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Effects of Electric Power Arc Inputs on the Fracture Surface and the Mechanical Properties 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 fracture surface and mechanical properties of 0.4%C steel was analyzed. The power inputs were controlled by varied welding current, arc voltage of 40 volts, welding speed of 3.2mm/sec and electrode gauge of 3.2mm. The currents were varied at 100A for low heat input, 112.5A for medium heat input and 125A for high heat input. Mechanical and fracture analyses were carried out on the specimens to determine their mechanical properties and fracture configurations. The results showed that increasing the welding current from 100A-125A caused a corresponding decrease in mechanical properties and an increase in brittleness of the specimens. On the mechanical properties, the results showed that the selected welding parameters had significant influence on the mechanical properties, the results indicated that the joints made by using low heat input exhibited higher tensile strength (515.90 Mpa) and from scanning electron microscopy (SEM) of tensile test fractured surface exhibited ductile failure, higher hardness strength (179.5 HRC) and impact toughness value of (6.5 Joules) than those welded with medium and high heat inputs respectively which exhibited brittle failure as the heat inputs increases. 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 process provided suitable welding procedures and precautions are adopted or followed. The high carbon content of these steels, along with manganese greater than 1% makes these steels hardenable and weldable, thereby changing phases on cooling to form hard microstructure, for this reason, they are commonly used in the quenched and tempered condition for such applications or production of machine parts such as: bolts, crankshaft, gears, axles, rail road rails, spanner, hammer heads and heavy duty forging [1]. During applications, these materials are subjected to welding, hence, the effect of welding process on the general mechanical properties of this steel needs to be known to ensure effective performance in service condition. As a result of great likelihood of martensite formation during welding and the higher hardness of the martensite formed, preheating is necessary. Procedures should be used to reduce the likelihood of hydrogen induce cracking by using low-hydrogen consumable or contaminants on the parent material. The high strength level of these steels may require the use of an alloy electrode to match with the base metal [2].

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 [3]. Welding processes is commonly used in joining sheet metals [4], 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. A welded joint is obtained when two clean surfaces are brought into contact with each other and either pressure or heat, or both are applied to obtain a bond. The tendency of atoms to bond is the fundamental basis of welding [4]. 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. 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, the process termed stress relieving (tempering) is applied; [5]. Also welding, more than any fabrication process exposes the part to rapid and extreme changes that can lead to cracks in the weldment [6]. Welding is more economical, convenient and less susceptible to failure or corrosion as compared to other joining processes. Owing to the advantages of welding over other joining process, numerous welding processes have been developed. As an industrial process, the cost of welding plays a crucial role in manufacturing decisions. Many different variables affect the total cost, including equipment cost, labor cost, material cost, and energy cost. Depending on the process, equipment cost can vary, from inexpensive for methods like shielded metal arc welding and oxy-fuel welding, to extremely expensive for methods like laser beam welding and electron beam welding. Because of their high cost, they are only used in high production operations. The cost of materials includes the cost of the base and filler material, and the cost of shielding gases. Finally, energy cost depends on arc time and welding power demand. For manual welding methods, labor costs generally make up the vast majority of the total cost. As a result, many cost-saving measures are focused on minimizing operation time. To do this, welding procedures with high deposition rates can be selected, and weld parameters can be fine-tuned to increase welding speed. Mechanization and automation are often implemented to reduce labor costs, but this frequently increases the cost of equipment and creates additional setup time. Material costs tend to increase when special properties are necessary, and energy costs normally do not amount to more than several percent of the total welding cost [4].

Mechanical properties of welded joints, the properties related to stress and strain are most often measured to show that such a weld and other similar welds will serve their purpose under loading conditions. Mechanical properties are such properties as strength, hardness and toughness, which not only influence the service life of a component but choice of manufacturing process for that component [7].

Materials are tested for the following reasons [8]:

i. To check chemical composition
ii. To determine suitability of a material for a particular application
iii. To determine data; that is, force deformation (or stress) values to draw up sets of specifications upon which the engineer base his design.
iv. To determine the surface or sub-surface defects in welded materials.

More rarely, several welds are compared to see which welding techniques, process, or chemistries provides the best combination of mechanical properties [2]. Mechanical testing is classified as destructive and non-destructive testing. In destructive testing, the component or specimen either breaks or remain no longer useful for further use and it includes tensile test, hardness test, fatigue test, creep test and impact test.

