JEAS

JOURNAL OF ENGINEERING AND APPLIED SCIENCES

Journal of Engineering and Applied Sciences, Volume 15, Number 1, December 2019, 143 - 150

Effect of Process Parameters on the Microstructure and Mechanical Properties of Micro-alloyed Steel Weldment

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Abstract
The detrimental effect of heat input from welding current on the integrity of welded structure in severe service applications has prompted the application of post weld heat treatment with the aim of relaxing residual stress and improving weld metal resistance to brittle fracture in service. In view of this, the effect of process parameters on the microstructure and mechanical properties of micro-alloyed steel weldment has been investigated. The welds were produced using shielded metal-arc welding unit with E7016 electrode at the preset welding current settings of 90, 94, 98, 102 and 106 ampere respectively. After the welding process, a total of 40 as-welded samples were inserted in turn into the heating chamber of a muffle furnace and tempered at 450^{0}C for 60, 90 and 120 minutes respectively. The mechanical properties (hardness, impact and tensile strength) of the un-tempered and tempered samples were evaluated using Brinell hardness testing machine, Charpy impact testing machine and Universal tensile testing machine. The microstructures of the investigated samples were analyzed with optical microscope. The results showed that the tempered as-welded samples exhibited marginal decrease in hardness, yield and tensile strength with increase in soaking duration but impact strength and percent elongation increased. This could be attributed to continuous growth of the microstructural grains due to increasing soaking duration. Higher impact strength and percent elongation values were obtained in the tempered samples as compared to the un-tempered samples. This indicates the tendency of the tempered as-welded samples to resist brittle fracture in service. It was also observed that 60 minutes of soaking gave maximum hardness and longitudinal tensile properties. The computed quality index values indicate that welds produced with the current setting of 106 ampere, tempered at 450^{0}C for 60 minutes gave excellent combination of longitudinal tensile strength and percent elongation suitable for structural applications.

Keywords: micro-alloyed steel, current, soaking duration, microstructure, mechanical properties

1. Introduction
Heat treatment practice is widely embraced as an important industrial process that gives engineers the ability to tailor the mechanical properties of materials to suit a variety of different applications. There are different heat treatment processes so the choice of any among other factors depend on the prior thermal history of the material; mechanical work that the material may have been subjected to as well as the intended service requirements. Heat treatment may be carried out for a number of reasons; among which is to relieve thermal residual stresses induced in materials as a result of cold working, welding, grinding operations; and it may also be as a result of impacting ductility at the expense of hardness and strength. Adedayo*et al.* (2011) reported that due to the varied peak temperature reached across the different zones of steel weldment during welding, the mechanical properties of steel weldment are affected negatively with detrimental threat to its performance in service.

Therefore, to tackle the issues related to the effect of peak temperature arising from heat input of welding current, Hornsey (2006) and Trudel*et al.* (2013) suggested the use of post weld heat treatment techniques capable of relieving residual stresses and imparting the required microstructure with the desired mechanical properties that will meet service requirements.

Micro- alloyed steels are widely used in the fabrication of structures where load bearing and weight saving are critical for example in oil and gas pipeline, bridges, heavy-duty high ways and off-road vehicles, farm machinery, storage tanks, lawn mowers, etc. (American Society for Materials 2001; Hakansson 2002; Malock*et al.* 2005; Maciej and Danta, 2015; Uranga 2019). Micro-alloyed steels can be welded by all conventional welding processes due to their low carbon equivalent values. Adopting the appropriate welding procedures results in 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.

