15th International Conference on
AEROSPACE SCIENCES & AVIATION TECHNOLOGY,
ASAT - 15 – May 28 - 30, 2013, Email: asat@mtc.edu.eg ,
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Effect of SMAW Welding Parameters on Mechanical and Structure Properties of Welded Joints of the Armoured Steel 0.32%C, 1%Cr, 1.8%Ni and 0.7% Mo

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Abstract: This paper introduces the effect of Shielded Metal Arc Welding (SMAW) welding parameters on the mechanical and structure properties of welded joints of the quenched and tempered armoured steel 0.32%C, 1%Cr, 1.8%Ni and 0.7% Mo. In this study, three welding consumables – low-carbon & low-alloy which are both Low Hydrogen Ferritic (LHF) electrodes, and austenitic stainless steel (ASS) electrode - and three heat inputs were used. Furthermore, the effect of preheating of the armoured plates on the mechanical properties of both the welded joint and the heat affected zone was investigated. The use of the low-hydrogen ferritic electrodes provided superior tensile properties while the austenitic electrodes exhibited pronounced toughness. Higher heat input and/or preheating should be performed when using LHF electrodes, however, caution should be given when using low-alloy steel electrodes due to their sensitivity to the applied cooling rate. On the contrary, preheating is less important when using ASS electrodes due to their high resistance to cold cracking. Higher heat input and preheating temperatures increase the softening of the hardened region, adjacent to the fusion zone, which decrease the possibility of Hydrogen induced cracking (HIC).

Keywords: HAZ: Heat Affected Zone, **SMAW**: Shielded Metal Arc Welding, **LHF**: Low Hydrogen Ferritic, **ASS**: austenitic stainless steel, **HIC**: Hydrogen induced cracking

1. Introduction

The high strength of low-alloy steels is derived from a heat treatment comprising quenching from the austenite region followed by a low-temperature tempering. In other words, these steels can be shortly termed quenched and tempered (Q&T) steels [1]. Q&T steels are used in military applications owing to their high hardness, high strength to weight ratio, and excellent toughness. These grades of quenched and tempered steels are prone to hydrogen induced cracking (HIC) after welding and they, also, exhibit heat affected zone (HAZ) softening, which leads to poor ballistic performance [2]. Hydrogen is introduced into the weld during the welding process, from the atmosphere, hydrocarbons on the material being welded, or using electrodes of flux containing moisture, which depends on what type of flux that is used [3]. The usage of Q&T steels includes many critical applications, in defense, such as construction of the hull, and the turret of combat vehicles. Performance and safety requirements in these applications dictate that weldments must be sound and of good quality [4]. This has led to a need for improved knowledge of the influence of the manufacturing process on these high strength steels. The above-mentioned problems affect the quality of the welds and they are characteristic features of weld thermal cycle, welding consumables and welding process.

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Austenitic stainless steel (ASS) welding consumables are traditionally used for welding of high hardness Q&T steels as they have higher solubility for hydrogen in austenitic phase. Consequently, these stainless steel consumables are known for their good resistance to cold cracking and hot cracking.

In view of the need to conserve strategic metals like Ni and Cr the use of costly ASS consumables for a non-stainless steel base metal must be avoided. In recent years, the development of low hydrogen ferritic (LHF) steel consumables that contain no hygroscopic compounds is attempted for welding of Q&T steels [5]. The majority of armor fabrication is performed by the fusion welding process, which demands for the highest welding quality. Shielded metal arc welding (SMAW) is widely used in the fabrication of combat vehicle structure. HAZ softening exists during welding of quenched and tempered steels and it is inevitable. The degree of softening in the HAZ is a function of the weld thermal cycle (which is a characteristic of the welding process), the kinetics of the phase transformations, and the chemistry of the steel [6]. During welding, rapid heating and cooling take place which produce severe thermal cycle near weld line region. Thermal cycle causes non uniform heating and cooling in the material, thus generating harder heat affected zone, residual stress and cold cracking susceptibility, in the weld and base metals. Detrimental residual stresses commonly result from differential heating and cooling, in the different weld regions, from the bead to the base metal through the heat affected zone. These all are problems, that may arise during the process of production of the weldment. To get rid of these problems some heat treatment before welding (Preheating) and after welding (Post Weld Heat Treatment (PWHT)) are employed. Effective preheat and post heat are the primary means by which acceptable heat affected zone properties and minimum potential for hydrogen induced cracking are created [7]. In addition, the heat of welding also produces a tempered or softened zone of parent metal beyond the hardened zone. To keep this softening effect to a minimum, the heat input of welding must also be kept within controlled limits [8]. The objective of this work is to investigate the effect of SMAW welding consumables, preheating, and heat input on the performance of the quenched and tempered steel joints, of the armor steel (0.32%C, 1%Cr, 1.8%Ni and 0.7% Mo) that are used in military applications.

