Effect of Stress Relieving on Mechanical and Metallurgical Properties of Shielded Metal Arc Welded Joints of A517 Steel

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Abstract

Stress relieving is a common practice among manufacturing codes for reducing the magnitude of residual stresses in welded, quenched, and tempered steel structures and pressure vessels. The present work investigates the effect of stress relieving at 480, 560, 620, and 680°C on the microstructure and mechanical properties of 20 mm ASTM A517 Gr. B steel plate weldments produced by shielded metal arc welding (SMAW). For this purpose, metallographic analysis, hardness measurement, charpy V-notched impact test, and tensile test were performed. Result showed that stress relieving reduced the impact toughness of all the base metals but better mechanical properties (hardness, tensile stress and impact toughness) were achieved when it was accomplished at 560°C.

Keywords: A517 Gr. B steel, SMAW, Impact toughness, Mechanical properties, Stress relieving.

1. Introduction

Low alloy quenched and tempered (QT) steels are widely used in applications where high strength, weldability, and good fracture toughness are of critical importance [1)]. The increased strength of these alloys facilitates the use of thinner sections which leads to reduced weight and gives rise to potentially improved payload, mobility, and fuel economy [2)]. ASTM A517 steels are high strength steels of QT type, which are used for welded construction of all kinds such as pressure vessels, penstocks, bridges, and structures as well as transport vehicles, hoisting, earthmoving equipment, and shipbuilding applications for use in different climatic conditions [2, 3)].

This class of steel is produced through the Q&T route, where the steel is austenitized at about 900°C followed by water or oil quench to obtain a hard martensitic or bainitic structure. The quenched steel is extremely hard and brittle, and is subjected to a subcritical heat treatment known as tempering to soften it. The tempering treatment is carried out at temperatures of 480 to 600°C or higher, resulting in a tempered martensitic/bainitic microstructure associated with the right combination of strength, ductility, toughness, and weldability properties. After welding, the microstructure of the weld metals consist martensite and acicular ferrite due to the faster cooling rate. The areas of Heat Affected Zone (HAZ), a microstructure consisting of tempered martensite and coarse bainite [3)]. Post weld heat treatment (PWHT) with the aim of stress relieving is a mandatory and costly step in the manufacture or weld repair of transportable pressure vessels fabricated from Q&T steels. There have been limited reports on the adverse effects of the stress relieving process on the base plate toughness. Some observations have reported that the impact properties of simulated coarse-grained heat affected zone and weld metal (WM) structures are superior to the base plate, even with increased heat treatment time [4)].The present study investigated the effects of different stress relieving temperatures on the properties of shielded metal arc welds of A517 steel.

2. Materials and Methods

2.1. Materials

The base material used in this study was ASTM A517 Grade "B" (quenched and tempered), low-alloyed steel (with the chemical composition given in Table 1). Weld depositions were made in the grooves of 300*1000*20 mm steel plates. Metrode electrodes (E11018-M) of 2.5 and 3.2 mm in diameter were used as consumables. The selected welding process was shielded metal arc welding and double-v groove weld deposition was preferred to avoid the distortion of the weldment. SMAW electrodes were baked at tempera-

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tures from 250 to 350°C for 1 to 2 hours. Welding of the test plate was performed at uphill 3G position.

Preheat and interpass temperatures, respectively, were maintained at 100 and 205 °C during welding. After weld deposition was completed, the test plate was cut into 5 pieces to be used as specimens subjected to different heat treatment cycles in a resistance furnace. In order to compare the stress-relieved and non-stress-relieved conditions, one specimen was retained in its as-welded condition (without PWHT) to be used as control. Temperatures of stress relieving cycles were 480, 560, 620, and 680 °C, and the holding time was 75 min. As given in Table 2, the specimens were designated based on their stress relieving cycle.

2.2. Metallographic Assessments

In order to carry out metallographic assessments, preparation of the specimens was carried out according to ASTM E3:01 requirements and the etching solution was selected according to ASTM E407:99. The specimens used included weld metal, base metal (BM), coarse grain heat affected zone (CGHAZ), and fine grain heat affected zone (FGHAZ). After abrading and polishing, the specimens were etched in 2% Nital solution. Different areas of the specimens were observed using an optical microscope, and metallographic photographs were taken using a camera with a Japanese Jenoptic.