However, in fusion welding where welded joints are accomplished through the melting of the surface of the metals to be joined by heat from the welding current, the variation in the heat input across the different zones of the steel weldment results to uneven cooling causing restraint in expansion and contraction. This restraint leads to the development of welding residual stresses which vary in magnitude across the different zones of the steel weldment depending on the peak temperature attained. Hornsey (2006) reported that welding residual stresses can reduce the structural behaviour of welded component, thus, causing premature failure of the component in service. The welding of micro-alloyed steel is however, not without its complications. The tremendous change in the microstructure of the weld zones with the attendant effect on the entire structure and mechanical behaviour of the fabricated component and also the negative effect of residual stresses introduced into the steel weldment due to the non-uniform heating and cooling of the welded metal result to cracks and distortions in the HAZ and weld metal significantly impair their performance in service. Therefore, to retain the excellent strength to weight ratio of micro-alloyed steel for continued application in service, the negative effect of residual stresses introduced in them during welding must be given serious attention. Several seasoned researchers have advocated different techniques that can be applied to tackle the danger associated with residual stresses in steel weldment (Ahmed and Krishnan 2003; Jun Yi and Jun Lee 2017). However, the most notable technique is the application of post weld heat treatment (PWHT). According to Entrekin (1983) PWHT process is one of the most common means through which the properties of many weldments can be improved.

Several reports available in the public domain have also supported this claim (Abdelmaoula, *et al.* 2015). PWHT process is therefore one of the most effective and efficient means widely utilized in the fabrication industries to improve the deteriorated properties of welded structures and to reduce the likelihood of brittle fracture in the HAZ and the weld areas before the welded components are applied in stringent service conditions. Entrekin (1983) also, stated that the most common form of PWHT usually consists of heating the weldment to an elevated temperature below the lower critical transformation temperature and holding it long enough to relax the residual stresses embedded in the weldment. However, one of the major challenges encountered by most heat treatment personnel in industries is selecting the most appropriate soaking duration that will result to excellent combination of mechanical properties for enhanced steel weldment performance in stringent service applications. It is in view of this that PWHT process is being adopted in this research work to help overcome the metallurgical problems encountered during the welding of micro-alloyed steels.

Several works on the effect of PWHT on the microstructure and mechanical properties of steel weldment are available in the public domain. However, most of the works are limited to the effect of PWHT temperature, with very few focusing on the influence of tempering soaking time on the properties of low carbon steel weldment. Abson*et al.* (2006) asserted that PWHT is applied to steel assemblies primarily to reduce the likelihood of brittle fracture by reducing the level of tensile welding residual stresses and by tempering hard, potentially brittle, microstructural regions. They stated also that some fabrication codes stipulate that the PWHT should be exempt in structures where the materials thickness is very low. Ghosh *et al.* (2004) revealed that PWHT coarsened the microstructure of weld and HAZ and significantly influenced the properties of welded joints. Milan *et al.* (1999) concluded that heat treatment of the welded joints improves tensile strength and ductility and changes the fracture mechanism from brittle to ductile.

The improved strength and ductility were attributed to the finer ferrite-pearlite microstructure. Olabi and Hashmi (1995) and Hashmi and Olabi (1993) concluded that post weld treatment improve toughness by 15%, without significant effect to the tensile strength and hardness but significantly reduces the residual stresses by 70%. Thomas *et al.* (1993) concluded that the as-welded specimens exhibited about 80% of the tensile ductility and about 90-95% of the impact/fracture toughness of the base metal. The low temperature stress relieving carried out subsequent to the welding operation improves the tensile properties but decreases the toughness at the fusion zone. Krishnan and Rao (1990) showed that the PWHTs and the heat input affected the shape of the ferrite network, and the network transformed to globules in some of the PWHT conditions. Burget and Blauel (1988) concluded that lower fracture toughness characteristic values were obtained at the heat affected zone. Salkin (1988) established that stress relief heat treatment produces a softening of the base metal and can also have an influence on brittle fracture resistance. He also posited that stress relief heat treatment has a negligible effect on the coarse grain structure and the residual stress heat treatment allows an increase of the endurance limit ranging from 10 - 15%.

