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Influence of electrode coating on mechanical properties of structural steels

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ABSTRACT: The need to obtain mechanical properties in welded joints commensurate with those of the parent metal requires well assessed Welding Procedure Specification (WPS) including choice of welding electrode. This paper investigated the effects of electrode coating on mechanical properties (yield strength, tensile strength, ductility and toughness) of structural steel welded joints. ASTM A53B and ASTM A106B steels were welded with electrodes of different coatings and the welded joints subjected to mechanical tests at 30°C. There is a definite influence of the electrode coating on the final microstructure of the Weld Metal (WM). The study found that electrodes with cellulose coating produced welded metals with higher tensile strengths than the parent metals but the % elongation of the welded metals decreased (from 32 to 26.5 for steel type A); also the higher the basicity of the electrode coating, the higher the combination of mechanical properties. This is explained as the product of macro- and micro-reactions between the slag and the molten weld metal; and the shielding effectiveness provided by the slag over the molten metal to minimize ambient incursion/reaction with the molten weld pool. The study further established that the coating composition influences the ageing stability of the WM mechanical properties. The presence of Si (0.3%) in the base metal did little to enhance the ductility of the WM. The observed WM embrittlement with cellulose type electrode is probably a consequence of the reducing gas action evolved during combustion.

Key Words: Electrode coating, structural steels, weld metal, mechanical properties.

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INTRODUCTION

One of the challenges in welding metallurgy is to obtain WM of the same or even superior mechanical qualities as the base metal. The challenge becomes more sensitive when the welded joints are for structural services, where there is great demand for strength, fatigue-load bearing capabilities and toughness (Higgins, 1994). The choice of matching welding rod with microstructure-preserving or -enriching capabilities makes or mars the mechanical properties of welded joints and thus determine their service endurance level compared with the parent metal. For some alloys, the WM continues to undergo microstructural changes long after welding has occurred (ageing), this phenomenon could be aggravated or mitigated by the action of the weld rod coating consumable used during the weld process (Lancaster, 2005). In structural works, heavy steel sections and tubulars are in service and their failure could result in severe damages including impact on life. Essentially, the electrode coating provides "environmental

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protection” to the molten weld pool to avoid or minimize ambient incursion into the WM, and, in addition to this service, could be a source of dilution of the WM due to alloy loss to the molten coating slag.

Steels used for structures have failed in service and some of these have been traced to the welded joints. A case is the crane beam (boom) failure in Nigeria Delta Steel Complex, Aladja where crane used for off-loading iron ore from ships buckled under iron ore load (Horowitz, 1998). Other instances are the “sagging” of trailer beds I-beams of some trailers conveying cement bags from Nigeria Onne Sea Port to the hinter lands. In these failures, investigations revealed the welded metals (WMs) have different (lower) mechanical properties compared with those of the base metals. Optical microscopy identified microstructures of WMs that are different from the parent metals (Pinnow, and Moskowitz, 1980).

Electrodes used for manual and automatic arc welding of low and medium carbon steels including low alloy steels are generally made from 0.12% carbon steels, the standard electrode diameters being 4.00, 5.00, 6.30, 8.00 and 10.00 mm (Thomas and Yapp, 1999). The degree of shielding over the weld pool provided by the burning electrode coating in great measure determines the final microstructure of the WM. This characteristic affects the mechanical properties either immediately or after a long time (ageing) upon weld completion (Folkhard, 1998). It is also known (Horowitz, 1998) that the weld thermal cycle (also influenced by electrode coating) affects the precipitation of the brittle sigma Fe-Cr phase in the microstructure if exposed to high temperatures for a certain length of time.

This study investigates the effects of electrode coating on mechanical properties of welded joints deployed in structural service; hence determine the electrode coating required for optimum mechanical properties in the WM in relation to the parent metals.

MATERIALS AND METHODS

Two types of structural steels in the form of hot rolled I-beams: Steel Type A (ASTM A53B) and Steel Type B (ASTM A106B) were used for this study. The elemental compositions are listed in Table 1. The matching welding electrodes as per AWS A5 were selected upon determination of the elemental composition of each steel type as shown in Table 1. The electrode types selected are: Cellulose Coated Electrode: AWS E 6010, Acid Coated Electrode AWS E 6020 and Basic Coated Electrode AWS E 7018.