2.3. Hardness Testing

After stress relieving, macro hardness measurements were carried out using the Koopa (model UV1) hardness tester in order to evaluate hardness reduction.

Vickers hardness (HV) tests were conducted according to EN 1043-1:96 using an applying load of 10 kg to find out whether or not the hardness values of the quenched and tempered steel were in the acceptable range. The areas of the specimens subjected to hardness tests included weld metal, base metal, CGHAZ, and FGHAZ, as schematically shown in Fig. 1.

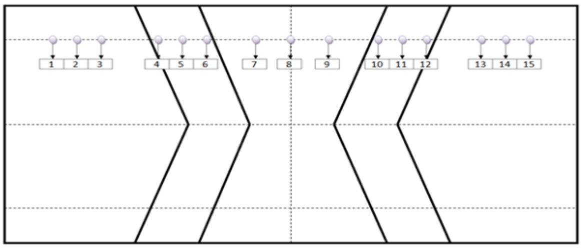

Fig. 1. Areas of sample in which Hardness test was performed.

2.4. Tensile test

The tensile test yields such varied information as yield point, tensile strength, elasticity module, and elongation percentage. In the present work, this test was carried out in order to compare the tensile strengths of the joints subjected to different post weld heat treatment cycles. For this purpose, a Gotech machine (model AI-700-LA20) was used and the testing and sampling were performed according to ASME Sec IX: 10 [5].

2.5. Charpy V-notch impact test

The impact test was performed to determine the impact toughness of the specimens. This test can simulate the resistance of the specimens to impact loads (i.e., the force exerted in accidents on a portable pressure vessel [4]). The dimensions of specimens used in this study were determined based on ASME Sec IX: 10 [5]. To evaluate the impact toughness of each area of the weld (such as base metal, weld metal, and HAZ), the notch was placed in that area. Impact tests were performed at -51±1°C using a Santam machine (model SIT-300) for three times. According to the ASME standard, for carbon and low-alloy steels with thicknesses in the range of 10 to 32 mm, the approved conditions for the impact test are:

- The absorbed impact energy for each specimen must be at least 27 joules.
- The average value of impact test results must not be less than 27 joules.
- None of the impact results must be less than two thirds of the average value [5].

2.6. Scanning electron microscopy

A Zeiss scanning electron microscope was used to study the fractography of the base metal impact specimens. The same microscope was used for Energy Dispersive X-Ray Analysis (EDAX) for performing elemental analysis of the specimens to determine the chemical composition of impurities on the fracture surface.

3. Results and Discussion

Metallographic images of all the specimens (T-480, T560, T-620, T 680, and AW) from both the coarse and fine grain heat affected zones (CGHAZ and FGHAZ) are shown in Figs. 2 and 3, respectively. Stress relief had no significant effects on the metallographic microstructure of either the weld metal or the base metal (images not shown). According to the literature, austenitizing at 900°C with subsequent quenching in oil and tempering at 620°C produces a martensitic structure in A517 steel [6]. The tempered martensitic structure of the base metal can also is observed in Fig. 3 in the areas marked by ‘BM’. Comparison of the images of specimens stress relieved at 480, 560, 620, and 680°C (Figs. 3a, b, c and d) with that of the control AW specimen (Fig. 3e) reveals no considerable changes in the optical microscopy images at 400 × magnification of the microstructure of the stress-relieved BMs.

In addition, small amounts of ferrite grains and acicular ferrite (which are more brittle than the base metal grains due to the rapid cooling of welding) along with pearlite areas are clearly seen in Fig. 3. In Figs. 2b and e, in areas marked ‘WM’ (which are related to the weld metal of the specimens) it is observed that the microstructure of the weld metals are martensite and acicular ferrite due to the faster cooling rate. Also in Fig. 2 which is generally related to CGHAZ, in the areas marked ‘CGHAZ’, a microstructure consisting of tempered martensite and coarse bainite is obtained.