2. Experimental

The base metal used in this investigation is the quenched and tempered armoured steel (0.32%C, 1%Cr, 1.8%Ni and 0.7% Mo), that is closely confirming to AISI 4340 specification, and widely used in combat vehicle construction. The base metal was delivered in the form of rolled plates, 5 mm in thickness. Its microstructure revealed a tempered lath martensite features as shown in (Fig. 1). The welding joint edge was prepared in the form of single 'V' butt joint configuration, as shown in (Fig. 2).

ASS (E307-15(THX) and two LHF steel (E7018-1, E11018-G) consumables– low-carbon steel & low-alloy steel electrodes - were employed to elaborate the joints using SMAW. The chemical composition of the base metal and weld metals are presented in Table 1. The different process parameters used are given in Table 2. The heat input was varied from 0.4 KJ/mm up to 1.2KJ/mm, by using the same current and different welding travel speeds. Laser cutting machine (Model: Bysrtronic Bylaser 4400) was used to cut the armour plates into rectangular strips having dimensions of (100mm x 25mm x 5mm) to be welded along its width (25mm), so that, the arc strick, and arc extinguishing are established outside the indicated width. These strips were directly used as tensile specimens to evaluate the effect of the value of the heat input during welding on the tensile properties. Preheating to a temperature of 300oC was applied on some specimens before welding by mean of digital electronic furnace to evaluate the effect of preheating on the mechanical properties.

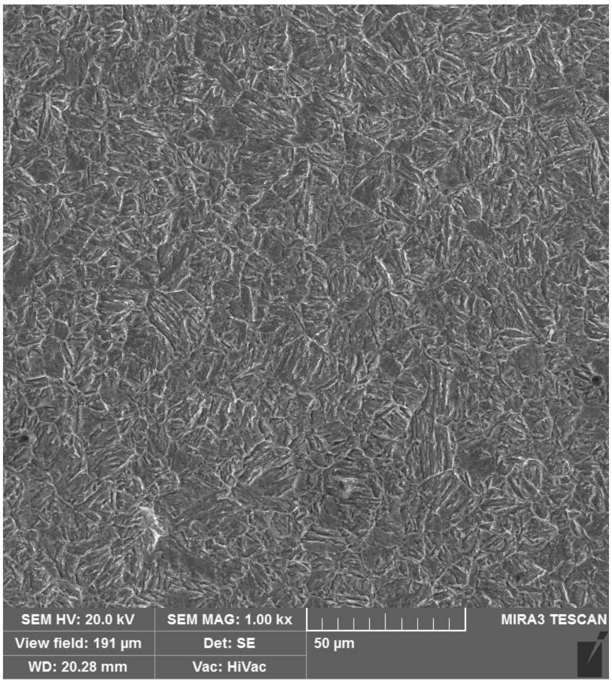

Fig. 1 Microstructure of the base metal

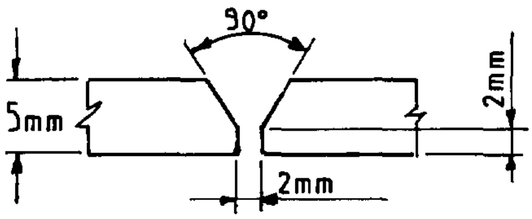

Fig. 2 Joint configuration

Table 1. Chemical composition in weight percent of base metal and filler metal

Material	C	Si	Mn	P	S	Cr	Ni	Mo	B
BM	0.32	0.1-0.4	1.2	0.015	0.010	1.0	1.8	0.7	0.005
E7018-1	0.04	0.4	1.4	0.016	0.001	0.05	0.04	0.03	__
E11018-G	0.06	0.3	1.5	__	__	0.35	1.8	0.4	__
E307-15 (THX)	0.10	0.6	7.0	__	__	18.5	8.0	__	__

Table 2. The process parameters

Welding parameters	Notation
Electrode type	E7018-1(low-carbon steel LHF electrode)(AWS A5.1) E11018-G (low-alloy steel LHF electrode)(AWS A5.5) E307-15 (ThermanitX)(ASS electrode)(AWS A5.4)
Electrode diameter	Ø 3.2 mm
Heat inputs	0.4, 0.8, 1.2 KJ/mm (for every type of electrodes)
Preheating temperature	300^{o}C

Vicker's microhardness testing machine (Model: Omnimet MHT) was used for measuring the hardness profile through the HAZ using 500 gf load. Microstructural analysis of the HAZ was done using scanning electron microscope (Model: TESCAN MIRA3) incorporated with an image analyzing software. Conventional metallographic procedures were followed to prepare the specimens for microstructural examinations. The specimens were etched with 4% of Nital reagent to reveal the microstructure.

