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Effect of Electric Power Arc Inputs on the Microstructure and Fracture Surface of 0.4%C Steel

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ABSTRACT

The result of an investigation on the effect of electric power arc inputs on the microstructure and fracture surface of 0.4%C steel was analyzed in this study. The power inputs were controlled by varied welding current, at constant arc voltage of 40 V, welding speed of 3.2 mm/sec and electrode gauge of 3.2 mm. The currents were varied at 100 A for low heat input, 112.5 A for medium heat input and 125 A for high heat input. Microstructural and fracture analyses were carried out on the specimens to determine their microstructural configurations. The results showed that increasing the welding current from 100 A-125 A caused a corresponding increase in microstructural grains of the specimens. At 100 A, the time for solidification was less and resulted in smaller fine grains. At 125 A, the time required for solidification increases and yielded coarse grains. The fracture surfaces showed dimples of varying sizes and shapes indicating ductile to brittle transition kind of failure. Low heat, shows a classic mechanism of ductile fracture known as microvoid coalescence. Medium heat shows microvoids coalescence with some tear ridges and river pattern markings which points to the origin of failure. High heat shows trans-granular form of fracture which indicates brittle fracture in which the failure occurred with lower plastic deformation.

1. INTRODUCTION

Medium carbon steels with carbon composition ranging from 0.25 to 0.5%C are heat treatable steels and can be successfully welded by all of the arc welding processes provided suitable welding procedures and precautions are adopted. The high carbon content of these steels, along with manganese greater than 1% makes these steels easy to harden and weld, thereby changing phases on cooling to form hard microstructure. For this reason, they are commonly used in the quenched and tempered condition for applications such as production of machine parts like bolts, crankshaft, gears, axles, rail road rails, spanner, hammer heads and heavy-duty forging (Onyekpe, 2002). Because of the greater likelihood of martensite formation and hydrogen induced cracking during welding, preheating and use of low-hydrogen consumables are necessary to reduce the likelihood of hydrogen induce cracking and high hardness of martensite formed on the parent material (ASM International, 1991).

Welding involves the operation of joining two pieces of metal by the application of intense heat, pressure or both to melt the edges of the metals so that they fuse permanently (Parma, 2010). Welding processes is commonly used in joining sheet metals and, the heat is produced after the electrical energy has been converted to light energy which passes through the flux to the electrode to strike an arc, and the light energy is converted to heat energy which helps in welding (Mohammed *et al.,* 2013). The welding process generally involves melting and subsequent cooling and the result of this thermal cycle is distortion, if the welded item is free to move; or residual stresses if the items are securely held or the internal forces still remain (Welding Technology Institute of Australia, 2006). There comes a point when the amount of residual stresses can create potential problems either immediately or during the life of the welded structure and it needs to be reduced or removed, through the process termed stress relieving (tempering) (Welding Technology Institute of Australia, 2006). Also welding, more than any fabrication process exposes the part to rapid and extreme changes that can lead to cracks in the weldment (Desia, 2010). Usually, the rapid heating and cooling characteristics of welding produces a hard microstructure in the heat affected zone (HAZ), one factor responsible for deterioration and properties of welded joint.

Structure of steel consists of the macro and micro structure. The micro structure is the structure that is visible with the help of the etchant chemical which is poured on the surface of the polished steel (Abioye, 2017). The visible macro-structure is the parent metal, the heat affected zone, the fusion zone (Roger, 2008). The parent metal is the normal unaffected part of the metal whose structure was not altered. The heat affected zone (HAZ) is the area of the base material of metal that has had its microstructure and properties altered by welding or heat intensive cutting operation. The fusion zone (FZ) is where melting and solidification takes place and the principle controls the size and shape of the grain, segregation and distribution of inclusion and porosity. The microstructure which shows the way the atoms and phases are arranged. This can only be detected by the use of the metallurgical microscope (Choudary, 2007). The internal structure of the plain carbon steel that has been tempered is different from that which has been welded (Wan *et al.*, 2015).