Comparison of the images of all the stress-relieved specimens including pictures (a) to (d) in Figs. 2 and 3, with the images of the AW specimens and picture (e) in Figs. 2 and 3 reveals no considerable microstructural changes. Studying the effects of stress relieving at 580°C on welded BIS80PV quenched and tempered steel joints, Sterjovski et al. 7) also reported no microstructural changes in different areas of their weldments.

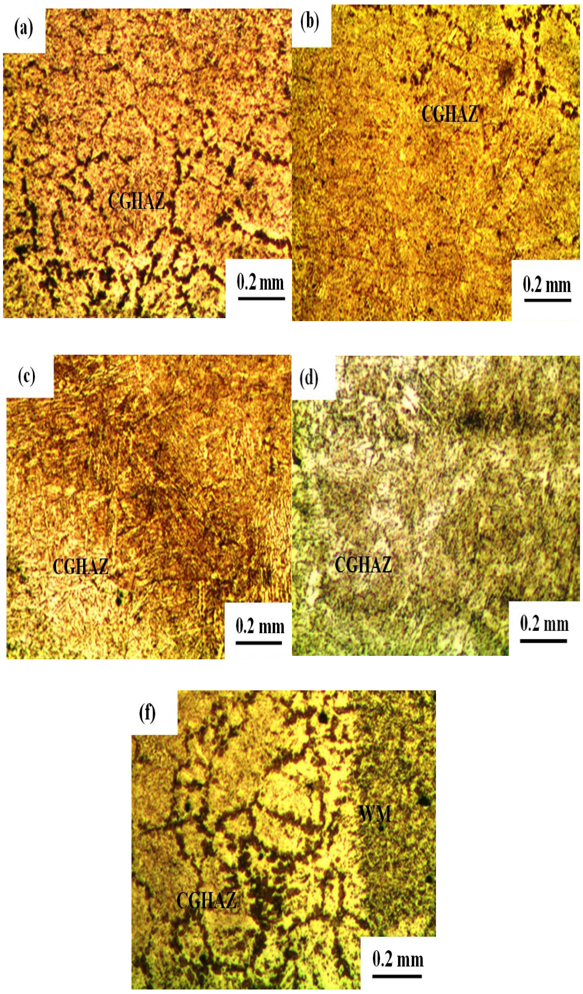

Fig. 2. Metallographic images of coarse grain heat-affected zone (CGHAZ) of samples: (a) T-480, (b) T-560, (c) T-620, (d) T-680 and (e) AW.

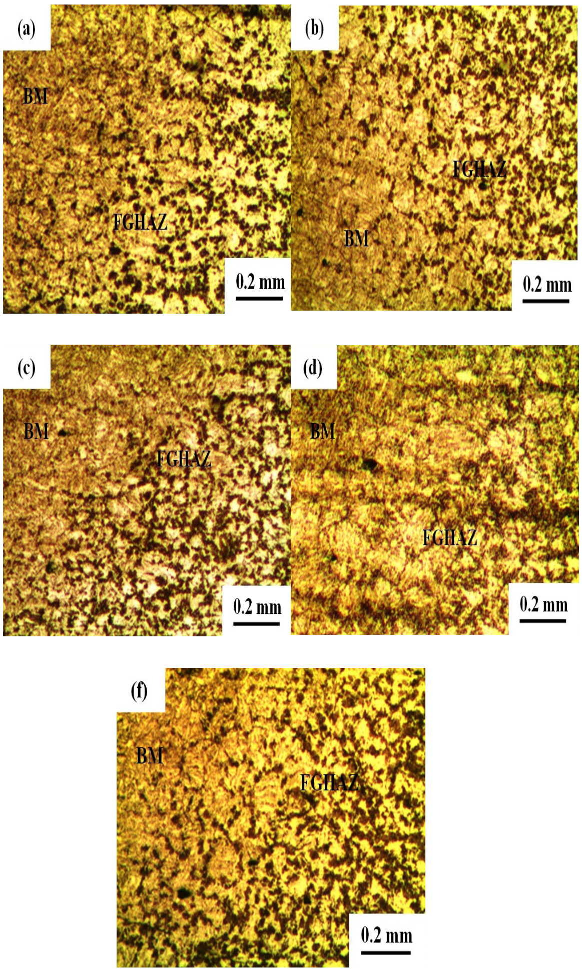

Fig. 3. Metallographic images of fine grain heat-affected zone (FGHAZ) of samples: (a) T-480, (b) T-560, (c) T-620, (d) T-680 and (e) AW.