3. Results & Discussion

The optimization of the quality of SMAW welding joints are confined to the evaluation of the obtained microstructure in the HAZ, together with the resulting distribution of hardness, along this zone, from the bead region to the base metal, and the tensile characteristics obtained when loading these welded joints to fracture

3.1 Hardness and Microstructure

Hardness profiles, in the weldments, using three different electrodes, of the same diameter 3.2mm, under a constant heat input of 0.8 KJ/mm, without and with preheating at 300°C, are shown in Figs. 3, 4, and 5. Three separate regions can be identified, along these profiles, which correspond to specific values of hardness and corresponding features of microstructures. These regions are as follows: **A-region,** named as “coarse-grained HAZ” or un-tempered martensite zone, **B-region,** named as **“**softened HAZ” or mixed structure zone, and **C-region,** named as “recovery HAZ”, in which, the hardness values attain that of the parent base metal. The hardness values across the **A-region** revealed a significant upwards trend in hardness, followed by a declining trend in the **B-region**. During the **C-region** the hardness values approaches and attains the initial hardness of the base metal. We can, also, note that, for the three types of electrodes, the maximum hardness, traverse the HAZ, was obtained in the overheated region, near the fusion line. Moreover, by applying preheating the values of hardness in this hardened zone was reduced by about 10%, while the width of the softened HAZ region was significantly increased.

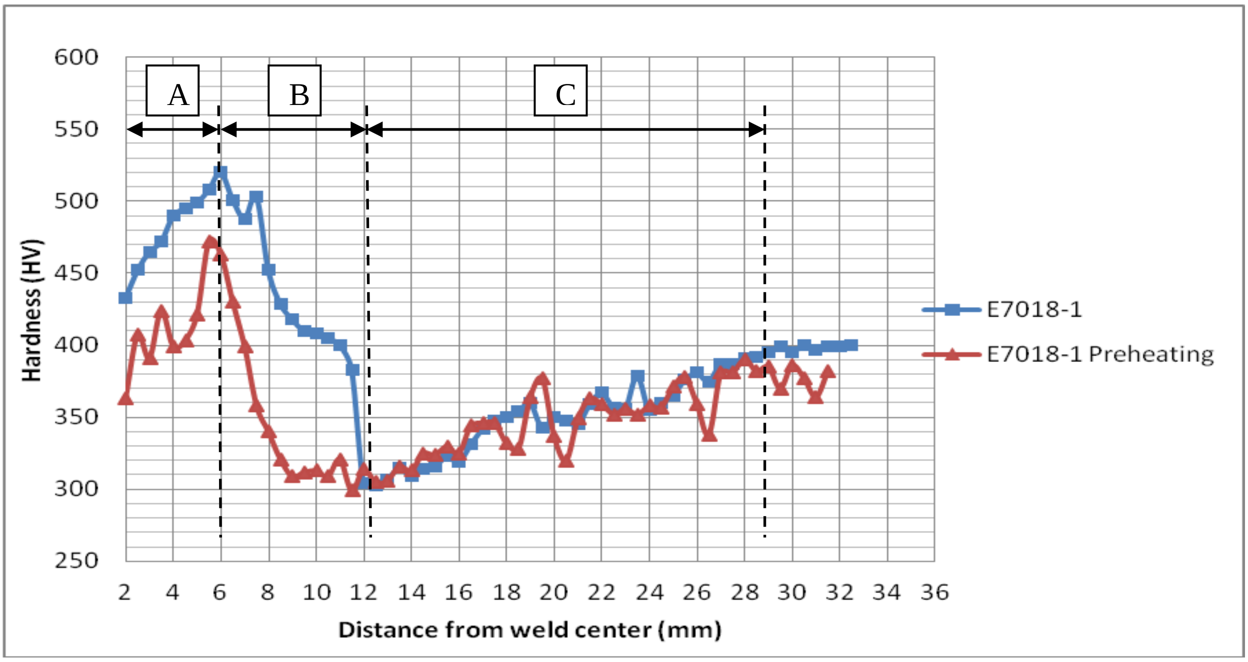

Fig. 3 Hardness profile from the weld bead centre to the base metal, through the HAZ using SMAW electrode E7018-1, without and with preheating at 300°C