Tensile Test

From each steel type, 21 pieces specimens were cut. 18 pieces of the specimens were paired in abutting single V-groove profile and welded with SMAW process to give 9 welded pieces -3 welded joints per electrode coating type. The remaining 3 specimens for each steel type were not welded; they were subjected to mechanical tests for base line data used for studies of the welded ones. The welding procedure specification (WPS) are based on American welding society [AWS] D1.1/D1.1M:2004). All welded pieces were partially cleaned in 10% HCl-methanol mixture to remove slag particles trapped in the weldments. The test specimens were prepared as per AWS B4.0: 2009. They were machined on the lathe to ensure the sides are smooth and parallel. 18 welded specimens were tested, 3 for each electrode coating type per steel type. For the un-welded specimens, 3 specimens per steel type were tested, this brought the total number tested to 24.

Table 1: Chemical Composition of Steel Materials

Element	Steel Type A [ASTM A53B] (% by weight)	Steel Type B [ASTM A 106B] (% by weight)
Carbon (C)	0.25	0.25
Manganese (Mn)	1.10	0.95
Silicon (Si)	0.00	0.30
Phosphorus (P)	0.025	0.020
Sulphur (S)	0.023	0.020
Iron (Fe)	98.602	98.46

Impact Test

From each steel type, specimens were cut; the edges of the cut specimens were prepared and abutted in single V-profile. Paired specimens were welded with SMAW process using different electrode coating types earlier selected. Also, from each steel type, specimens were cut and prepared for testing without welding. The test data from these un-welded specimens were used for base-line studies of the welded ones. Test specimens were standardized to 55 x 10 x 10 mm dimensions. They were etched and V-notched. Charpy impact testing machine was used. Tests were conducted at 30°C.

Micrography

Specimens were cut from each steel type according to the welding electrode coating used. The cutting was made to reveal the weld metal. Specimens were also cut from the as-received, un-welded structural steels. All the test samples were ground roughly and finely. Abrasives of 320, 400 and 600 grits corresponding to particle sizes of the silicon carbide of 33, 23 and 17 microns respectively were used for fine grinding. Rough polishing was done with powdered diamond dust abrasives (size = 6 microns). The dust was poured on emerald cloth which covered the surface of the rotating polishing wheel. Final polishing was done with the gamma form of alumina (Al_2O_3) powder (particle size = 0.05 micron). This was also poured on the emerald cloth which covered the polishing wheel. Distilled water was used as lubricant. Etching was done with 3% by volume of solution of nitric acid in methanol at 30 seconds for each specimen. The specimens were studied under Leitz optical microscope and the images (micrographs) captured at magnification of x100.

RESULTS AND DISCUSSION

The optical micrographs of steel types A and B are shown in Figures 1 and 2. Steel type A has 0.0% Si but contains more Mn than type B. Type B contains 0.3% Si.

Cellulose Coated Electrode AWS E 6010

Figures 3 and 4 are the optical micrographs of WM deposits of steel types A and B. Both have fine grain structure, though Fig. 4 is a bit coarse. The microstructures of both welded metals are pearlite (ferrite + cementite [Fe_3C]). This interleaved plates (lamellar structure) of Fe_3C and ferrite emerges, since the % carbon is more than could be dissolved by the ferritic iron (% C is 0.25%, maximum C dissolubility by ferrite iron is 0.025% C) (Downs, 2001; Davies and Oelmann,

Table 2: Mechanical Properties (Yield, Tensile, Impact and % Elongation) of Specimens

Steel Type	Electrode Coating Type	Yield Strength MPa, at 30°C (Average of 3 Specimens)	Tensile Strength MPa, at 30°C (Average of 3 Specimens)	% Elongation at Fracture, at 30°C (Average of 3 Specimens)	Impact Energy Absorbed J, at 30°C (Average of 3 Specimens)
Steel Type A [ASTM A53B]	Base Metal (Not welded)	241	415	32	71.5
	Cellulose Coated: AWS E 6010	248	420	26.5	100.5
	Acid Coated: AWS E 6020	244	419	29	75.5
	Basic Coated: AWS E 7018	245	420	31	74
Steel Type B [ASTM A106B]	Base Metal (Not welded)	241	415	30	76.5
	Cellulose Coated: AWS E 6010	250	435	25.5	109.5
	Acid Coated: AWS E 6020	248	430	27.5	80
	Basic Coated: AWS E 7018	245	420	29.5	80

2003). In type B, the WM has in its microstructure strings of martensite induced by the quick cooling associated with "fast thermodynamic cycle of welding and cooling." Si in the matrix remained an ameliorating source for ductility and strength and accounts for the high impact energy absorbed (100.5 J for steel type A and 109.5 J for steel type B) (Table 2). The % elongation measured at fracture is low compared with that of the base metal (Table 2). The Si did not seem to have affected the ductility as expected (Rabbe and Heritier, 1999).