It has been reported that welding of medium carbon steel is more difficult than welding of low carbon steels because of the greater tendency of martensite formation in the heat affected zone (HAZ) and this makes the weldment susceptible to hydrogen induced cracking and therefore leads to catastrophic failure (Asibeluo and Emifoniye, 2015). Research has shown that medium carbon steel fail in the industry due to poor choice of welding parameters and welding practice and as a result leads to gaseous molecule entrapment, irregular grain sizes and internal stress in weldment and heat affected zone which affects its fracture and microstructural properties when subjected in service i.e. under load bearing capacity (Dodo *et al.,* 2016). Therefore, the aim of this study is to investigate the effect of electric power arc inputs on the microstructure and fracture properties on this steel, so that adequate measures can be adopted to improve the fracture and micro-structural properties when subjected in service; under load bearing capacity.

2. MATERIALS AND METHODS

2.1. Materials

The materials used for this research work is hot rolled ribbed medium carbon steel rod of 16 mm diameter and 1 m long obtained from Universal Steel Rolling Mill, Ogba-Ikeja, Lagos; Nigeria and the chemical composition of the steel analysis was determined at the same company using the mass analyzer. The equipment used for this research work are: mass analyzer, lathe machine, vice, hack saw, Variosfabrieken Groningen shielded metal arc welding machine, a low hydrogen electrode having a rating E6013 and a composition of 0.12%C, 0.1%Si and 0.45%Mn. The electrode is coated with titanium-potassium materials which can be operated in all positions. It has a diameter of 3.2 mm and a length of 350 mm which has an advantage of deep penetration. Others include angle grinding machine, wire brush, file, silicon carbide paper, motor driven polishing machine, etchant chemical, metallurgical microscope with in-built camera, scanning electron microscope.

2.2. Methods

2.2.1. Sample preparation

The 16 mm ripped medium carbon steels rod was turned (using lathe machines) to 13 mm diameter and the welding samples were sectioned using a hacksaw into twelve (12) pieces. Three (3) pieces each served as control sample for micro-structural properties and were un-welded and the other nine (9) were welded. The edge that were prepared for the weld geometry is single ''V'' groove butt weld each beveled around the edges with the aid of a grinding machine to an angle of 30° to the horizontal. The beveled faces were cleaned properly and smoothened to ensure sound weld. Heat generated was minimized to avoid changes in the microstructure of the specimens and surface uniformity was ensured when using lathe machine.

2.2.2. Welding process

The welding process used is SMAW with E6013- low hydrogen electrode and with the following welding parameters: Welding currents of 100 A, 112.5 A, and 125 A, welding voltage of 40 V, welding speed of 2.5 mm/sec and electrode diameter of 3.2 mm. The faces of two pieces of the beveled rods were placed 5 mm apart from each other, and welding machine was appropriately set with proper amperage and voltage. The electrode was placed in the holder and the welding machine was turned on. The assembly was tack-welded to ensure alignment and an arc was struck. A single bead was made to ensure uniform fusion of the rods. The weld was de-slagged, cleaned and welded again. The finished bead was spread round the joint to ensure proper weld. After the final welding process, the specimen was allowed to cool on the floor and subsequently a chipping hammer was used to remove the hard slag from the surface of the welds and the specimens were allowed to cool before further investigations were carried out. An analysis of the weldments of medium carbon steel was carried out to determine the micro-structural properties with reference to the parent metal, HAZ, and the weld metal. An alternating current supply was used in filling completely the V-Notch samples which maintains an arc gap of 3 mm in between. In accordance with this fundamental fact, three different heat input combinations corresponding to different welding currents were selected for this study, i.e. 100 A (low heat input), 112.5 A (medium heat input), 125 A (high heat input). The reasons for using these specific welding current values are two-fold:

i. This spectrum of heat input combinations results in arc energies which are sufficient to cause adequate fusion of the base and weld metal selected for the present study

ii. A step increase of 12.5 A was anticipated to be sufficient enough to cause a direct and significant influence on the microstructure and mechanical properties of the welded joint.