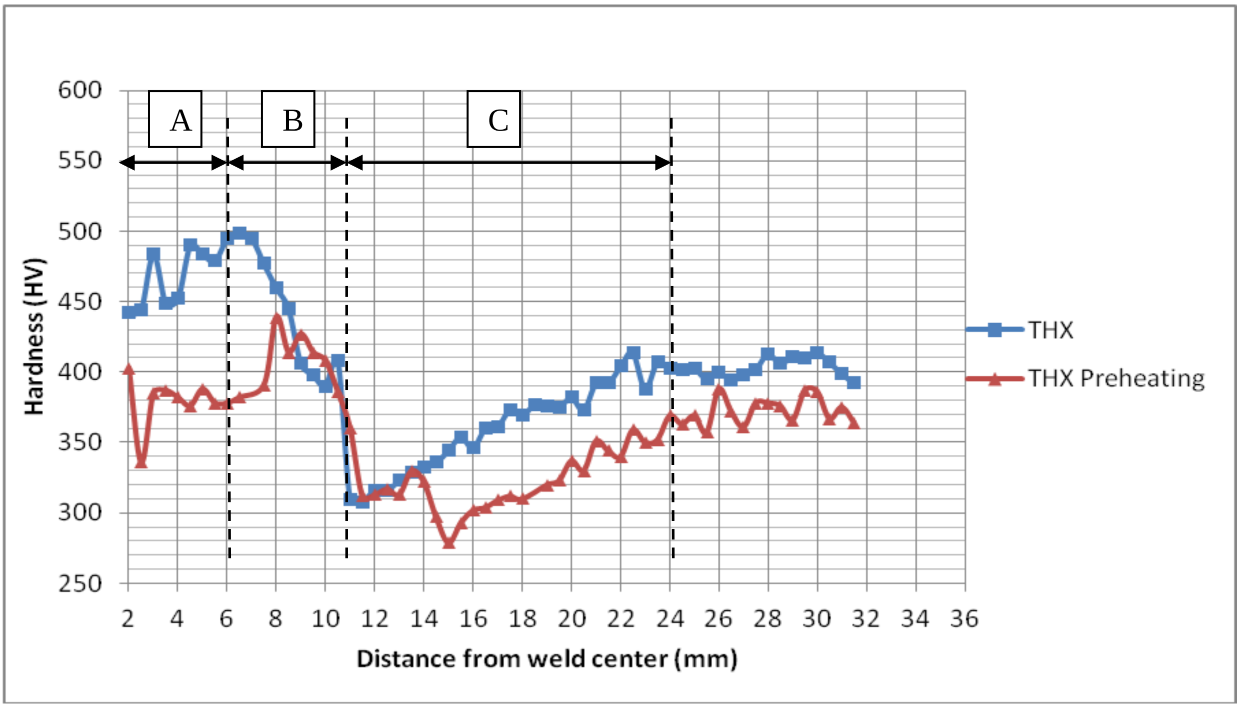

Fig. 4 Hardness profile from the weld bead centre to the base metal, through the HAZ using SMAW electrode E11018-G, without and with preheating at 300°C

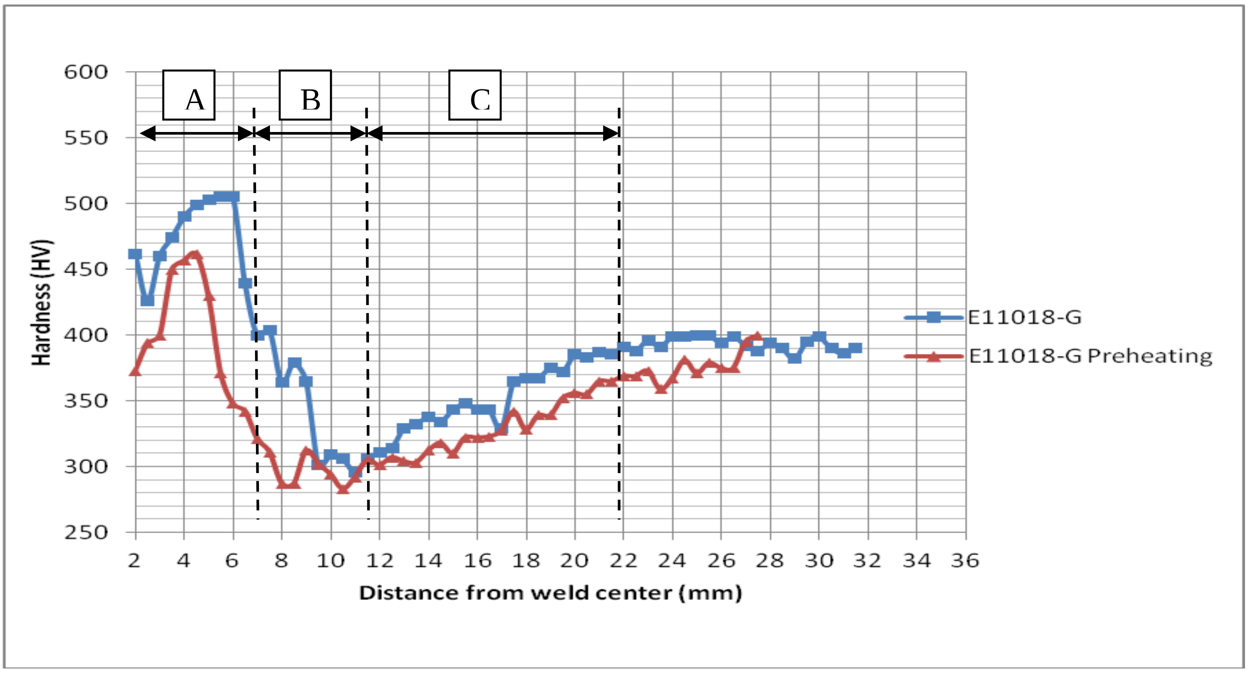

Fig. 5 Hardness profile from the weld bead centre to the base metal, through the HAZ using SMAW electrode ThermanitX (E307-15), without and with preheating at 300°C

The microstructure features of the coarse-grained HAZ corresponding to A-region are shown in Fig.6. This micrograph reveals hard and coarse grained un-tempered lath martensite. The micrograph of the structure obtained in B-region is shown in Fig.7, this region comprises a mixture of, relatively, fine-grained structure of lath martensite and ferrite.