Tensile tests are carried out to determine the ultimate tensile strength, yield strength and ductility of materials. The test is carried out on a bar of uniform cross section, usually circular (but in some cases flat) in testing machine, which indicates the tensile load being applied. For the very small strain involved in the early part of the test, the elongation of measured length (called the gauge length) is recorded by extensometer [1]. The tensile testing machine is designed to elongate the specimen at a constant rate and to continuously and simultaneously measure the instantaneous applied load and resulting elongations. A stress-strain test typically takes several minutes to perform and is destructive, that is, the test specimen is permanently deformed and usually fractured [9].

Hardness represents the resistance of material to indentation and involves the measurement of plastic deformation caused when a loaded ball or diamond is applied to the surface of the material [1]. Hardness testing of weld provides an indication of two parameters, significant to the determination of successful weld joint and they are:

i. Strength
ii. Microstructure of a known material.

Welding can impose a variety of thermal cycle on steel at various location that produce:

i. Undesirable hard microstructure susceptible to cracking and brittle fracture
ii. Excessively soft microstructure susceptible to plastic collapse under load.

The factors that can influence the resultant hardness includes: pre-heat, weld heat input, cooling rate, total thickness at the weld, alloy content of the steel, alloy content of any flux and the original micro-structural condition of the steel. The hardness can therefore be a useful indicator to determine if the thermal cycle induced by welding has rendered the heat affected zone (HAZ) adjacent to the weld susceptible to cracking or plastic collapse.

Structure of steel consists of the macro and micro structure. The micro structure is the structure that is visible with the help of the enchant chemical which is being poured on the surface of the polished steel [10]. The visible macro-structure is the parent metal, the heat affected zone, the fusion zone [11]. The parent metal is the normal unaffected part of the metal whose structure was not altered. The heat affected zone (HAZ); which 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 study of weld metallurgy is very important because the overall mechanical properties of weldments are determined by the characteristic properties of individual microstructure present in the weld deposit and the weld heat affected zone. It has been long recognized that one of the major problems associated with welding fabrication arises from the inability to obtain uniform mechanical properties throughout the weldment. Both chemical inhomogeneity and changes in metallurgical structure result during welding operations because most fusion welding processes generates high rates of heating and cooling in the weld metal and parent metal adjacent. In the present study, effort have been made to analyze the mechanical and metallurgical properties of medium carbon steel using shielded metal arc welding process [4].

2. Methodology

2.1 Materials

The materials used for this research work is hot rolled ribbed medium carbon steel rod of 16mm diameter and 1m long and the chemical composition of the steel analysis is shown in Table 1. 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 and also angle grinding machine, wire brush, file, silicon carbide paper, motor driven polishing machine, enchant chemical, metallurgical microscope with in-built camera, scanning electron microscope.

2.2 **Method**

2.2.1 Sample Preparation

The 16mm ripped medium carbon steels rod was turned (using lathe machines) to 13mm 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 at 100A, dual welding current of 100A and 125A, and current of 125A respectively, welding voltage of 40V each, a welding speeds of 2.5mm/sec and electrode diameter of 3.2mm. The faces of two pieces of the beveled rods were placed 5mm 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 as shown in Plate 1-4. An alternating current supply is used in filling completely the V-Notch samples which maintains an arc gap of 3mm 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. 100A (low heat input), 112.5A (medium heat input), 125A (high heat input). The reasons for using these specific welding current values are two-fold:

i. Firstly; 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. Secondly; a step increase of 25A 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 the formula as stated in Equation 1.

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

The efficiency is dependent on the welding process used, with shielded metal arc welding having a value of 0.75≈ 0.8 (Mohammed et al, 2013).

Table 1. Welding process parameters

Heat Type	Voltage (V)	Current (A)	Electrode Gauges (mm)	Welding Speed (mm/sc)	Heat Input (kJ/mm)
Low heat	40	100	3.2	2.5	72
Medium heat	40	112.5	3.2	2.5	81
High heat	40	125	3.2	2.5	90

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

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, polishing, etching and microscopic viewing.

a. 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), and rub until all traces of saw cuts are removed. The specimens were turned through 90° and rubbed on the next (finer) paper (320 grit) until the previous scratches were removed. Next ground on (400 grit) and then on the final one (600 grit) each time turning through 90°.

b. 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.

c. Etching

The specimens were then etched with 5ml nitric acid (Nital) and 95ml 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. The acid is always added to the alcohol and not vice versa. The carbide will show darkened surface.

c. 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 snapped by the attached camera to obtain the micrograph. This was viewed at a magnification of X200 and X500. The results are presented in Plate 1- 8.