The heat inputs were calculated according to Equation 1.

$$Q = \left(\frac{V \times I \times 60}{S \times 1000}\right) \times Efficiency \tag{1}$$

Where Q= heat input (kJ/mm), V= voltage (V), I= Current (A) and S= welding speed (mm/min).

The samples were clamped firmly on the vice to prevent movement during welding. The completely filled welded joints were thereafter ground with grinding machine in order to level off and clean the weld with the base metal to standard dimension. During and after welding the joints were visually inspected for their quality and it was ensured that all weld beads possessed good geometrical consistency and were free from visible defects like surface porosity, blow holes.

2.2.3. Temperature measurement

A thermocouple was used to measure the temperature variation across the weld regions. The K-type thermocouple with range of temperature of -200 ˚C to +1350 ˚C was used. The thermocouple was placed at different zones of the weld; immediately after filling the V-notched grove. One at the fusion zone, the others at the heat affected zone and the unaffected base metal and the temperature readings were taken at interval of five seconds until a fairly constant temperature was obtained. Before measuring the temperature of the weld, the initial temperature reading of the thermocouple was noted and recorded.

2.2.4. Micro-structural examination

The micro-structural examination was carried out as follows:

Grinding: Silicon carbide paper was used. Samples for micro-structural examination were ground using a set of abrasive papers rubbed to and fro on the strips starting with the roughest cloth (240 grit), until all traces of saw cuts were removed. The specimens were turned through 90° and rubbed on the next (finer) paper (320 grit) until the previous scratches were removed and then ground on (400 grit) and finally on (600 grit) each time turning through 90°.

Mechanical polishing: This was done in two stages, with a coarse and a fine abrasive or polishing agent respectively. The specimen was held against horizontal rotating wheel and polished on a rotating disc of a synthetic velvet polishing cloth impregnated with micron alumina paste and finally polished with diamond paste.

Etching: The specimens were then etched with 5 ml nitric acid (Nital) and 95 ml alcohol by submerging or swabbing with this chemical reagent that removes the surface layer produced on polishing and attacks preferentially grain boundaries and second phase precipitates.

Microscopic viewing: The samples were illuminated by a reflected light which was mounted on the microscope. The specimens were viewed with an optical microscope and scanning electron microscope through the eyepiece of the microscope so as to determine the microstructure and fracture surface, which was subsequently recorded by the attached camera to obtain the micrograph. This was viewed at a magnification of X200 and X500.

3. RESULTS AND DISCUSSION

The chemical composition of the steel substrate as presented in the Table 1 reveals that the material is a medium carbon steel as the carbon in this material is between 0.25% - 0.5%, while the others are alloying elements present in this material, as steel is basically an alloy of iron and carbon, and other alloying elements (Onyekpe, 2002).

Table 1. Chemical composition of the steel

Elements	C	Si	Mn	S	P	Cr	Cu	Ni	Nb	Al	B	W	Mo	V	Ti	Fe
Composition (%)	0.4	0.3	0.9	0.1	0.1	0.2	0.3	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	97.6

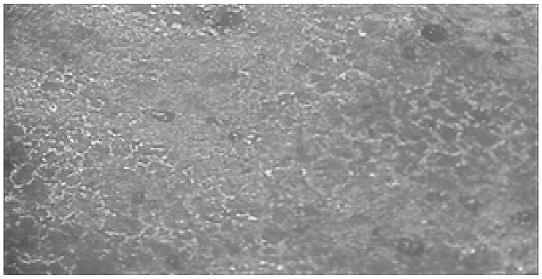
Plate 1: Micrograph of control steel specimen at 200X

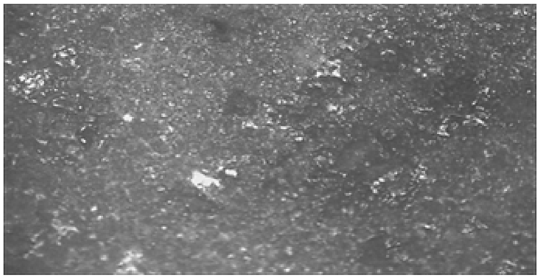
Plate 2: Micrograph of test specimen for low heat input (100A) at 200X