As already mentioned, the hardness of the specimens in this study was measured at points shown in Fig. 1. For easier comparison, the results are illustrated graphically in Fig. 4.

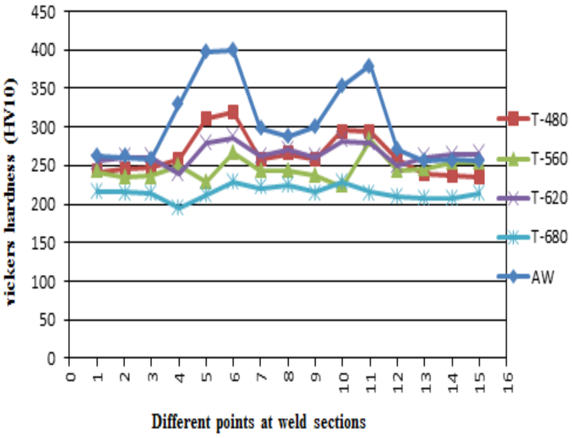

Fig. 4. Hardness profiles of all samples.

Clearly, the minimum hardness measured for the base metal of the AW specimen was 258 HV at point no. 3, and the maximum hardness measured for CGHAZ of this same specimen was 400 HV at point no. 6. Since the CGHAZ area of the control AW specimen is adjacent to the weld metal and experiences thermal cycles with higher temperatures (compared to the base metal) during welding, austenite grains may grow and grain boundaries may reduce in this area, which makes diffusional transformation more difficult (or, increases hardenability). Therefore, fast cooling after welding along with increased hardenability of CGHAZ may produce a coarse and high-carbon martensitic structure which results in maximum hardness. The results obtained for the AW specimen are similar to those reported by Sterjovski et al. 7) who experimented with BIS80PV steel weldments before stress relieving.

They reported maximum hardness in the CGHAZ area at about 420 HV. Also, their results for the non-stress relived specimen (which was the same as the AW specimen in this work) showed that the hardness of the weld metal was higher than that of the base metal 7). It is seen in Fig. 4 that stress relief had almost similar effects on the weld metal of both T-480 and T-620 specimens, and compared to the AW specimen, the two experienced approximately similar hardness reductions.

Moreover, the maximum hardness reductions in both weld and base metals were obtained in the T-680 specimen. On the other hand, the weld metal of AW exhibited a greater hardness than all the stress-relieved specimens. It is also observed in the same figure that the T-560 specimen is almost similar in hardness to its base metal. Nevertheless, compared to the AW specimen, its hardness reduction is not too much, but it has maintained its good properties after PWHT. The T-680 specimen also exhibits very close hardness values in its weld metal and base metal, but compared to the primary condition of the plate (i.e., AW), the hardness reduction in this specimen is so high that the steel has lost its ideal properties. The results of weld metal hardness test in the present work agree well with those reported by Huang et al. 8) who investigated the effect of PWHT on SAE 4130 steel weldments. They also reported reduced hardness in the martensitic structure of weld metal. According to their results, the specimen stress relieved at higher temperatures (530°C) exhibited a much higher reduction in hardness compared to the one undergoing stress relieving at lower temperatures (320°C). In welded, quenched, and tempered steels, maximum degradation of properties after welding occurs in HAZs. Hence, the most important reason for stress relieving (or PWHT) of the welded QT steel joints is improving the mechanical properties of the weld areas and homogenizing the properties in these areas compared to the adjacent base metal.

