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Effect of Welding Consumables on the Mechanical Properties of Micro-Alloyed Steel Weldment

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Abstract:- The increasing demand for higher performance of steel weldment in stringent service applications has prompted careful selection of welding consumables and current, for the welding of metal. This paper therefore, investigated the effect of welding consumables on the mechanical properties of micro-alloyed steel weldment by employing shielded metal arc-welding process. Weld beads were deposited with E7016, E7018 and E7024 electrodes using preset current of 90, 94, 98, 102 and 106 ampere respectively. Thereafter, the welded specimens were machined to the required dimensions for hardness, impact and tensile strength tests. A standard metallographic technique was applied to examine the microstructure formed across the steel weldments. The results showed that for each electrode type, the hardness, yield strength, and tensile strength decreased with increasing welding current but the impact strength and percent elongation increased correspondingly. This trend is indicative of microstructural grain coarsening due to the increasing slow cooling rate associated with increasing heat input. Higher hardness values were observed in the weld areas than the heat affected zones and base metal. The results also revealed that excellent hardness and longitudinal tensile properties were obtained from welds made with E7016 electrode. Whereas superior impact strength and percent elongation was obtained in welds made with E7024 electrode. The quality index values indicated that weldment of excellent combination of tensile strength and percent elongation can be obtained using E7018 electrode at the welding current setting of 94 ampere.

Keywords:- *Micro-Alloyed Steel, Current, Electrode, Microstructure, Mechanical Properties.*

I. INTRODUCTION

Welding is an important fabrication process that is widely used in industry to join metals by the application of heat and/or pressure, with the use of filler wire or covered electrode. There is hardly any engineering structure that does not have a welded component. Therefore, to ensure the safe performance of welded components in service, deliberate effort must be taken in selecting the proper welding consumables, as well as the correct welding parameter (current) that will be used to produce welds with satisfactory combination of properties suitable for specific applications. This is very necessary in prolonging the service life of engineering structure. Reports available in the public domain indicates that the premature failure of some welded components in service emanated from inappropriate choice of welding consumables and welding current (Thomas *et al.*, 2016 and, Yusof and Jamaluddin, 2014). The issues related to inappropriate choice of welding consumables and welding current are formation of undesirable metallurgical microstructures and welds that contain defects like porosity and slag inclusions, etc., which do impair the mechanical behaviour of the welded component in service.

The term welding consumables refers to the covered electrodes or filler wires employed by welders to establish a complete joint. The selection of the most appropriate welding consumable is of prime importance to achieving quality most suitable in terms of fitness for service and cost. The selection usually involves study of metallurgy of the base metal and service conditions (Raj *et al.*, 2012). There are different types of electrode with varying alloying contents available commercially in the market for use by welders. However, the challenge frequently encountered by most welders is selecting the electrode with the right alloying contents that will produce welds with the desired metallurgical microstructures to provide optimal combination of mechanical properties suitable for stringent service applications.

Micro-alloyed steels also known as high strength low alloy steels are increasingly receiving greater attention for structural applications. The continuing increase in its demand are as a result of the enhanced mechanical properties and greater resistance to atmospheric corrosion which it offers when compared to the conventional carbon steels (AZO materials, 2019). Micro- alloyed steels are widely used in the fabrication of structures where load bearing and weight saving are critical. The areas where these considerations are of prime importance are the construction of critical infrastructure such as, oil and gas pipeline, bridges, heavy-duty high ways and off-road vehicles, farm machinery, storage tanks and lawn mowers, etc. (American Society for Materials, 2001). Micro-alloyed steels can be welded by all conventional welding processes due to their low carbon equivalent values. Adopting the appropriate welding procedures will produce welds with mechanical properties meeting the same requirements for strength, toughness and ductility as the parent material and at the same time free from defects. Therefore, with the increasing application of micro-alloyed steel for structural applications coupled with the demand for materials with improved properties that will meet the service requirement of critical infrastructure. Attempt is made to study the effect of welding consumables on the mechanical properties of micro-alloyed steel weldment. The objective of the research is to determine the electrode wire with alloying contents and also the correct welding current setting that will be used to produce welds with enhanced mechanical properties suitable for structural applications.