3. Results and Discussion

3.1 Result.

Table. 2. 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

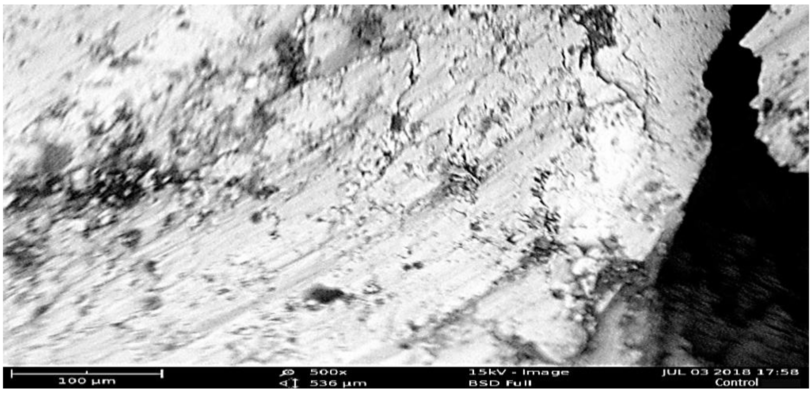

Plate 1. Fracture Surface of Control Specimen at 500X Magnification

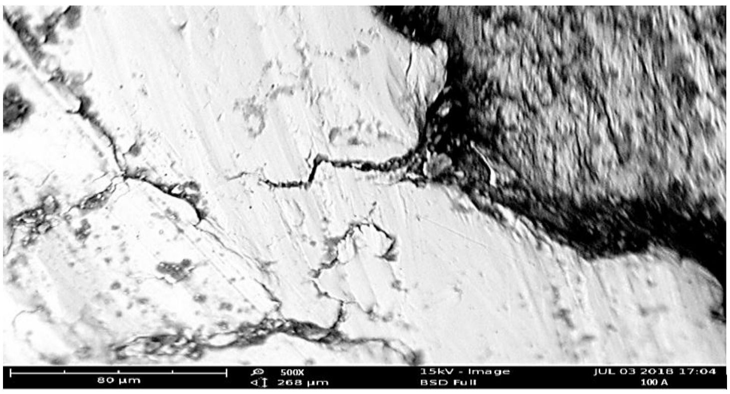

Plate 2. Fracture Surface of the Test Specimen of Low Heat Input at 500X Magnifications

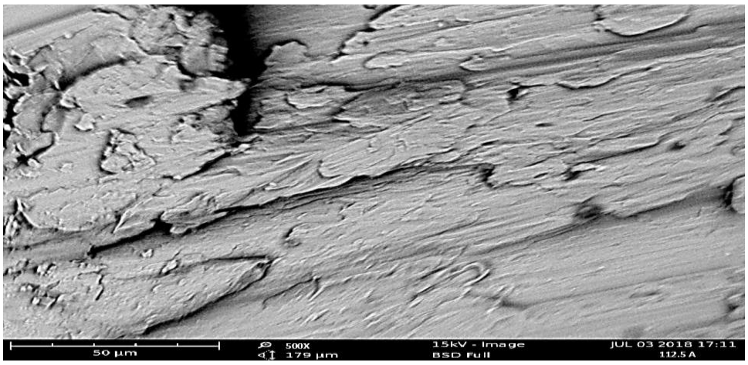

Plate 3. Fracture Surface of Test Specimen of Medium Heat Inputs at 500X Magnifications

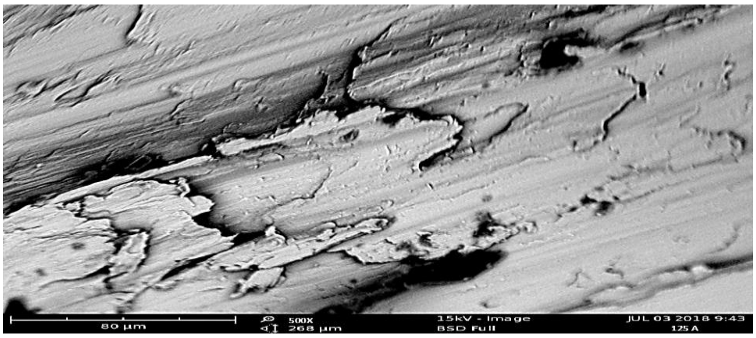

Plate 4. Fracture Surface of Test Specimen of High Heat Inputs at 500X Magnifications