The study also revealed that high energy input from welding process does result to improvement in the mechanical properties of welded metal. Vinokurov (1987) revealed that heat treatment is the most effective method for relieving residual stresses in the welded components. He explained that post weld heat treatment has two aspects, first, relieving the negative stresses effect and second, improving the mechanical properties. Evans (1986a) showed that heat treatment improved the notch impact strength and reduced the hardness and the tensile strength. Mashinson*et al.* (1986) showed that it was possible to ensure stable impact toughness values of 20 J/cm^2 in high frequency pipes welded joints. Bmankirski, (1985) revealed that tempering reduced yield strength and hardness but increased impact toughness. Hrivnak (1985) revealed that heat treatment with soaking temperatures of 550 to 700°C produced microstructure with the most improved mechanical properties. Fidler (1982) indicated that applying PWHT for 1 hour at 650 °C significantly reduced residual stresses. Takemoto *et al.* (1982) revealed that the application of post weld cooling to butt welded AISI 304 pipes profoundly reduced the residual stresses with significant improvement in the properties.

Therefore, this study is aimed at investigating the effect of process parameters on the microstructure and mechanical properties of micro-alloyed steel weldment with the view of establishing the soaking duration to produce the desired weld metal microstructures and mechanical properties suitable for structural applications. Major focus is placed on the microstructures, tensile strength, impact strength, yield strength, hardness and ductility of the steel weldment because of the significance on service behaviour.

2.0 Material and methods

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

Table 1: Elemental composition of test materials (wt%)

Material \ Comp.	C	Si	P	S	Ti	AL	Cr	Mn	V	Nb	Zn	Cu	N	Ca	Fe
Micro-alloyed steel	0.15	0.40	0.05	0.03	0.01	0.02	0.08	0.35	0.12	0.03	0.002	0.16	1.1	0.001	97.00
E7016	0.12	0.75	0.03	0.034	0.021	0.03	0.06	0.30	0.01	-	0.001	0.13	0.04	0.002	98.00

2.1 Welding operation

Prior to the welding process, the open circuit voltage (60 V) of the welding unit (Model: Safex M340) and the arc voltage (29 V) were measured using a digital multimeter. The arc voltage and the measured average welding speed (2.4 mm/s) were used to compute the heat input for the different welding current. Fifty (50) 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 electrode with a preset welding current of 90, 94, 98, 102 and 106 amperes respectively. After the welding process, a total of 40 as-welded samples were inserted in turn into the heating chamber of a muffle furnace preset to the tempering temperature of 450^0C and soaked for 60, 90 and 120 minutes respectively. These parameters were selected in order to minimize the reduction in hardness and strength associated with tempering, and to obtain balance properties in the tempered samples. After the welding and tempering process, test samples were cut out from the weld metal region (WM), heat affected zone (HAZ) and base metal (BM) and machined to the required dimensions for hardness, impact and tensile strength tests. Samples for optical microscopy were prepared in accordance with standard metallographic procedure and etched in 2% nital before being analyzed.

2.2 Mechanical tests

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

3.0 Results and Discussions

3.1 Microstructural analysis

Fig. 1 shows the optical micrograph of the base metal (BM). The white patches and dark spots may be fine grains of ferrite and carbide precipitates with little 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. 2 shows the optical micrograph (a) WM and (b) HAZ of 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. Fig. 3 shows the optical micrograph (a) WM and (b) HAZ of welds made at the current setting of 106 ampere, tempered at 450^0C for 60 minutes. The microstructure consists of pearlite and coarse carbide precipitates homogeneously dispersed along the ferrite grain boundaries. HAZ reveals fine distribution of ferrite and carbide particles. The coarse size of the carbide precipitates and fine grained ferrite microstructure account for the enhanced impact strength and percent elongation, and reduced hardness and tensile strength.