Acid Coated Electrode AWS E 6020

The optical micrographs for the WM deposits of steels A and B are shown in Figs. 5 and 6. The coating transferred large quantity of Mn to both the WM and slag and this action provided the pedestal for other "micro-actions." Usually, high welding current and welding speed is economical for this coating to minimize the effects of the secondary actions or reactions due to the acidic reaction of the slag (Lancaster, 2005). The acidic reaction of the coating dissolved basic oxides and their instability at high temperatures reduced the protective effectiveness of the shielding during welding; this reduced effectiveness enhanced "ambient incursion" into the WM. The microstructure of the welded metal is homogeneous in both types of steels, with steel B having more patches of cementites. The appreciable increase in strength and toughness could be explained by the enhanced quantity of Mn in the deposits (Downs, 2001). There is a drop in ductility (from 30 % elongation to 27.5 % eleongation) [Table 2] in type B steel in spite of the 0.3 % Si in the base metal.

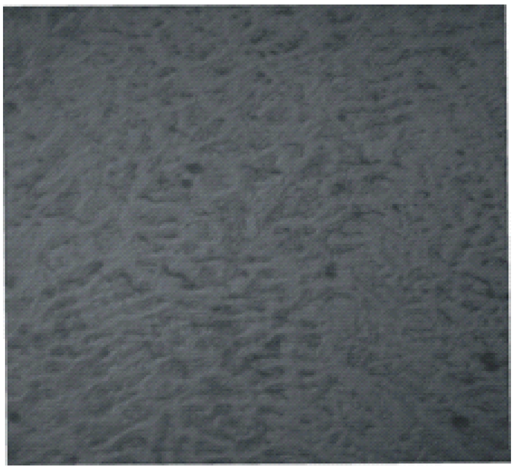

Fig. 1: Type A steel optical micrograph of BM X100

Fig. 2: Type B steel optical micrograph of BM X100

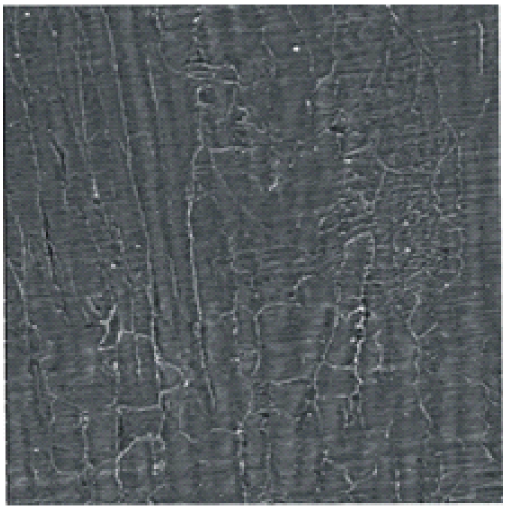

Fig. 3: Type A steel optical micrograph of WM welded with cellulosic coated electrode X100

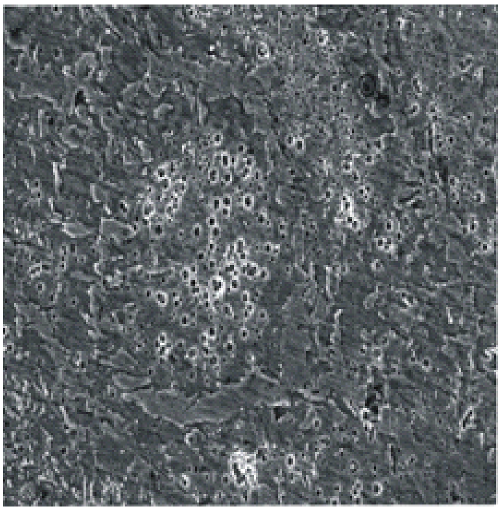

Fig. 4: Type B steel optical micrograph of WM welded with cellulosic coated electrode

