Weld penetration is interrelated with arc length and welding current, as increase or decrease in current can result in further increase or decrease in arc length and in the weld penetration depth. Studies have shown that weld penetration is influenced by welding current, polarity, arc travel speed, electrode diameter etc. [5]. Memduh et al. [6] noted that weld penetration is directly proportional to welding current, and that deep penetration can be achieved in operations where DCEP polarity is employed whereas, shallow penetration can be achieved as a result of DCEN polarity. Penetration decreases with the increase in welding speed because the time at which the arc force is allowed to penetrate into the material's surface decreases. The penetration decreases with the increase in electrode diameter due to decrease in current intensity and arc length [7]. British Standard Institution (BSI) describes arc length as the accumulative distance from the tip of the welding electrode to the adjacent surface of the weld pool [8]. According to Egerland [9], an average arc length may be expressed by equation 1,

$$l_{arc\_av} = c_1 * L_{arc\_max} + c_2 * L_{arc\_min} \quad (1)$$

Where, l_{arc_av} is the average arc length, L_{arc_max} is the maximum arc length, L_{arc_min} is the minimum arc length, c_1 and c_2 are constants showing current correspondence and pulse current time.

Tewari et al. [10] studied the effect of welding current, arc voltage, welding speed and heat input rate on the weldability of Mild Steel specimens of 50mm× 40mm× 6 mm dimensions using metal arc welding. The result obtained showed that the depth of penetration increased with increasing welding speed up to 110.39 mm/min which was optimum value to obtain maximum penetration. Therefore, increasing the speed of travel and maintaining constant arc voltage and current resulted in increased penetration until optimum speed was reached at which penetration was maximum. Increasing the speed beyond this optimum resulted in decreased penetration. Ghazvinloo et al. [11] reported that if the welding speed decreases beyond a certain point, the penetration also will decrease due to the pressure of the large amount of weld pool beneath the electrode, which will cushion the arc penetrating force. However, high welding voltage produces wider, flatter and less deeply penetrating welds than low welding voltages. Depth of penetration is maximum at optimum arc voltage [7].

Welding voltage varies with the arc length between the welding electrode and molten weld metal. An increase in arc length oftentimes lead to increase in the arc voltage because extension of the arc exposes the entire arc column to the cool boundary of the arc [12]. Similarly, the arc column continues to lose the charge carriers through radial movement into the cool boundary of the arc, thereby, introducing a higher requirement for maintaining adequate charge carriers between the welding electrode and the weld material [5]. The shape of the weld bead cross section and its physical appearance is mainly determined by the voltage. Furthermore, if the welding voltage is increased with constant welding current and welding speed, a flatter, wider, and less penetrated weld beads may be obtained which tends to reduce the porosity due to corrosion or scale on steel materials. Increasing arc voltage can equally lead to increase in the size of droplets as well as increase in the droplet transfer movement time and thus, decreasing the number of droplets [10]. Also, the possibility of breaking the arc may increase with increasing voltage and affecting the welding process. Increasing welding voltage can increase flux consumption which in turn increases or lessen the alloying elements, thereby, affecting the mechanical and metallurgical properties of the weld metal [11, 13]. In addition, extremely high voltage has the tendency of producing wider bead geometry that is prone to cracks, increased undercut and difficulty in slag removal. Low voltage produces a stiffer arc, which improves penetration in a deep weld groove and resists arc blow, whereas, extremely low voltage produces a narrow bead geometry and results in difficulty during slag removal along the bead edges.

In a given arc welding operation carried out with constant voltage and amperage, the thermal efficiency of heat source is given [14] as shown in equation 2;

$$\eta = \frac{Q_s t_{weld}}{VIt_{weld}} = \frac{Q_s}{VI} \quad (2)$$

Where, Q_s is the rate of heat generated, t_{weld} is the welding time and η is the thermal efficiency.