Researches available in the public domain on the area of weldment show that extensive work on the factors affecting steel weldment properties using different welding processes have been investigated. However, not much has been done on the effect of welding consumables, using wider range of welding current settings on the mechanical characteristics of micro-alloyed steel weldment. Okonji, *et al.,* (2015) in their study established that excellent tensile property can be obtained in stainless joint with filler wire that contain high carbon and chromium contents.They study also showed that uniform distribution of fine grains in the microstructure formed resulted to higher tensile strength in the welded joints. Study carried out by Kaiser and Shorowordi (2014) showed that heat inputs are the main welding parameter responsible for the structural changes that occurred in steel weldment which led to variation in the mechanical properties across the steel weldment. They also revealed that the welding current setting of 150 ampere produced excellent yield and tensile strength values. Ekici and Ozsarac (2013) in their study established that weld joint produced with gas metal active welding process using ER100SG filler wire with a gas protection composition of 15% CO_2 + 85% Ar produced welded joint with the excellent hardness and ductility properties compared to the welded joints produced with electric arc-welding process. Study carried out by Ghassemy *et al.,* (2013) revealed that excellent tensile strength and ductility can be achieved in weld metal when the composition of manganese and molybdenum is 1 and 0.4 % respectively. The study also showed that acicular and grain boundary ferrite significantly improved tensile strength and ductility. Study carried out by Okediran *et al.,* (2013) revealed that maximum different mechanical properties cannot be obtained using one electrode for welding. They also showed that maximum tensile strength and impact strength of 508.25N/mm^2 and 152.76J was obtained using Oerikon and Powder Master electrodes for Homus steel respectively. Also, the maximum tensile strength of 482.96N/mm^2 and impact energy of 137.033J was obtained with Powder Master electrode for Universal steel. Adedayo *et al.;* (2011) in their study revealed that the overlapping heat inputs from multi runs weld resulted to welds with excellent toughness and correspondingly lower hardness values. In the study carried out by Boumerzoug *et al.,* (2010) they established that hardnesss of weld metal and heat affected zones can be significantly affected by residual stresses, microstructural grain sizes, phase composition and metallic inclusion in the welds. Pouranvari, (2010) revealed in his study that welding of grey cast iron with nickel based filler wire and applying post weld heat treatment will minimize the cast iron weldability problems. Nnuka *et al.*; (2008) reported that maximum tensile strength can obtained when low carbon and medium carbon steels are welded with stainless steel electrode. They also revealed that excellent hardness and impact strength properties can be obtained in medium carbon steel when gauge 12 electrode use.

Therefore, the present study is aimed at investigating the effect of welding consumables on the mechanical properties of micro-alloyed steel weldment with the view of establishing the electrode with the alloying contents and welding current (WC) that will produce the desired weld metal microstructures and mechanical properties suitable for structural applications. Major focus is placed on the microstructure, tensile strength (TS), impact strength (IS), yield strength (YS), hardness (BHN) and percent elongation (% E) of the steel weldment and parent metal because of the significance of these on service behaviour.

II. EXPERIMENTAL

A. Materials Preparation

Materials utilized for this experimental study are micro-alloyed steel plate of 5mm thickness and E7016, E7018 and E7024 electrodes. The commercial grade of the micro-alloyed steel was supplied by Donasula Brother's Limited Warri, Delta State, while the electrodes (E7016, E7018 and E7024) were obtained from welding materials and allied products section, Bridge Head Market, Onitsha, Anambra State. The chemical constituents of the electrodes (E7016, E7018 and E7024) core wires and the micro-alloyed steel were analyzed using EDX3600B energy dispersive x-ray fluorescence spectrometer and the results presented in Table 1 and 2 respectively.

Elements	**Concentration (wt%)**			
	Base metal			E7016
		E7018	E7024	
C	0.15	0.12	0.07	0.05
Si	0.40	0.75	0.61	0.35
P	0.05	0.03	0.015	0.02
S	0.03	0.034	0.011	0.014
Ti	0.01	–	-	–
Cr	0.08	0.06	0.03	0.03
Mn	0.35	0.45	0.4	0.35
Mo	0.05	0.30	0.02	0.01
V	0.12	0.01	0.06	0.01
Nb	0.03	–	-	–
Ni	1.1	0.04	0.02	0.02
Cu	0.16	-	-	–
Fe	9.03	98.21	98.76	99.18