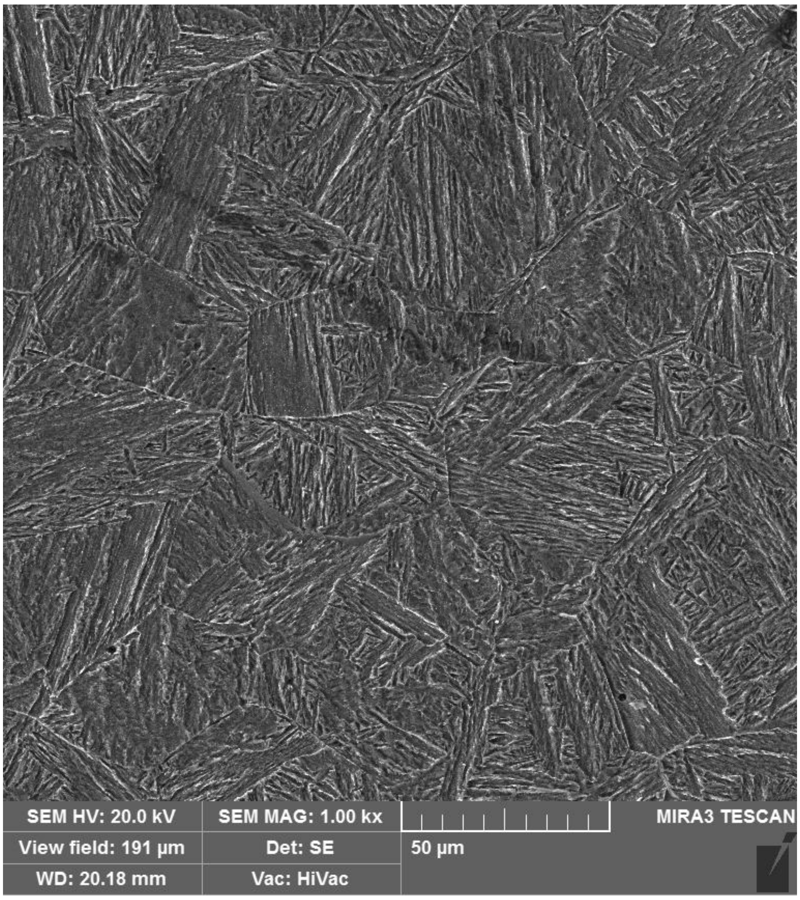

Fig. 6 Microstructure of the A-region, characterized by coarse-grained un-tempered lath martensite

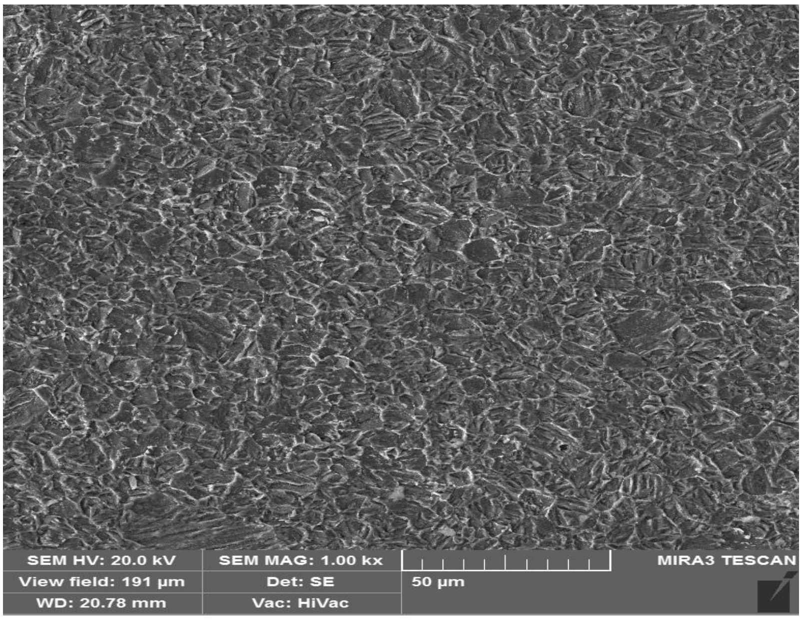

Fig. 7 Microstructure of the B-region, characterized by, relatively, fine-grained mixed structure of lath martensite and ferrite.