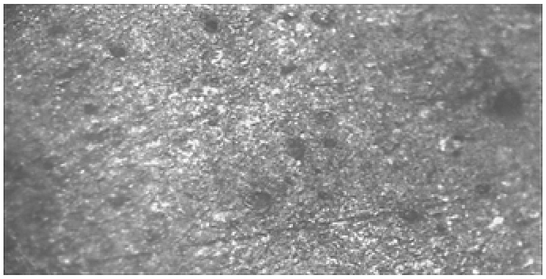
Plate 3: Micrograph of test specimen for medium heat input (112.5A) at 200X

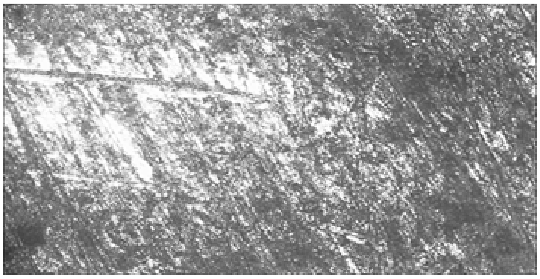
Plate 4: Micrograph of test specimen for high heat input (125A) at 200X

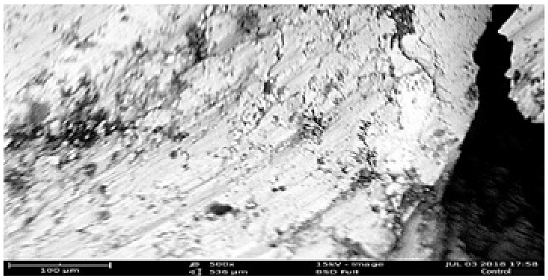
Plate 5: Fracture surface of control specimen at 500X

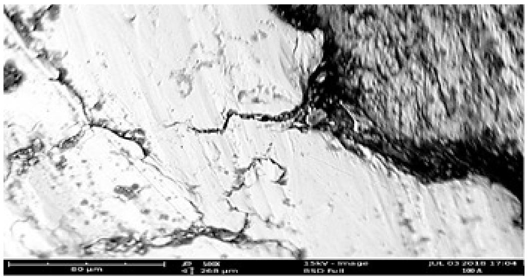
Plate 6: Fracture surface of the test specimen of low heat input at 500X

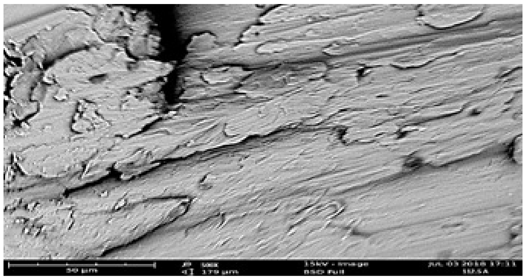
Plate 7: Fracture surface of test specimen of medium heat inputs at 500X

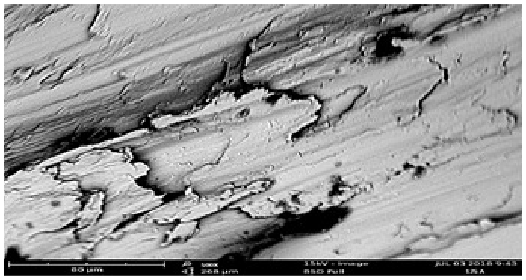
Plate 8: Fracture surface of test specimen of high heat inputs at 500X