Table 2:- Elemental Composition of Test Materials

B. Welding Operation

Prior to the welding process, the open circuit voltage (60 V) of the welding unit (Model: Safex M340), the arc voltage (29 V), and the electrode travel speed (2.4 mm/s) were measured using a digital multimeter and stop watch. These parameters were used to compute the heat input for the different welding current using equation 1 (IPRM, 2007). Sixty (60) samples of the micro-alloyed steel plate of dimensions 300 mm x 60 mm x 5mm were prepared. Using bead-on-plate welding technique, weld beads were deposited longitudinally on a straight line marked with chalk at the center of each plate using E7016, E7018 and E7024 electrodes, with a preset welding current of 90, 94, 98, 102 and 106 amperes respectively. After the welding process, the samples were cut out from the weld metal region (WM), heat affected zone (HAZ) and base metal (BM) and machined to sizes for the hardness, impact and tensile strength tests. The hardness, impact and tensile strength values were taken from three samples each and averaged.

The hardness measurement was done using a Brinell hardness testing machine (Model: 900-355) at a loading force of 7355N and dwelling time of 5 seconds. Two indentations were obtained in each sample and the average taken. The indentation diameters were measured using a micrometer with an in-built microscope of magnification x20. The impact strength of the samples was conducted in accordance to ASTM E23 using Charpy impact testing machine (Model: JB-300b/500B). The yield strength and the tensile strength of the samples were measured using a universal tensile testing machine (Model: T42B2) of 500 kN maximum capacity.

Welding current (Ampere)	Heat input (kJ/mm)
90	0.87
94	0.91
98	0.95
102	0.99
106	1.02

Table 2:- Calculated Heat Input Per Unit Length for the Different Current Used

$$\text{Heat input} = \frac{\text{Welding current x arc voltage x K}}{\textit{Welding current x } 1000} \quad (1)$$

Where,
K= thermal efficiency of the welding unit
K= 0.8, for SMAW

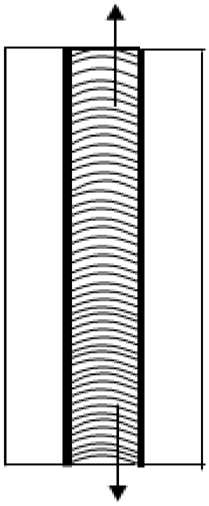


Fig 1:- Tensile Test Specimen, Showing the Direction of Loading

III. RESULTS AND DISCUSSION

A. *Microstructural Analysis*

Fig. 2 shows the optical micrograph of the base metal (BM). The micrograph reveals white patches of fine grains of ferrite with dark spots indicating scattered carbide precipitates and small patches of pearlite. The characteristic features of these microstructure account for the relatively high values of hardness, yield strength, and tensile strength with corresponding low impact strength and percent elongation. Fig. 3 shows (a) WM and (b) HAZ of E7016 electrode as-welded specimen at welding current of 94 ampere. The microstructure of WM consists of finely dispersed carbide precipitates (dark patches), small patches of pearlite in ferrite microstructure. HAZ shows coarse distribution of ferrite and carbide precipitates. This explains the high hardness value obtained at the WM and low hardness at the HAZ, and improved yield strength, tensile strength, impact strength and percent elongation. Figure 4 shows (a) WM and (b) HAZ, of E7018 electrode as-welded specimen at the welding current of 94 ampere. The microstructure consists of fine distribution of Widmanstatten ferrite and carbide precipitates at the WM and coarse distribution of ferrite and carbide precipitates. The characteristic features of these microstructures account for the relatively improved mechanical properties of the weldment. Figure 5 shows (a) WM and (b) HAZ of E7024 electrode as-welded specimen at the welding current of 90 ampere. The microstructure reveals coarse distribution of carbide precipitates in ferrite matrix at the WM and coarser ferrite grains, pearlite and some carbides phase at the HAZ. This is responsible for the relatively lower hardness value recorded at the HAZ. The characteristic features of these microstructure account for the relatively lower values of hardness at the WM and HAZ regions, yield strength, tensile strength, but higher impact strength and percent elongation of the weldment.