For welding operations where electric arc serves as the welding source, heat conduction through the workpiece is the primary mode of heat transfer, and the partial differential equation for transient heat conduction is expressed by equation 3;

$$\rho c \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + f \quad (3)$$

Where p is the density, c the specific heat and k is the thermal conductivity which are all dependent on the temperature T. t is the welding time and f is the additional heat generated in the workpiece. Considering the heat generated as a result of arc welding process, the heat flux vector is shown in equation 4;

$$\vec{q} = -k\nabla T \quad (4)$$

The relationship between enthalpy and the temperature is expressed by equation 5;

$$H = \int_{T_{ref}}^{T} c(\tau)\, d\tau \quad (5)$$

This implies that;

$$c = \frac{dH}{dT} \quad (6)$$

From equation (3) and (6), the apparent heat capacity equation can be expressed by equation 7;

$$\rho \frac{\partial H}{\partial t} = \nabla.(k\nabla T) + f \quad (7)$$

Welding current is the electrical amperage in the power equipment used in carrying out welding operation. It is usually read from the power meter, but depending on the connection could have a separate ammeter. Welding current is one of the most influential welding parameter because it has high tendency of affecting bead geometry, control the rate at which electrode is melted, controls deposition rate, heat affected zone, penetration depth and the amount of base metal melted depending on how the amperage is regulated during welding operation [15].

If the amps is too low, may result in a tall, narrow bead lacking in penetration. The weld will be difficult to start and the arc prone to straying towards one side of a joint in preference to the other. In cases where the bead is too high, the bead has a wider appearance that is flat and irregular, and a small undercut can observed on the right hand side of the weld in the other sectioned of the image below. A deep crater forms at the end of the weld, and removing the slag from the edges of the weld may be difficult. Hence, excessive current should not be compensated by excessive travel speed [16]. This has a high tendency of resulting in slag inclusions due to rapid cooling of the weld. Moreover, with the amps correctly adjusted, a bead of smooth round shape is obtained, and the slag can be removed easily. The increase in electrode melting rate in kg/min as a result of increase in welding current is given by the relationship in equation 8,

$$\text{Electrode Melting Rate} = \frac{1}{1000}\left[0.35 + \frac{d^2}{645} + 2.08 \text{ x } 10^{-7} \text{ x } \left(\frac{IL \text{ x } 25.4}{d^2}\right)^{1.22}\right] \quad (8)$$

Where, d = thickness of the melted electrode L = length of the melted electrode I = welding current.

2. Methodology

5 pieces of mild steel plate with 10mm thickness and dimension of 50mm x 100mm each were grinded to smoothen the surfaces and joined together in series of five (5) different welded grooves (joints), and the arc length which contributes to the depth of weld penetration was measured during the welding operation. Using TIG welding machine with AC currents of 50A and voltage ranges of 200V, 240V, 280V and 320V; 100A with the same voltage ranges; 150A with the same voltage ranges and 190A with the same voltage ranges on each welded plate; the procedure was carried out on four (4) different 10mm mild steel plate of the same specification. The welding set-up consisted of speed control unit, TIG welding touch and clamp, tungsten electrode, gas cylinder containing argon gas. Several welding variations noted during the welding experiment are reported in this study. Figure 1-4 represent the four (4) mild steel plates used for the experiment.

Fig 1. Workpiece welded with 50A Current

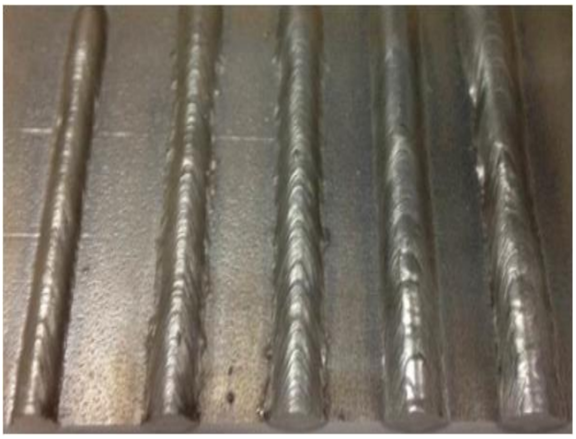

Fig 2. Workpiece welded with 100A Current

Fig 3. Workpiece welded with 150A Current

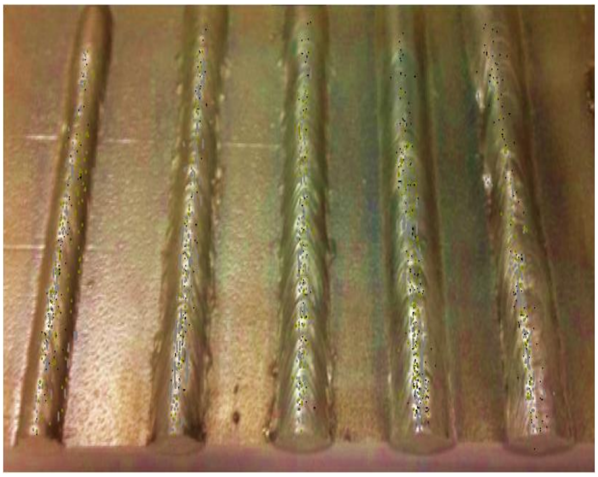

Fig 4. Workpiece welded with Current of 190A

3. Results

Results obtained from the welding conditions and process parameters stated earlier in the methodology are presented as follows;