The microstructures of the medium carbon steel were illustrated clearly in Plates 1-4, for the structures of as-received and as welded samples. The microstructures contain some colonies of pearlite which is represented by brown region; ferrite is represented by white region and cementite {iron carbide (Fe_3C)}

represents the black region in Plates 1-4. The microstructure of as-received steel in Plate 1. contains fine ferrite and pearlite, while microstructure of as-welded samples varies across the weldment; and it was observed that a large amount of pearlite is present in the ferrite matrix. As depicted in Plates 2-4, as the current was increased, the pearlite become finely distributed within the coarse ferrite matrix with an increase in the proportion of the ferrite in pearlite, and with ranges of fine dispersion of iron carbide in a strained ferrite matrix in the weld and in the HAZ (Abioye, 2017). The weld microstructure is controlled mainly by the cooling cycle. At lower energy input (i.e. with low level of current) the time for solidification is less. This rapid cooling promotes smaller grains that leads austenite to transform into martensite and form fine grain microstructure and as compared with higher energy input, the time required for solidification decreases and therefore cooling rate slows down which makes austenite to have enough time to transform to pearlite and yields coarse grain microstructure (Mohammed et al., 2013). This coarse grain in the microstructure indicates lower hardness, tensile and impact strength. This is in agreement with Abioye (2017) who observed that this cooling rate which is a function of the heat input utilized determined the proportion of ferrite and pearlite formation in the microstructure of the weldments and that these in turn, influences the tensile, impact and hardness behavior of weldments. Conclusively, it can be stated low heat input produces fine microstructure and in turn improves the mechanical properties of the welded samples. However, increasing the heat input values causes' expansion towards the microstructure's grain sizes; which becomes coarse and decreases the mechanical properties which led to the loss of ductility at the welded joint, and resulted in brittleness of the material (Dodo *et al.*, 2016).

The fracture surfaces of the welded medium carbon steel specimen are illustrated clearly in Plates 5- 8, for the structures of as-received and as welded samples. The fracture surfaces were evaluated by SEM. Plate 5. shows a scanning electron micrograph of the control specimen showing dimples of varying sizes and shapes observed in the fractured surface. It is observed that fractured surface of the control specimen contains a large population of small and shallow dimples which indicative of its relatively high tensile strength and ductility as is observed by (Wan *et al*, 2015). As seen in Plate 6. The scanning electron micrograph of low heat inputs specimen appearing ductile under static loading and shows dull, fibrous and irregular appearance structure produced by stretching of crystals given a number of tear ridges and dimples. It also shows a classic mechanism of ductile fracture known as microvoid coalescence. The rough fracture surface indicates that a large amount of energy was absorbed during fracture according to (Mohammed *et al.*, 2013). Plate 7 shows the scanning electron micrograph of medium heat inputs specimen of mixed ductile/brittle fracture surface showing microvoids coalescence with some tear ridges and river pattern markings visible, which points to the origin of failure observed by (Wan *et al.*, 2015). Plate 8 shows fully brittle crystalline fracture broken with high heat input, trans-granular form of fracture of quasi-cleavage along the crystal planes, inter-granular structure occurring along the grain boundaries and a river pattern of branching cracks. This indicates brittle fracture and that failure occurred with lower plastic deformation as compared with the control sample and lower heat inputs according to (Mohammed *et al.*, 2013).

4. CONCLUSION

The analysis of microstructures of the welded specimens confirmed the heat input directly affected the mechanical properties and microstructure of the weldment. In general, the higher the heat inputs, the slower the cooling rate which resulted in coarse grains in both HAZ and weld metal while the lower the heat input, the fast the cooling rate which resulted in fine microstructure. Finally, the scanning electron micrograph showed dimples of various sizes and shapes observed in the control sample which is an indicative of its relatively high tensile strength and good ductility. That of low heat input showed dull, fibrous and irregular appearance structure produced by stretching of crystals given a number of tear ridges and dimples, an indicative of ductile fracture called microvoid coalescence. The medium heat input showed a mixed ductile/brittle fracture surface of microvoid with some tear ridges and river pattern markings which points to the origin of failure. The high heat input showed trans-granular form of fracture of quasi-cleavages along the crystal planes, inter-granular structures occurring along the grain boundaries and a river patter of branching cracks which is an indicative of brittle failure that occurred with lower plastic deformation as compared with the control sample and lower heat inputs.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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