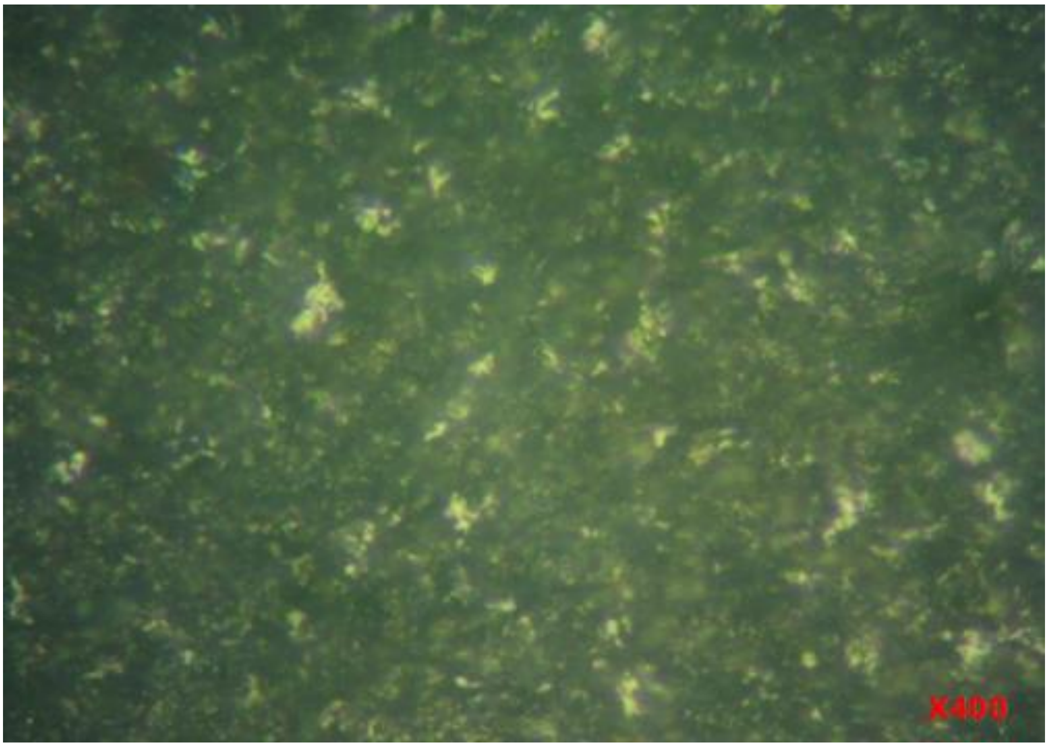


Fig 2:- Micrograph of Base Metal (BM) As-Received

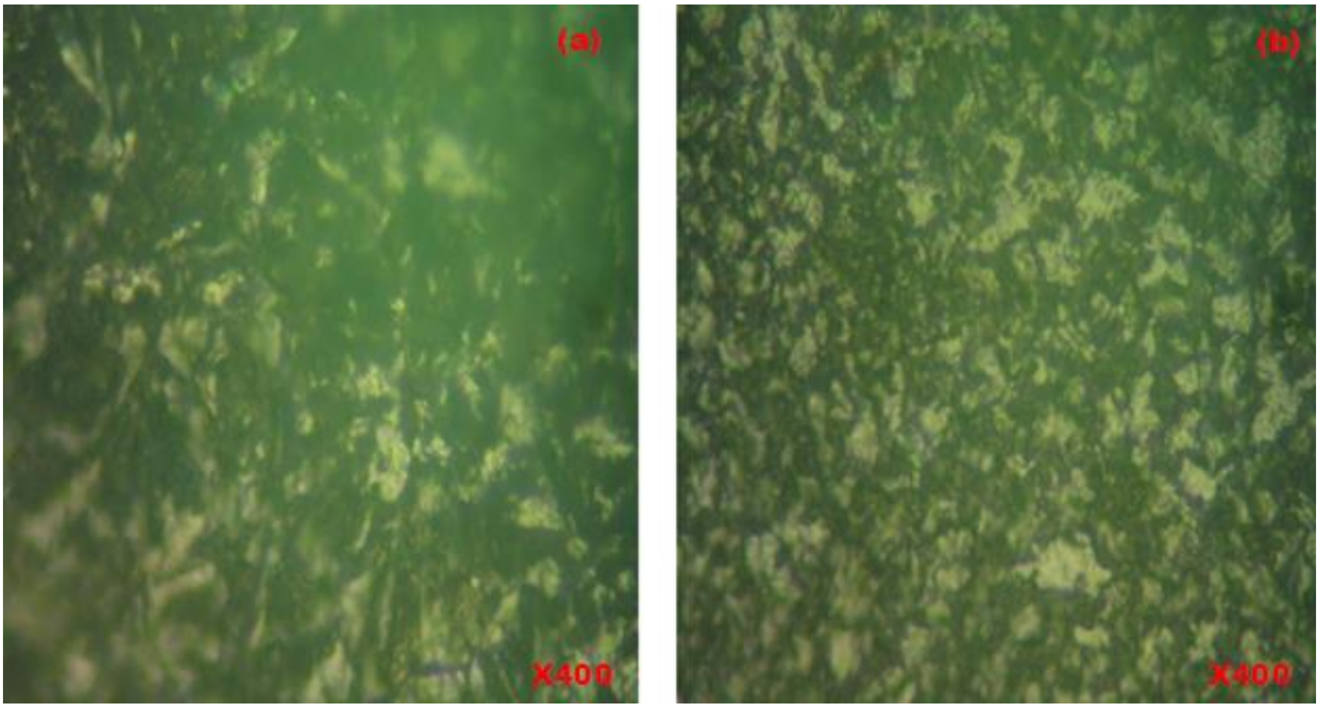


Fig 3:- Micrograph of (a) WM and (b) HAZ of the Specimen