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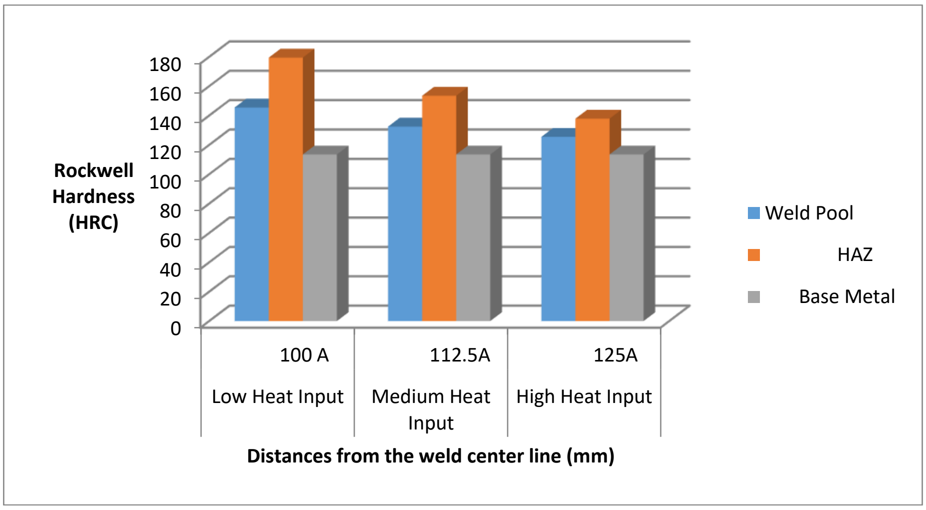

Figure 1. Micro-hardness results at different zones of the weldments with different heat inputs.