The microstructure formed in the HAZ is a function of the steel and the weld thermal cycle. The region of the HAZ near the fusion zone experiences a high peak temperature, exceeding AC_3, and also is subjected to fast cooling rates, which would result in coarse-grained HAZ. The peak temperature controls the austenite grain size, whilst the cooling rate controls the transformation products, formed from austenite during cooling. High cooling rates nucleate martensite while lower cooling rates may lead to the formation of bainite or even pearlitic structures. Both of these are, in turn, a function of the composition of base metal, the heat input of the welding process and the preheating temperature. The hardness distribution across the weldment serves as a guide to correlate the microstructure as a function of location. The highest hardness found near the fusion boundary corresponds to two microstructures: (i) coarse martensite grains formed due to the high temperature reached exceeding AC3 which caused grain growth, and (ii) a martensitic microstructure developed in a region reaching a temperature just above AC3 in which grain growth was avoided. A hardness drop is observed at around 6 mm from the fusion boundary. In this region, peak temperatures were between AC1 and AC3 and thus former tempered martensite on base metal was dissolved and transformed into a mixture of ferrite and martensite during cooling. From that point, hardness is progressively recovered in a region having different microstructures depending on the temperature achieved, causing an over-tempering of base material. The effect of preheating is to alter the weld thermal cycle that leads to changes in the cooling rates, which then influence the widths of the different HAZ regions. Applying preheating temperature on the base metal, which would result in low cooling rates, leads to a wider soft zone. It is therefore imperative to control the preheating temperature to keep the size of the soft zone as small as possible for better ballistic performance. On the other hand, preheating the base metal have a good effect on the hardened region by reducing the cooling rate in the HAZ, as rapid cooling after welding results in a hard and brittle martensitic microstructure. In addition, this hard structure is more susceptible to hydrogen cracking.

The comparison between the different hardness profiles, obtained using the three electrodes, indicates that lower favorable hardness values in the hardened zone were obtained by the ferritic low-alloy LHF electrode (11018-G) and the austenitic ASS electrode (E307-15). Furthermore, these two electrodes provided relatively shorter recovery regions and consequently smaller HAZ. Then these two electrodes can be used adequately to weld this type of armour steel, but, from the cost point of view, the ferritic low-alloy LHF electrode (11018-G) is considered an excellent candidate.

3.2 Tensile Behavior of the Welded Joints

To evaluate the tensile properties of the welded joints, welding was carried out, using different values of heat inputs, by varying the welding travel speed, and keeping the electrode diameters and welding current constant. Figure 8 illustrates the effect of the value of the heat input on the ultimate tensile strength of the joints welded using the three adopted types of electrodes (E7018-1, E11018-G & E307-15). During the tensile tests, all the specimens (joints) were found to fracture in the weld region. We can state that, the use of the ferritic LHF steel electrodes (E7018-1, E11018-G) for welding quenched and tempered armour steel has provides higher tensile properties than that obtained by the ASS electrode (E307-15), for all the values of heat input. Furthermore, the low-alloy LHF electrode (E11018-G) provided the highest values of ultimate tensile strength. On the other hand, we can note that, a significant drop of ultimate tensile strength can be observed in both low-alloy LHF & ASS electrodes at higher values of heat input, while this drop does not take place in the case when the low-carbon LHF electrode was used. Moreover, the effect of preheating at a fixed temperature of 300^{o}C with heat input of 0.8 Kj/mm on the tensile strength of the obtained joints by the different electrodes is illustrated in Fig. 9, where we can record the same effect of the heat input. In fact, increasing the value of the heat input or applying a preheating cycle on the joints have both a direct effect on reducing the rate of cooling after welding.

The demonstrated higher ultimate tensile strength of the joints produced by the ferritic electrodes relative to the austenitic electrode can be directly attributed to the microstructure of the weld metal zone obtained in these cases. LHF plain low-carbon and low-alloy low-carbon electrodes provide acicular ferrite or martensite and bainite structures, which are stronger than austenitic or austenitic-ferritic structures provided by welding using ASS electrodes. Furthermore, it's natural that, the low-alloy low-carbon electrodes show higher ultimate tensile strength than that of the Plain low-carbon electrodes, due to the presence of some alloying elements which harden the weld metal. It was reported [9] that the microstructure of the weld metal zone in LHF joint contains more of the acicular ferrite. A good combination of strength and toughness, of low-carbon steel welds, is achieved by the so-called acicular ferrite microstructure, which consists of small interweaving ferrite plates formed within austenite grains, and it is considered the most desired structure in low-carbon steels. Acicular ferrite is, also, the phase most commonly observed as austenite transforms during the cooling of low-alloy steel weld deposits. It is of considerable commercial importance because it provides relatively tough and strong welds. This is attributed to its fine grain size (typically 1-3µm), in which each lath is separated by high angle boundaries [10]. Hence, welds with acicular ferrite type of morphology usually have higher hardness and tensile strength. The LHF joint exhibited superior tensile properties, which may be owing to the presence of acicular ferrite morphology in the weld metal. It should be, also, stated that, the weld joint obtained by LHF low-alloy low-carbon electrodes is more sensitive to the cooling rate than LHF plain low-carbon electrodes. This can explain the observed drop of ultimate tensile strength at elevated heat input which reduces the cooling rate of the joint, when using this low-alloy low-carbon electrodes.

The electrode metal chemistry of ASS electrode contains (8 % wt of nickel). Being an austenite stabilizer, it influences the formation of austenitic phase in the ASS weld metal zone. Actually, this electrode provides fully austenitic structure deposits, but, with dissolution and merging with the ferritic base metal, the structure of the resulting weld metal zone of ASS joint contains a limited amount delta ferrite in a plain austenitic matrix. It is well known that nickel in weld metal plays an important role in microstructural control. It has been reported [11] that the weld metal toughness can be increased significantly by an increase of nickel content. The higher nickel content improves the toughness in two ways: nickel reduces the ferrite content of the weld (microstructural phase more brittle than austenite), and the nickel additions increase the toughness in fully austenitic compositions. A secondary benefit is that nickel stabilizes the austenitic structure against the formation of martensite [12]. Hence, the ASS joint has lower ultimate tensile strength but higher impact toughness than LHF joint because of high nickel content in weld metal and austenitic phase in the weld metal microstructure. The observed drop of ultimate strength, at higher heat input, may be explained by the coarsening effect which can take place in the delta-ferritic phase.