Table 1. Result of Welding Arc Length obtained with 50A and variable Voltage Ranges

Welding Current (A)	Arc Voltages (V)			
	200V	240V	280V	320V
	Arc Lengths (mm)			
50 A	0.62	0.92	1.4	1.19
	0.68	0.83	1.1	1.11
	0.52	0.96	1.3	1.5
	0.49	0.72	1	1.12
	0.68	0.81	1.4	1.16

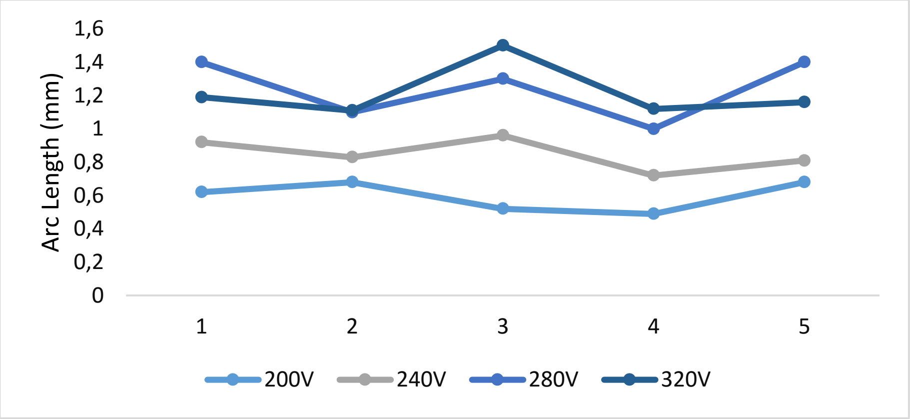

Fig 5. Trend of Arc length with 50A and Variable Voltage ranges

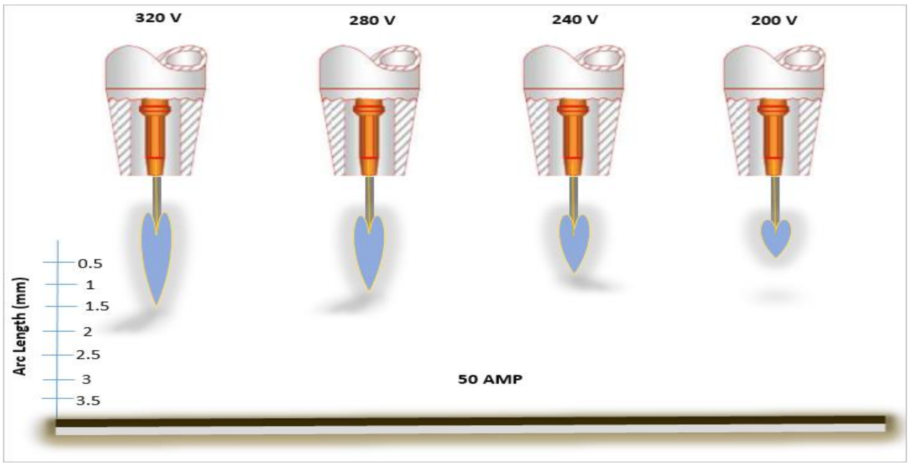

Fig 6. Measurement of Welding Arc Length with 50A and Variable Voltage Ranges

Table 2. Result of Welding Arc Length obtained with 100A and variable Voltage Ranges

Welding Current (A)	Arc Voltages (V)			
	200V	240V	280V	320V
	Arc Lengths (mm)			
100 A	1.24	1.32	1.58	1.88
	1.28	1.38	1.43	1.62
	1.2	1.36	1.49	1.93
	1.27	1.29	1.57	1.74
	1.25	1.34	1.46	1.86