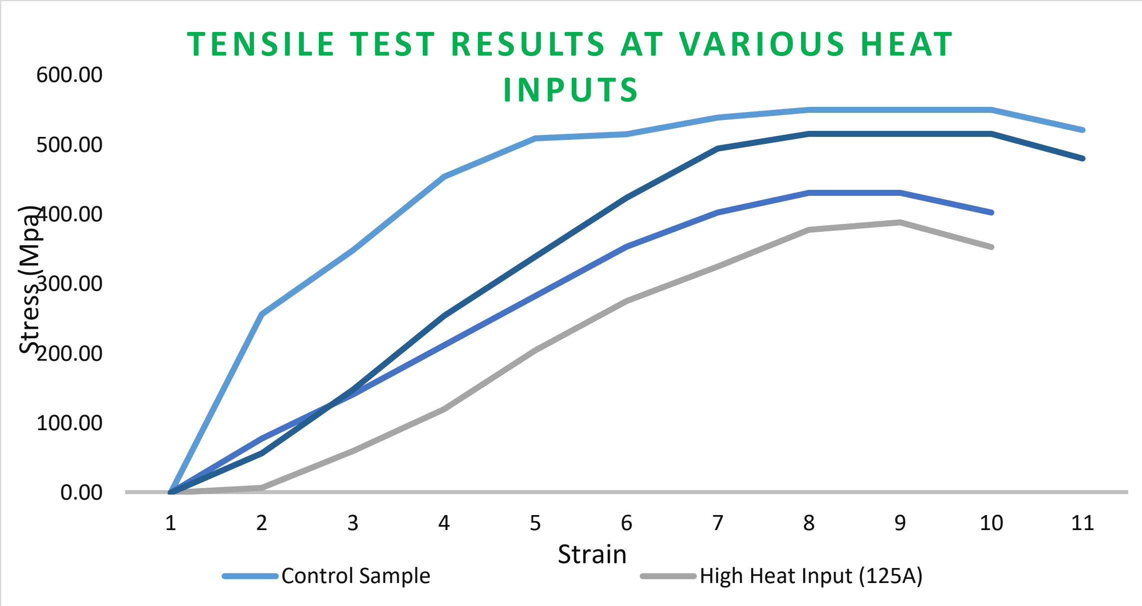

Figure 2. Tensile Test Results of the Samples

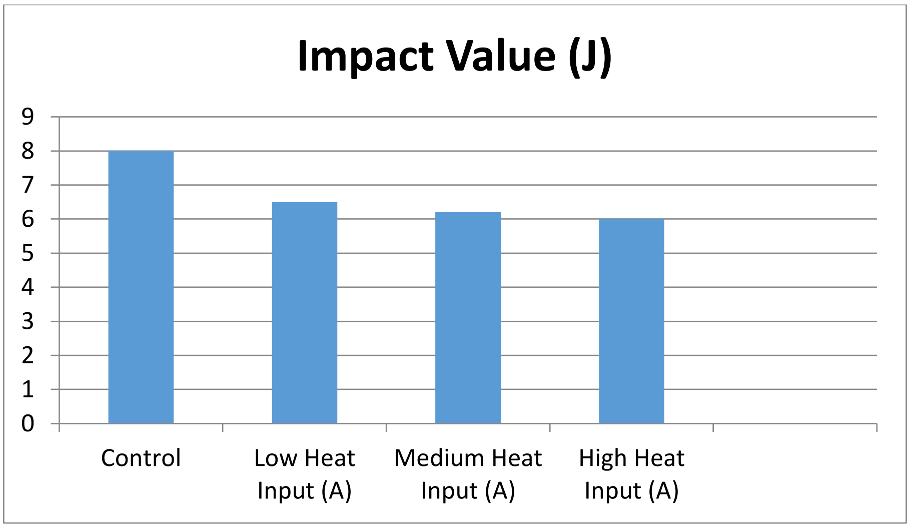

Figure 3. Impact Test Results at Different Heat Inputs

3.2 Discussion

The fracture surfaces of the welded medium carbon steel specimen are illustrated clearly in Plate 1-4, for the structures of as-received and as welded samples. The fracture surfaces were evaluated by SEM. Plate 1. show a scanning electron micrograph of 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 is an indication of its relatively high tensile strength and ductility as is observed by [10]. As seen in Plate 2. 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 [4]. Plate 3. show 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 [10].

Plate 4. Show fully brittle crystalline fracture broken with high heat input, trans-granular form of fracture of quasi-cleavage along the crystal planes , inter-granular structure occuring 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 [4].
In Figure 1 depicts the hardness profile for the test samples at different welding parameters. It can be seen that there is a hardness variation across the weldment. The variation is due to welding thermal cycle; the un-molten material reaches a maximum temperature, which depends on the distance from the fusion boundary and hence different microstructure are formed after cooling. The result is in agreement with the findings [10] which states that, variation across the weldment leads to property deterioration during service applications. From Figure 1, it is observed that as the indentor travels from the center of the weld/fusion zone towards the fusion boundary for different samples, the hardness properties decrease as the power inputs increases, this is supported by [7] who observed that increasing heat inputs results in decrease in hardness properties. The fusion zone has the hardness (145.5 HRC) at low heat input, decreases to (132.5 HRC) for medium heat input and (125.5 HRC) for high heat input. The heat affected zone has the highest hardness (179.5 HRC) for low heat inputs then decreases to (153.5 HRC) for medium heat inputs and (137.9 HRC) for high heat input. The base metal has approximately hardness value (113.5 HRC) across all the heat inputs. The area adjoining the base metal undergoes rapid cooling rate due to steeper thermal gradients and consequently has fine grained microstructure encountered in welding operation. This highest hardness is also attributed to the effectiveness of interstitial carbon atoms in hindering dislocation movement (as a solid-solution effect) and too relatively few slip systems along which dislocations moves as observed by [5]. This renders the weldment susceptible to cracking. With increased current, the heat generated increases causing the grains to recrystallized and grow in size. Increased in grain size, reduces the hardness value (strength) of the weldment and the heat affected zone as observed by [6] and shown in Figure 2. The heat persisted for a period of time and is gradually conducted away into the base metal as a result of low power density (the rate of energy flow (power) per unit volume, area or mass) of the welding process as reported by [9]. The amount of heat input from the heat source is given as stated in chapter of the literature review. This show that as the current increases more heat is produced into the weld causing expansion and contraction between the weldment and base metal. These increases the residual stresses in the weldment and heat affected zone which affects the engineering properties of the materials resulting in reduction of strength and hardness of weldment and the heat affected zone as shown Figure 1. This is in agreement with the findings of [13] who stated that the hardness strength of the weldment reduces with increase in heat input into the weld.