On the other hand, in this study, the effect of preheating of the base metal on the ultimate tensile strength is similar to the heat input, since they can be considered as a measure of the cooling rates and energy transferred from the weld. Then preheating is an important factor that affects the mechanical properties and metallurgical structure of the weld and the HAZ [13]. Preheating decreases the hardness of the hardened zone in the HAZ and the possibility of the HIC, but, on the other hand, preheating have a significant effect on the strength levels attained with certain low-alloy steel weld metals. These weld metals are affected by rapid cooling rates which tend to produce more martensitic or bainitic microstructures. These microstructures will often exhibit higher yield and tensile strengths with a decrease in ductility. The cooling rate can be retarded by utilizing a higher preheat [14]. On the other hand, there is no need to higher heat input or preheating temperature when using ASS consumables as they are known for their good resistance to cold cracking because they have higher solubility for hydrogen in austenitic phase.

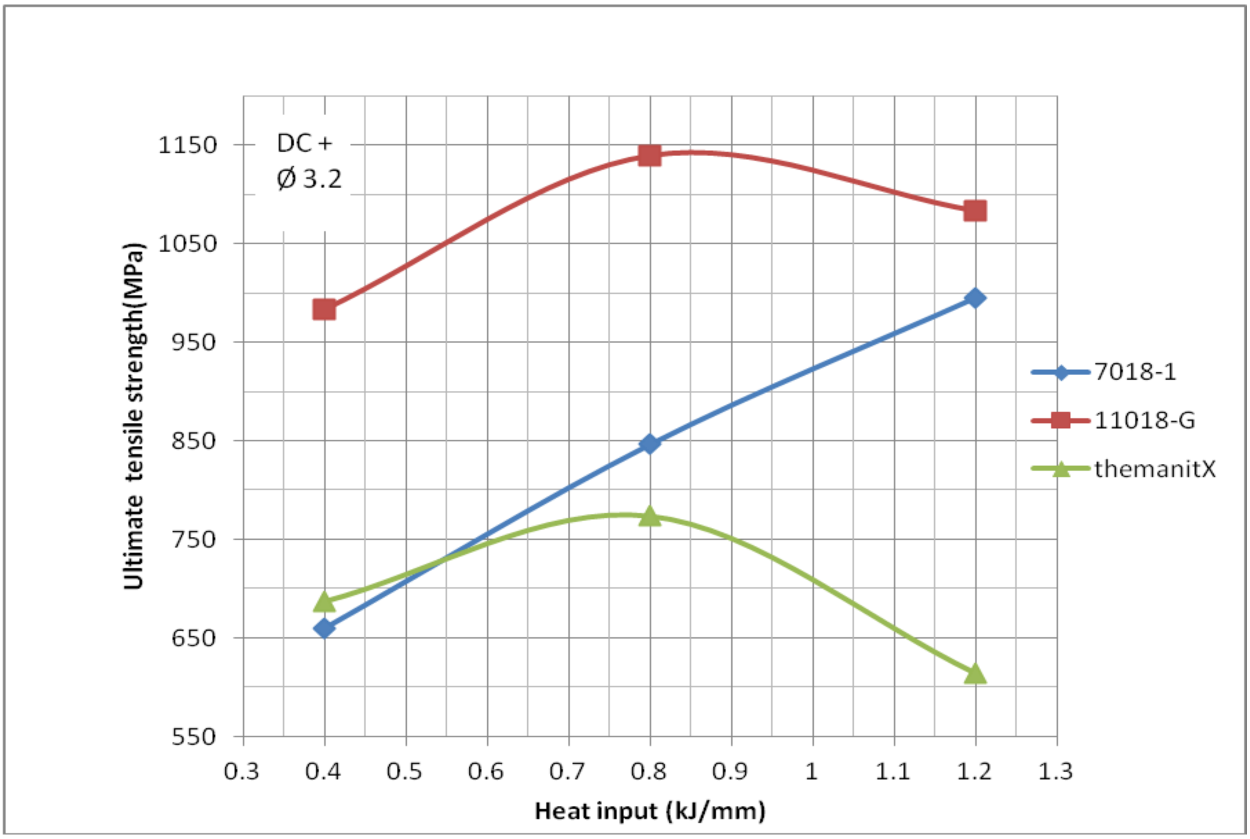

Fig. 8 The effect of heat input on the ultimate tensile strength of the welded joints using the three selected types of electrodes