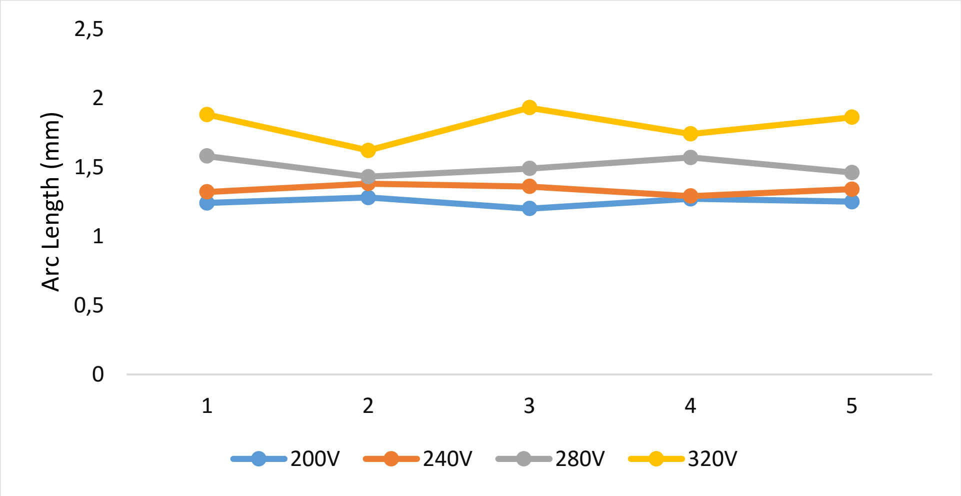

Fig 7. Trend of Arc length with 100A and Variable Voltage ranges

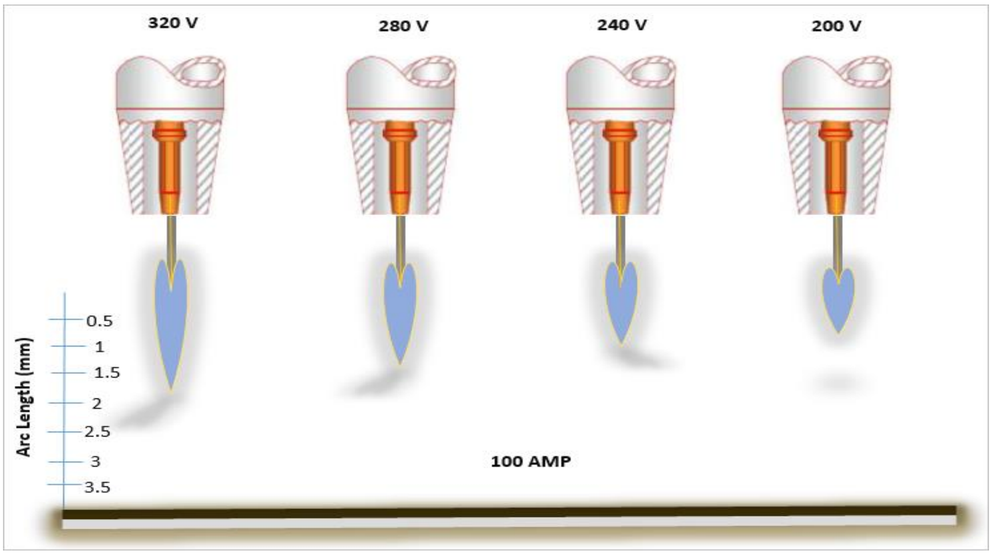

Fig 8. Measurement of Welding Arc Length with 100A and Variable Voltage Ranges

Table 3. Result of Welding Arc Length obtained with 150A and variable Voltage Ranges

Welding Current (A)	Arc Voltages (V)			
	200V	240V	280V	320V
	Arc Lengths (mm)			
150 A	1.51	1.72	2	2.51
	1.54	1.75	2.1	2.22
	1.59	1.54	1.92	2.32
	1.4	1.63	2.19	2.34
	1.46	1.6	1.84	2.54