The transverse tensile strength of all the welded specimen made using different heat inputs conditions has been evaluated. In each condition, three specimens were tested and the tensile strength of the three specimens per unit heat inputs was obtained. The tensile results so obtained shows that maximum tensile strength of 179.5 Mpa is possessed by the specimen made using low heat input combination followed by 153.5 Mpa using medium heat input and 137.9 Mpa using high heat input combination. The tensile strength of the weldment was observed to be lower compared to as-received sample, this is as a result of thermal stresses stored in the weldment during the welding operation and it is in agreement with [13] who observed that the high tensile strength and good ductility is possessed by the joint at low heat input, which can be attributed to smaller dendrite sizes and lesser inter-dendritic spacing in the fusion zone. Relatively lower tensile strength and ductility is possessed by the joints with long dendrite sizes and large inter-dendritic spacing in the fusion zone of the joint welded using higher heat inputs. This is supported by [12] who noted that with increased current, the heat generated increased causing the grains to recrystallized and grow in size. Increase in grain size decreases the tensile strength whereas decrease in grain size increases the tensile strength. Figure 2 show that the tensile strengths of medium carbon steel used decreases with increase in welding parameters (welding current, voltage, and welding speed). It is shown that during low heat input condition, the grain size of the HAZ is small which varies when changes to higher heat input. During higher heat input, it was observed that carbide precipitates a lot along the grain boundaries leading to sensitized zone around grain boundaries which helps in grain coarsening of HAZ zone and significant grain coarsening was observed in the HAZ of all the joints and it was found that the extent of grain coarsening in the HAZ zone increased with increase in heat input. This is in agreement with [10] who observed that this behavior was attributed to the fact that increased current meant an increase in heat input which could create room for defect formation, thus the observed reduced mechanical properties and they also established that service failure of arc welded joints is due to cracking in the HAZ and also that, the performance of the welded structure is usually limited by failure initiation within the HAZ of the base material, particularly within the coarse-grain region of HAZ adjacent to the weld metal as a result of increase in heat input.

The ability of a material to withstand an applied load is referred to as toughness. The transverse impact strength of all the welded specimen made using different heat inputs conditions has been evaluated. In these conditions, three specimens with control specimen were tested and the impact strength of the three specimens with the control specimen per unit heat inputs was obtained. It was observed that the impact toughness values are proportionally decreasing when heat inputs increase. This is in agreement with [4] who observed that this attribute is as a result of fine ferrite and pearlite matrixes distributions in low heat input when compared with coarse ferrite and pearlite matrixes distributions as heat input increases. From Figure 3, it was observed that the control specimen has the maximum impact toughness value of 8 Joules (J), followed by the low heat input with impact toughness value of 6.5 Joules (J). At medium heat input and high heat input, the impact toughness values are 6.2Joules (J) and 6Joules (J) respectively. Therefore, low heat input has the best impact strength of 6.5 Joules (J) while the high heat input has the lowest impact strength of 6 Joules (J). These results showed that the increase in heat input coarsens the grain structure both in the weld metal and heat affected zone and is in agreement with [12] who noted that the notch toughness of the coarse grained HAZ decreases with an increase in energy input. They also found that stress relieving reduced the notch toughness of both the weld metal and HAZ as a result of embrittlement caused by carbide precipitation.

4. Conclusion

The scanning electron micrograph showed dimples of various sizes and shapes observed in the control sample which is an indication 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. Then, 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. On the mechanical properties, the results showed that the selected welding parameters had significant influence on the mechanical properties, the results indicated that the joints made by using low heat input exhibited higher tensile strength (515.90 Mpa) and from scanning electron microscopy (SEM) of tensile test fractured surface exhibited ductile failure, higher hardness strength (179.5 HRC) and impact toughness value of (6.5 Joules) than those welded with medium and high heat inputs respectively which exhibited brittle failure as the heat inputs increases.

Nomenclature

Q Heat input (kJ/mm)
V Voltage (v)
I Current (A)
S Welding speed (mm/min)

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