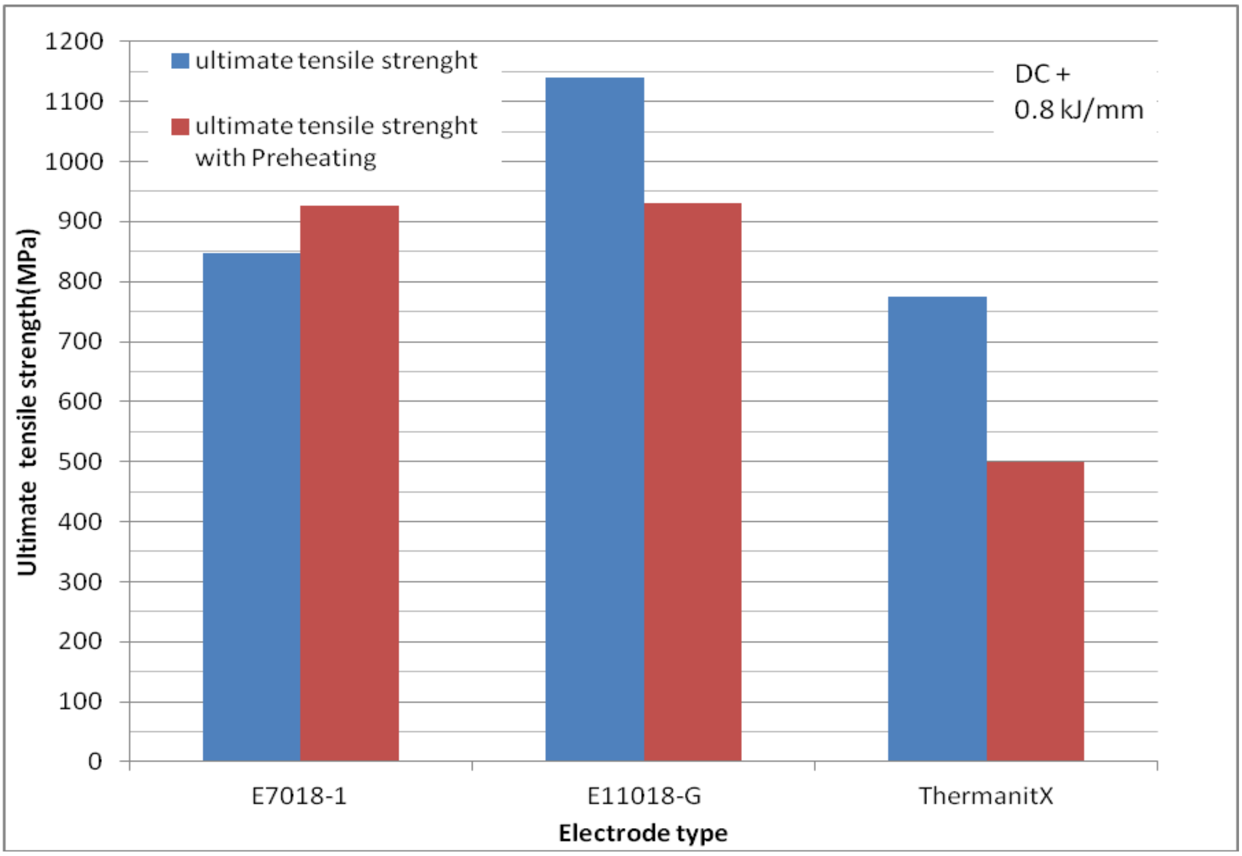

Fig. 9 The effect of preheating at 300°C on ultimate tensile strength of the welded joints using the three selected types of electrodes

4. Conclusion

1- The joints fabricated by LHF (low-carbon steel & low-alloy steel) consumables have superior tensile properties owing to the presence of ferrite morphology in the weld metal microstructure while The joints fabricated by using austenitic stainless steel consumable exhibited lower strength, but higher toughness owing to the presence of higher nickel content and austenitic phase in the weld metal.

2- Higher heat input and preheating temperature is essential when using LHF consumables to avoid HIC by softening the hardened region near to the fusion zone but excess heat input and preheating temperature may reduce the strength level attained by these electrodes especially low-alloy steel electrodes which are sensitive to the cooling rates during welding. So it is necessary to limit the heat-input and preheating temperature to obtain the strength required from these electrodes and avoid HIC.

3- There is no need for higher heat input or preheating temperature when using ASS consumables as they are known for their good resistance to cold cracking because they have higher solubility for hydrogen in austenitic phase. Also excess heat-input and preheating temperature may decrease the strength of the welded joint due to the coarsening of delta ferrite.
4- HAZ shows hardened region near to the fusion zone which is susceptible to hydrogen cracking. Higher heat input and preheating temperatures increases the softening of this region which decrease the possibility of HIC.

5- HAZ softening has been observed in the present steel as in other quenched and tempered steels. The width of the softened zone is a function of heat-input and preheating temperature. The greater is the heat-input and preheating temperature the wider is the soft zone. Softening can, result in microstructures other than a fully martensitic microstructure. So it is necessary to limit the heat-input and preheating temperature to decrease the width of the softening zone for good ballistic performance.

5. References

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