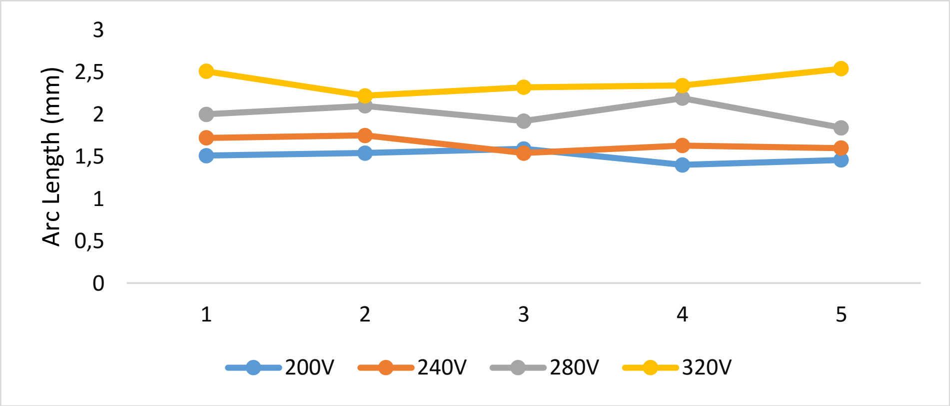

Fig 9. Trend of Arc length with 150A and Variable Voltage ranges

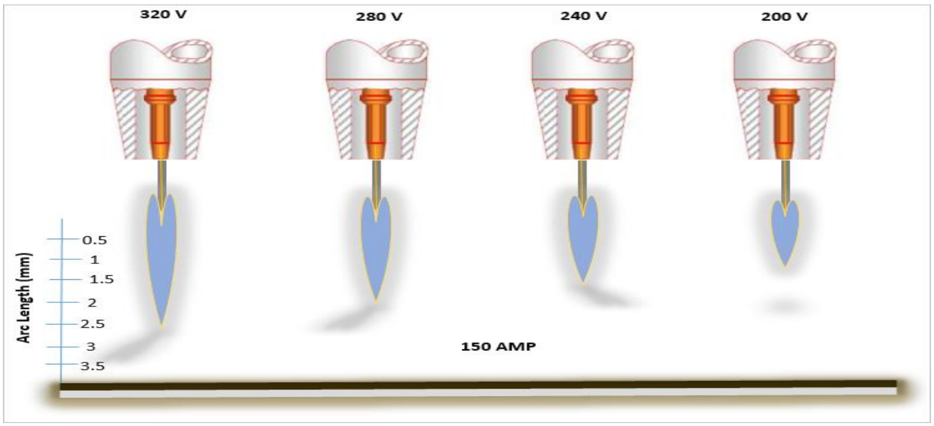

Fig 10. Measurement of Welding Arc Length with 150A and Variable Voltage Ranges

Table 4. Result of Welding Arc Length obtained with 190A and variable Voltage Ranges

Welding Current (A)	Arc Voltages (V)			
	200V	240V	280V	320V
	Arc Lengths (mm)			
190 A	2.33	2.63	2.72	2.78
	2.37	2.42	2.74	3.11
	2.26	2.54	2.63	2.91
	2.34	2.66	2.73	2.82
	2.28	2.49	2.68	3.12