As-Welded with E7016 Electrode at 94 Ampere.

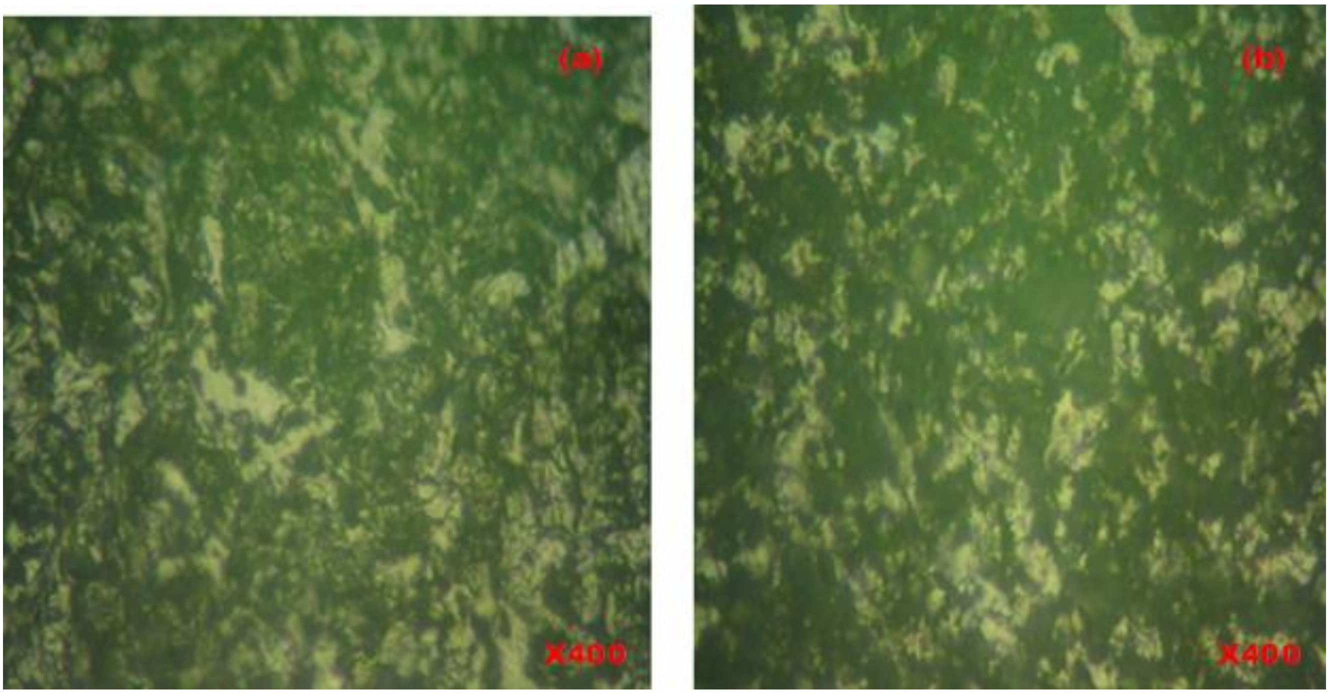


Fig 4:- Micrograph of (a) WM and (b) HAZ of the Specimen as-welded with E7018 Electrode at 94 Ampere.