Basic Coated Electrode AWS E 7018

The optical micrographs for the WM deposits of steels A and B are shown in Figures 7 and 8. The microstructure of each WM is very close to that of its parent steel. It is considered that the thermodynamic effect of the coating (coating combustion evolving mixture of CO and CO_2 gases [reducing agents]) provides a cooling slope which enables WM homogeneity. The iron powder additive in the electrode coating increased the deposition efficiency (about 170%) of the electrode (Thomas and Yapp, 1999). This “abundance” of deposits helps in higher welding speed by virtue of the higher current-carrying capacity of the coating (Sunwoo et al, 2008). Additional heat is input to the WM by part of the molten metal reacting with the slag to form calcium ferrite ($2\ CaO.Fe_2O_3$). This reaction has high heat of formation (about 21 kCal/mole) [Parmar, 2005] and this accelerates the welding process. The ductility and impact strength of each WM are close to those of its base metal. This is probably due to the high stability of the slag at elevated temperatures; which in turn provided high shielding effectiveness (ambient incursion kept to the barest) during the weld (Pinnow and Moskowitz, 1980).

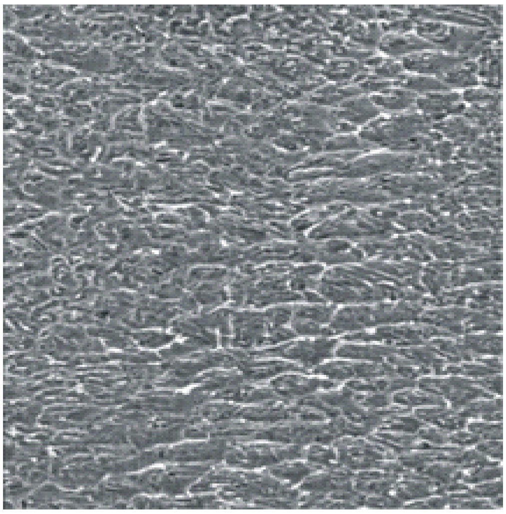

Fig. 5: Type A steel optical micrograph of WM welded with acid coated electrode

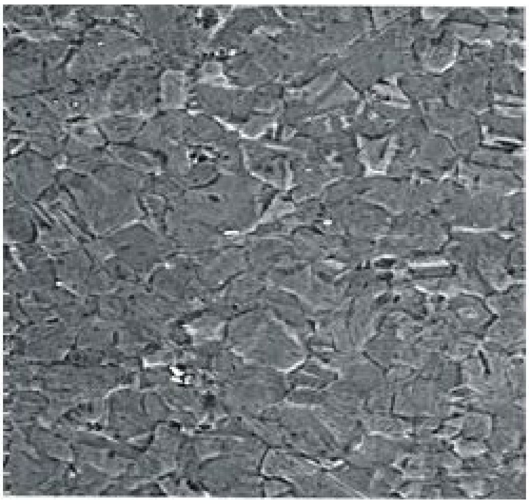

Fig. 6: Type B steel optical micrograph of WM welded with acid coated electrode

Fig. 7: Type A steel optical micrograph of WM welded with basic coated electrode

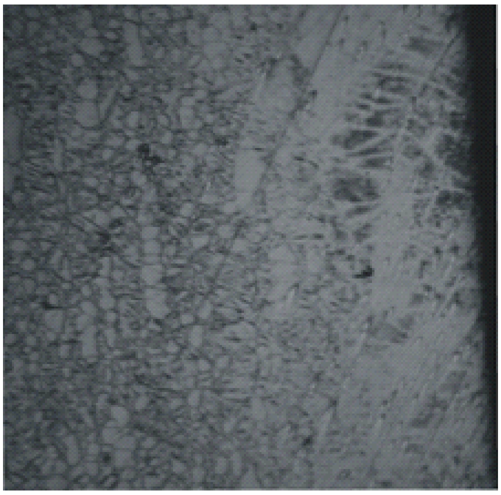

Fig. 8: Type B steel optical micrograph of WM welded with basic coated electrode

CONCLUSIONS

The results of this study showed that welded metal mechanical properties are influenced by electrode coating type. Cellulosic type electrode coating produced welded metals with higher tensile strengths than the base metals but the welded metals dropped significantly in % elongation (ductility). For this coating type, the welded metals high impact energy absorbed (100.5 J for steel type A and 109.5 J for steel type B) corresponded with the increased strength. Basic electrode coating produced welded metals with mechanical properties that were close to those of the base metals. When electrode baking temperatures are carefully managed, the mechanical properties of welded metals could serve the same confidence levels as the base metal. The higher the basicity of the electrode coating, the more stable the slag at elevated temperatures, the more the shielding effectiveness over the weld pool (ambient incursion kept to the barest) and the higher the combination of mechanical strengths obtained.

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