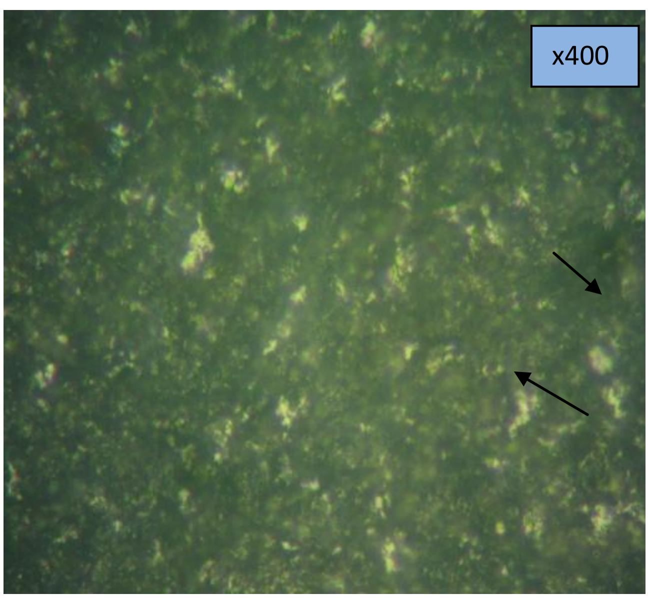

Fig. 1: Optical micrograph of base metal (BM) as-received.

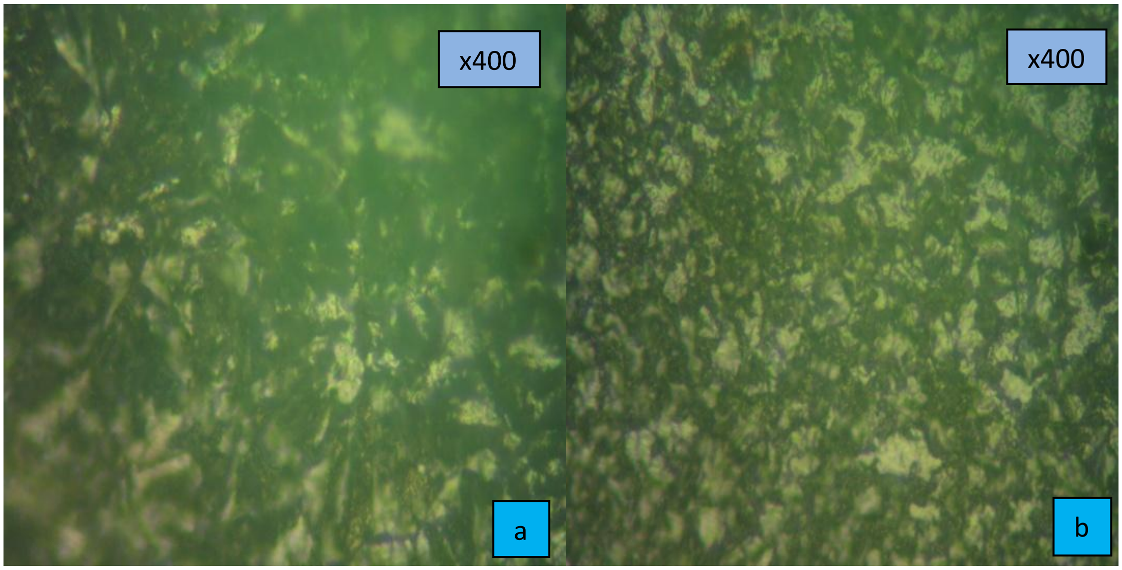

Fig. 2: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded at 94 ampere.

Table 2: Mechanical properties of the un-tempered as-welded samples

Sample ID	Welding current (amps)	Hardness BHN			Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
		WM	HAZ	BM					
TP0	-	-	-	138	14.0	168	216.8	8.0	376,018
TP1	90	170	135	-	15.0	192.8	255.2	17.2	1120185
TP2	94	167	134	-	16.3	178.4	253.6	17.5	1125477
TP3	98	165	130	-	16.7	173.6	246.4	17.8	1080691
TP4	102	155	127	-	17.2	172	244	18.1	1077602
TP5	106	148	123	-	17.6	170	243	18.4	1086502

$$\text{Quality index} = (\text{tensile strength})^2 * \text{percent elongation} \quad (1)$$