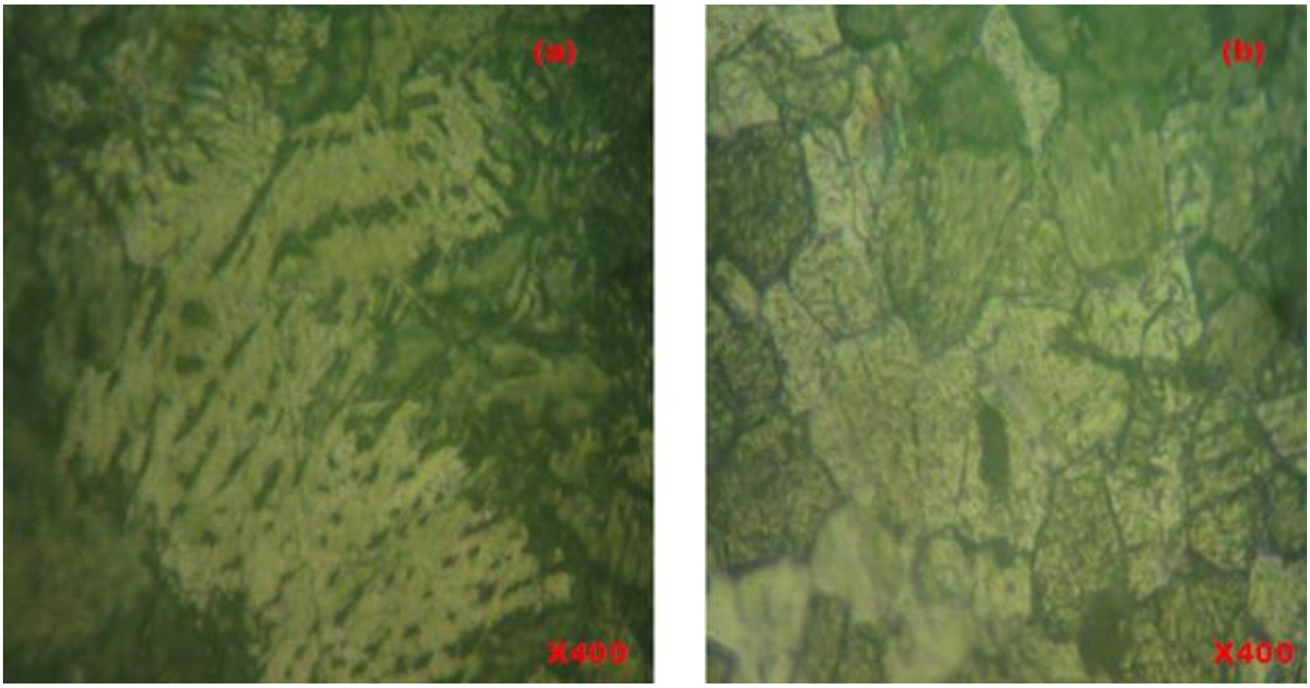