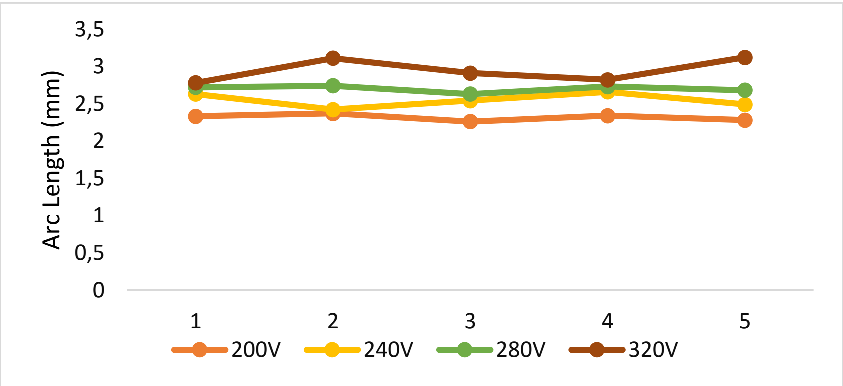

Fig 11. Trend of Arc length with 190A and Variable Voltage ranges

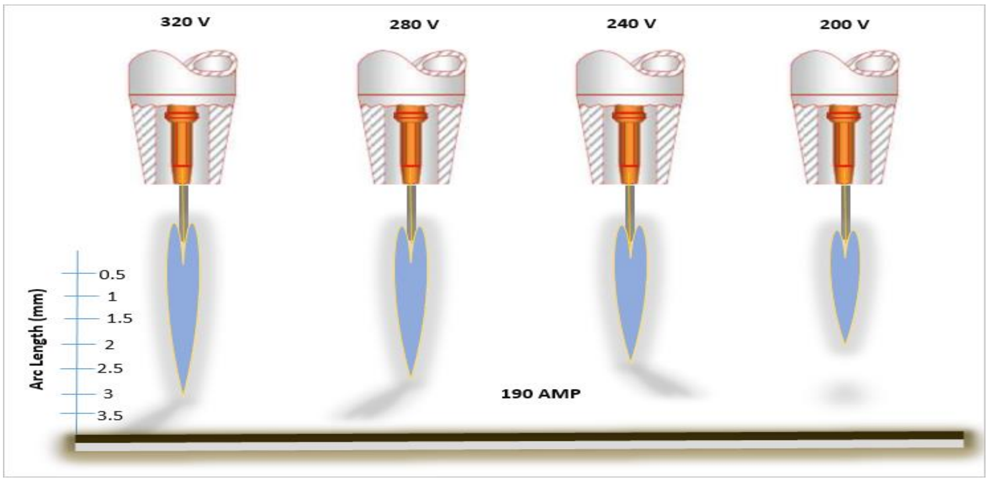

Fig 12. Measurement of Welding Arc Length with 190A and Variable Voltage Ranges

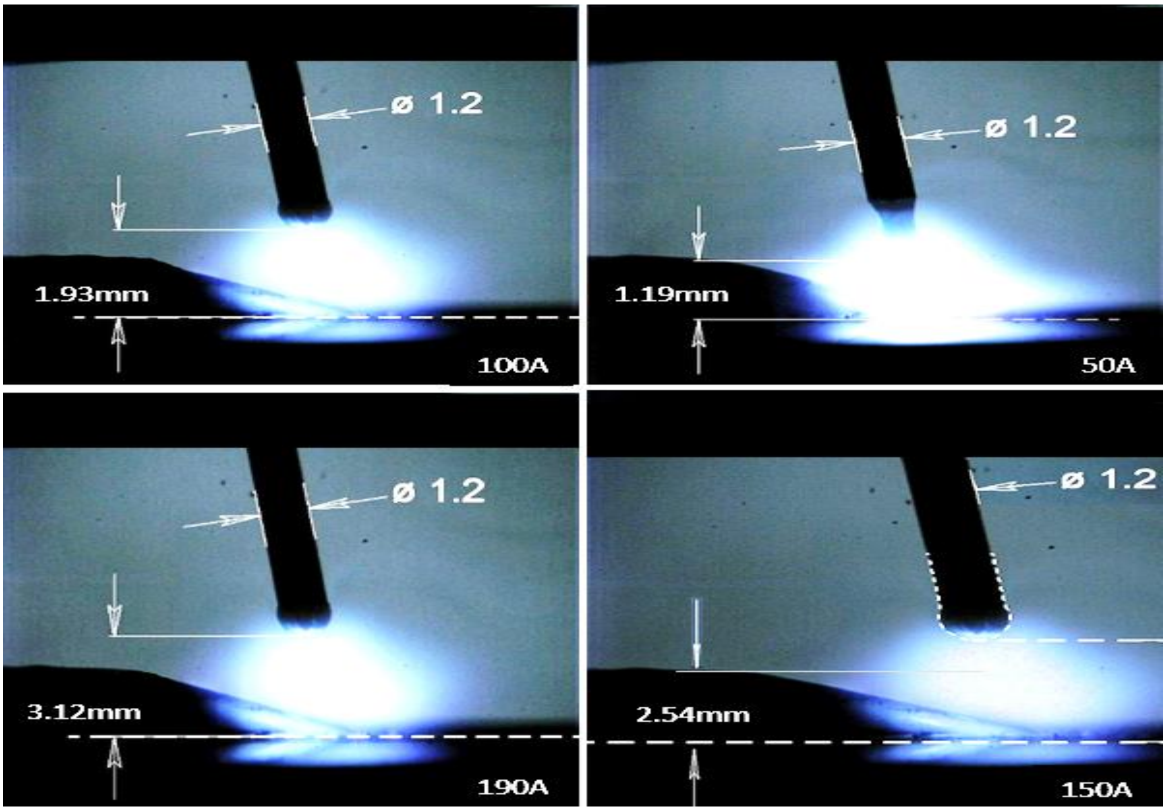

Fig 13. Maximum Arc length Measured for current applied in each of the Four (4) Welding Categories