Table 3 shows the mechanical properties of the tempered as-welded samples. The results indicated that after the PWHT tempering was carried out on the as-welded samples at 450^0C for 60-120 minutes of soaking; the hardness, yield strength and tensile strength decrease with increased in soaking duration but impact strength and percent elongation increase. The decrease in hardness and tensile properties and the correspondingly increase in impact strength and percent elongation exhibited by the tempered as-welded samples could be attributed to the coarsening of the microstructural grain sizes due to increase in soaking duration. Bmankirski (1985) also revealed that tempering reduce yield strength and hardness but increase impact toughness.

Longer soaking duration is widely reported to promote grain growth at the expense of nucleation and thus reduce hardness and strength. Warner and Brandt (2005) asserted that the longer the time a heat treated samples stayed at any given tempering temperature, the more the grains coarsen, leading to decrease in hardness, strength and increase in impact strength and ductility. Therefore, the coarsening of the grain size of the microstructure as a result of increase in soaking duration account largely for the reduction in hardness, yield strength and tensile strength, and increase in impact strength and percent elongation. The results also revealed that the tempered as-welded samples produced the highest values of impact strength and percent elongation than the un-tempered as-welded samples.

Table 3: Mechanical properties of as-welded samples tempered at 450^0C

Sample ID	Welding current (amps)	Soaking time (min.)	Hardness BHN		Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
			WM	HAZ					
TP6	90	60	168	130	22.0	184	253.6	26.0	1672137
TP7	90	90	166	128	24.0	180	249.6	26.4	1644724
TP8	90	120	164	127	24.6	176	244	27.1	1613426
TP9	94	60	165	129	25.4	176	246	26.8	1621829
TP10	94	90	163	127	25.8	173.6	244.8	27.3	1636008
TP11	94	120	162	125	26.3	172	236	27.7	1542779
TP12	98	60	160	127	26.6	173	245	27.5	1650688
TP13	98	90	158	126	26.9	171.2	240	27.9	1607040
TP14	98	120	157	125	27.4	169..6	235.2	28.4	1571061
TP15	102	60	155	126	27.7	172	242.8	28.2	1662442
TP16	102	90	154	124	28.2	165.6	234	28.6	1566022
TP17	102	120	152	123	28.7	164	227.2	28.9	1491813
TP18	106	60	151	125	29.1	168.8	242.4	28.7	1686348
TP19	106	90	148	123	29.5	163.2	233.6	29.1	1587957
TP20	106	120	146	121	29.9	160.8	225.6	29.5	1501413

The high impact strength and percent elongation values recorded is indicative of the high potential of the steel weldment to resist brittle fracture in service. The maximum hardness, yield strength and tensile strength of 168 BHN, 184 KN/m^2 and 253.6 KN/m^2 respectively were obtained from the samples welded at 90 ampere, and tempered at 450^0C for 60 minutes. The quality index values computed using equation 1 (Siefer and Orths 1970) indicated that excellent combination of longitudinal tensile strength and percent elongation was obtained from the welds made at the current setting of 106 ampere, and tempered at 450^0C for 60 minutes.

3.2 Mechanical properties analysis

Table 2 shows the mechanical properties of the un-tempered as-welded samples. The Table clearly illustrates that welding current strongly affected the mechanical properties of the un-tempered as-welded samples. The results show that as the welding current settings were increased, the hardness, yield strength and tensile strength increased but the impact strength and percent elongation decreased correspondingly. This phenomenal trend is expected since increase in welding current slows cooling rate of steel weldment and encourages coarse grains in the final microstructure formed. Hence, the decrease in hardness and strength, and the correspondingly increased in impact strength and percent elongation. The higher hardness observed at the WM zone as compared to the HAZ and BM could be attributed to the presence of the alloying elements in the electrode core wire which probably served as recrystallization centres in the local melt thereby creating the required nuclei for the near instantaneous solidification with the attendant fine equiaxed grain microstructure formed, thus resulting to the higher hardness. This report is in agreement with the observation of Nnuka*et al.* (2008). The variation in hardness at the HAZ could be linked to the various forms of thermal cycles induced by the heat input from the welding current which gave rise to the different cooling rates with the attendant effect on the microstructure formed. These results are consistent with those of Raghavan (1989) and Raj *et al.*, (2012).