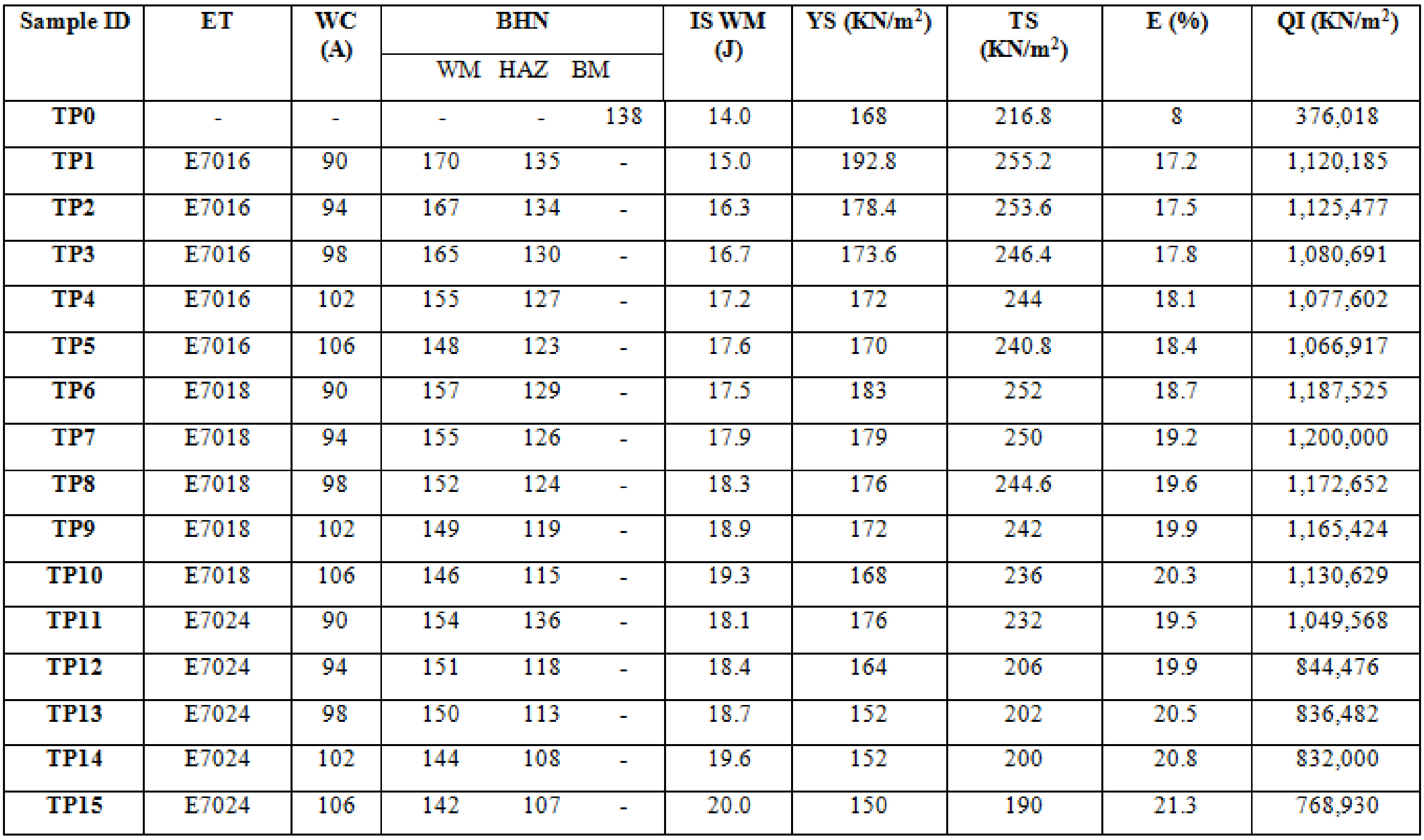