4. Discussion

Figure 1-4 indicates behaviour of the welded material under different current and voltage ranges. It can be observed in Fig 1 that using a current of 50A with voltage ranging from 200-320, only a handful of spatters were found on the base metal and the weldment which is quite acceptable. By definition, spattering in welding application implies having tiny droplet of electrodes on or beside the weldment and may either fuse on them. In Fig 2 where current of 100A with voltage ranging from 200-320 were used, the base metal and the weldment is smoother with little or no spatters on the surface. However in Fig 3 where current of 150A with voltage ranging from 200-320 were used, microscopically black and white spatters were found especially on the weldment with few more on the base metal. The spattering effect intensified in Fig 4 where current of 190A with voltage ranging from 200-320. The increasing number of spatters which rather produced roughness surfaces was as a result of increase in current input and vice versa. Table 1 represents the measured welding arc length obtained from a fixed current of 50A and variable voltage ranging from 200-320. It is obvious that with a fixed current and increasing voltage, the arc length is likely to increase as well. This can be observed with full clarity in Fig 5 showing the trend of Arc length with a fixed current (50A) and variable voltage ranges (200V, 240V, 280V and 320V), and in Fig 6 depicting the measured welding arc length with the same fixed current (50A) and variable voltage ranges (200V, 240V, 280V and 320V) respectively. The same trend of increase was likewise observed for subsequent fixed currents of 100A, 150A and 190A and similar voltage ranges (200V, 240V, 280V and 320V) as shown in Table 2-4 and Fig 7-12 respectively. Fig 13 depicts the maximum Arc length measured for 50A, 100A, 150A and 190A applicable to each of the four (4) welding categories. The maximum measured arc lengths were derived from the welding operation which also correlates with some of the arc length discussed by Egerland [9].

Although the welding arc penetration was not considered in this study, several existing studies have shown that arc penetration oftentimes increase with the increase in welding current. In other words, too high a welding current at a given welding speed can influence the depth of fusion or penetration by making it so high that the resultant weldment tends to melt through the metal being welded. High current application in welding operation may result in a waste of electrodes in the form of excessive reinforcement and can as well produce digging arc and undercuts which increases distortion in weldment and shrinkage. As the welding current increases, the bead width also increase until a critical point is attained and then gradually decreases if polarity used is that of Direct Current Electrode Positive (DCEP). Also, if the polarity used is that of Direct Current Electrode Negative (DCEN), the bead width increases as current for entire range increases. For the same flux, HAZ also increases with increasing welding current.

However, if current used for the welding operation is too low, inadequate penetration or incomplete fusion may occur, and too low a welding current may equally result in inadequate penetration, unstable arc and overlapping [17]. Welding current also influences the heat requirement for desired weld pool and fusion of similar and dissimilar metals. The area of heat incident on the workpiece surface determines the heat distribution on metal surface [18]. The arc behaviour varies depending on whether the electrode is connected to the positive or negative terminal of the power source. With electrode positive (d.c.+) polarity, the electrode generates greater output heat but less penetration during welding operation than with electrode negative (d.c.−) polarity. The current-carrying capacity of an electrode of a given size will therefore be lower with positive polarity than with negative polarity [19]. Jatinder and Jagdev [20] studied the effect of welding speed and heat input rate on stress concentration factor of butt welded joint of IS 2062 E 250 A steel plates using GMAW and observed that with increase in the heat input rate, flank angle and weld bead width, reinforcement height increases, whereas notch radius decreased with an increase in the stress concentration factor increases.

5. Conclusion

The following conclusions were dawned from the experimental approach conducted in this study;

i. The measured minimum arc length was 0.49mm with current of 50A and arc voltage of 200V.

ii. The maximum arc length measured was 3.12mm with current amperage of 190A and arc voltage input of 320V.

iii. Slight change in arc length caused significant change in current therefore, electrode melting rate and metal deposition changed rapidly in response.

iv. A change in welding current and arc voltage caused corresponding change in arc length.

v. Lengthening the arc exposed the arc column to cool boundary with more heat losses, thereby, necessitating high voltage requirement.

vi. Longer arc length produced unstable welding arc, reduced penetration, increased spatter, flatter and wider welds, and prevents shielding gas from protecting the molten puddle atmospheric contamination.

vii. Long arc length increased puddle heat, produced flatter welds, increased penetration, reduced spatter, produced stable welding arc.

viii. Short arc length produced flatter welds, less puddle heat, less penetration.

ix. Shorter arc length produced less puddle heat, high tendency of electrode to stick, poor penetration, uneven beads with irregular ripples.

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