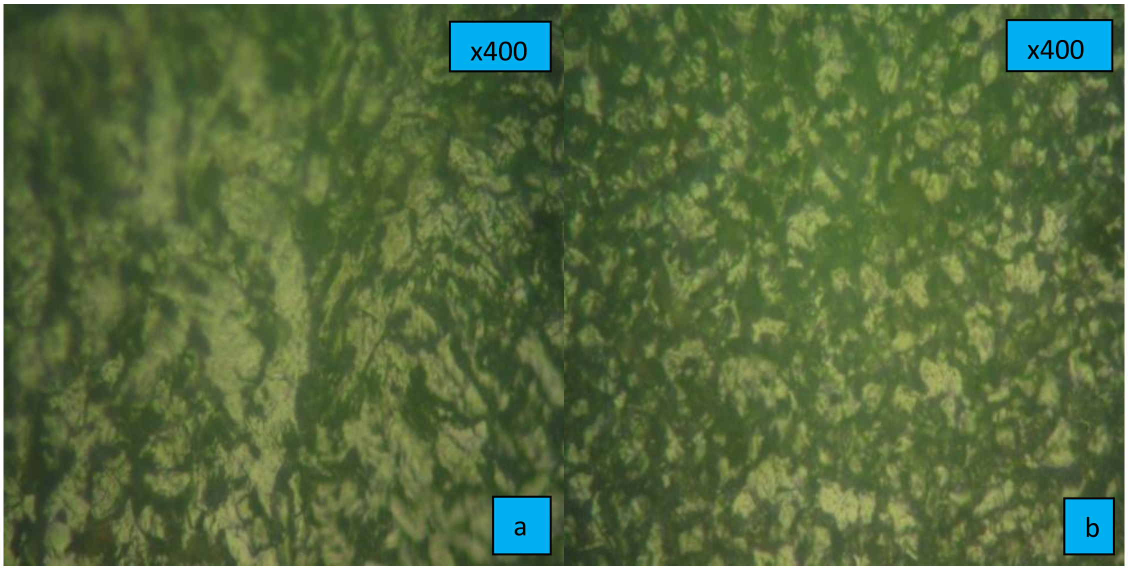

Fig. 3: Optical micrograph of (a) WM and (b) HAZ of sample as-welded at 106 ampere and tempered at 450^{o}C, soaked for 60 min.

4.0. Conclusion

Based on the results obtained from the study, the following conclusions have been drawn: The study established that the process parameters (welding current and soaking duration) had profound influence on the mechanical properties of the as-welded, and as-welded and tempered micro-alloyed steel weldment respectively. Increase in tempering soaking duration decrease the hardness, yield strength, tensile strength but increase impact strength and percent elongation with greater possibility of relaxing the welding residual stresses. The tempering soaking duration of 60 minutes gave the maximum hardness, yield and tensile values. Whereas maximum impact strength and percent elongation values were obtained at 120 minutes of soaking. The computed quality index values indicated that welds produced with welding current setting of 106 ampere, tempered at 60 minutes of soaking produced excellent combination of longitudinal tensile strength and percent elongation required for structural applications.

Acknowledgement

The authors are thankful to the Head of the Department of Industrial Metallurgy and Foundry Engineering, Metallurgical Training Institute, Onitsha, for his kind permission to use the muffle furnace in the materials testing laboratory. Dr. Abdulwahab Malik of the Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, for assisting with the tensile test and Engr. Emifoniye Elvis of the Department of Mechanical Engineering Technology, Delta State Polytehnic, Ogwashi-uku, for assisting with the Charpy impact test.

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