Fig 5:- Micrograph of (a) WM and (b) HAZ of the Specimen as-Welded with E7024 Electrode at 90 Ampere.

B. *Mechanical Properties*

Table 3 shows the mechanical properties of the specimens in the as-welded condition (not subjected to any heat treatment). It indicates variation in mechanical properties as welding current was increased with each of the electrode types used. The results clearly show hardness of the WM and HAZ, yield strength and tensile strength markedly decreasing, and impact strength and percentage elongation progressively increasing with increased in welding current for the different electrode type. Higher hardness values were observed in the WM than the HAZ and the BM. The gradual decrease in the hardness values observed at the WM despite the increasing dilution of the alloying elements in the WM as a result of increasing heat input associated with current increase could be attributed to the coarsening of the ferritic grains arising from slow cooling rate linked to high welding current. This observation is in agreement with Kah *et al.,* (2014). Kou (2003) and Pournavari (2010) who posited that increase in welding current will raise heat input which slows cooling rate of weldment and encourages coarse grains in the final microstructure. The higher hardness values obtained at the WM could be attributed to (i) the synergetic interaction of the chemical elements present in varying composition in the base metal and the electrode core wires (Table 1), which probably served as recrystallization centres in the local melt thereby creating the required nuclei for the near instantaneous solidification with the attendant fine grained microstructure formed resulting in the higher hardness (*Nnuka et al.,* 2008) and (ii) the cooling rate may have also impacted on the hardness in the WM. Fast cooling rate associated with low heat input has been reported to form fine grained microstructure with better mechanical properties. The variation in hardness in the HAZ is as a result of the various forms of thermal cycles induced by the heat input from the welding current which gave rise to the different cooling rates with its attendant effect on the final microstructure formed. These results are consistent with reports (Raghavan, 1989 and Raj *et al.*, 2012). The E7016 electrode produced weldment with higher hardness, yield strength, tensile strength values but relatively lower impact strength and percentage elongation values compared to E7018 and E7024 electrodes. The lowest values of hardness, yield strength, tensile strength but highest impact strength and percent elongation were obtained from weldment established with E7024 electrode. The variation in the mechanical properties observed for the welds made with different electrode types could be attributed to the precipitation strengthening caused by the presence of the carbide forming elements whose strengthening effect depends on their concentration. The highest amount of Mn, V and Cr content were observed in E7016 followed by E7018 and 7024 electrode core wire respectively. However, the general decreasing trend observed in the hardness, yield strength, tensile strength but increasing impact strength and percent elongation with increase in welding current could be linked to coarsening of the microstructure grain due to slow cooling rate. This view is also supported by Kaiser and Shorowordi (2014) where they observed in their study that the coarsening of microstructure grain due to increasing welding current resulted to higher toughness in the HAZ. The quality index values calculated using equation 2 (Siefer and Orths, 1970) show that the optimal combination of tensile strength and percentage elongation was obtained from the welds made with the E7018 electrode followed by E7016 and E7024 electrode respectively. The values of the tensile strength and percentage elongation that produced the maximum values of the quality index for the different electrode type are 250KN/m^2 and 19.2% for E7018 electrode at the welding current of 94 ampere, 256.6KN/m^2 and 17.5% for E7016 at the welding current of 94 ampere, and 232KN/m^2 and 19.5% for E7024 electrode at the welding current of 90 ampere. A larger value of quality index implies higher weldment performance in service.



Sample ID	ET	WC (A)	BHN			IS WM (J)	YS (KN/m^2)	TS (KN/m^2)	E (%)	QI (KN/m^2)
			WM	HAZ	BM					
TP0	-	-	-	-	138	14.0	168	216.8	8	376,018
TP1	E7016	90	170	135	-	15.0	192.8	255.2	17.2	1,120,185
TP2	E7016	94	167	134	-	16.3	178.4	253.6	17.5	1,125,477
TP3	E7016	98	165	130	-	16.7	173.6	246.4	17.8	1,080,691
TP4	E7016	102	155	127	-	17.2	172	244	18.1	1,077,602
TP5	E7016	106	148	123	-	17.6	170	240.8	18.4	1,066,917
TP6	E7018	90	157	129	-	17.5	183	252	18.7	1,187,525
TP7	E7018	94	155	126	-	17.9	179	250	19.2	1,200,000
TP8	E7018	98	152	124	-	18.3	176	244.6	19.6	1,172,652
TP9	E7018	102	149	119	-	18.9	172	242	19.9	1,165,424
TP10	E7018	106	146	115	-	19.3	168	236	20.3	1,130,629
TP11	E7024	90	154	136	-	18.1	176	232	19.5	1,049,568
TP12	E7024	94	151	118	-	18.4	164	206	19.9	844,476
TP13	E7024	98	150	113	-	18.7	152	202	20.5	836,482
TP14	E7024	102	144	108	-	19.6	152	200	20.8	832,000
TP15	E7024	106	142	107	-	20.0	150	190	21.3	768,930

Table 3:- Mechanical Properties of the Base Metal and the Welded Samples

$$QI = (\text{tensile strength})^2 \times (\text{percent elongation } \%) \quad (2)$$

Where,
QI = quality index

IV. CONCLUSIONS

A detailed study of the effect of welding consumables on the mechanical properies of micro-alloyed steel weldment has been conducted. The study established that the welding current had pronounced effects on the mechanical properties of the welded metals. The hardness, yield strength and tensile strength decreased with increasing welding current while the impact strength and percent elongation increased correspondingly with increasing welding current. The WM region showed higher hardness compared to the HAZ and BM in proportion that depends on the alloying contents of the different electrode types. The thermal and cooling cycles induced at the HAZ by the welding current caused microstructural changes which enhanced the mechanical properties of the welded zone. The weldments from E7016 electrode gave higher mechanical properties with exception of impact strength and percent elongation compared to the two other electrodes. The weldment made with E7024 electrode gave superior impact strength and percent elongation. The weldment made with E7018 electrode at the welding current setting of 94 ampere produced optimal combination of tensile strength percent elongation suitable for structural applications.

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