As shown in Fig. 4, it is evident that hardness in the heat affected zone, especially in the CGHAZ, of AW increased to great extent as a result of welding. Fig. 4 shows that PWHT in all the stress-relieved specimens (T-480, T-560, T-620 and T-680) greatly reduced the hardness of CGHAZ. Comparison of the hardness of the specimens in Fig. 4 reveals that maximum and minimum hardness values of HAZs occurred in AW (400 HV at point No. 6) and T-680 (195 HV at point 4), respectively. These results are in agreement with those reported by Bhadeshia et al. 9) who studied the effects of PWHT on the Cr-Mo steel weldments with the aim of stress relieving and tempering of the structure and observed hardness reductions in the weld metal and the HAZ (especially CGHAZ). Fig. 5 presents the results of tensile testing of the specimens. Except for T-680, rupture occurred in the weld metal of all the other specimens. Rupture in the HAZ of T-680 and the minimum hardness observed in its CGHAZ among all the specimens indicate that high temperature PWHT leads to undesirable microstructural changes. Sterjovski et al. 7) reported that ruptures occurred in the weld metal of BIS80PV quenched and tempered steel weldments during tensile testing. The tensile test results in the present study are in agreement with their results.

As illustrated in Fig. 5, compared to AW, the reductions gained in the tensile strength of T-480, T-560, T-620, and T-680 are 2, 5, 6, and 18%, respectively, and that these reductions increase up to their maximum (18%) in T-680 with increasing PWHT temperature. In other words, the ductility of the welds increases with increasing stress relieving temperature.

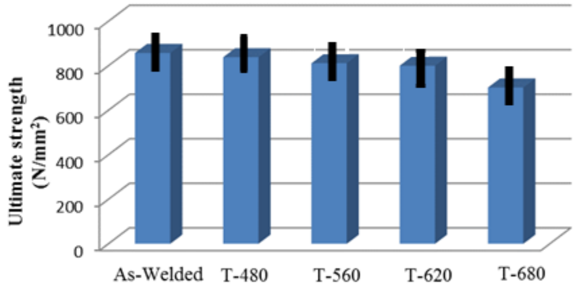

Fig. 5. Results of tensile strength test of all welded samples.

For easy evaluation and comparison, the average values of impact energy in each of the three areas (the base metal, HAZ, and weld metal) of the specimens are plotted in the diagram in Fig. 6.

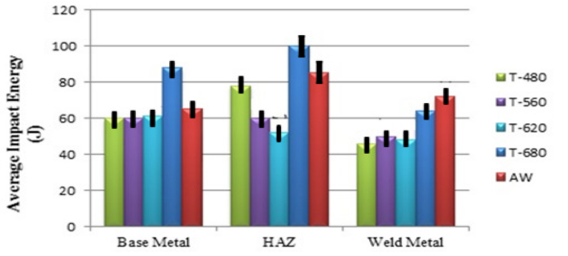

Fig. 6. Columnar graphs of absorbed energy of all samples at different weld areas (WM, HAZ and BM).

It is evident that the absorbed impact energy measured at the HAZ in most specimens has a rather high dispersion. Different areas (including FGHAZ and CGHAZ) with different microstructures may result in this dispersion in HAZs. Comparison of the impact energies of AW with those of T-480, T-560, and T-620 in Fig. 6 reveals that the impact energy reduced in their HAZs by 8, 29, and 32%, respectively, as a result of stress relieving. In other words, the three specimens with higher stress relieving temperatures became more brittle in their heat affected zones. The minimum impact energy of HAZs was obtained for T-620, which is probably due to the formation of detrimental carbides. In the case of the base metal, as observed in Fig. 6, the specimens (except for T-620) exhibited almost the same values of impact energy. This means that T-480, T-560, and T-620 in the base metal, compared to AW, had no significant changes in their impact toughness, but only a slight decrease. In other words, by conducting stress relieving heat treatment for 75 minutes at 480, 560 and 620°C, the absorbed energy of the base metals reduced to 8% and the base metals became slightly more brittle. However, by stress relieving at 680°C, the absorbed energy of the base metals increased by about 35% and the base metal became less brittle. This loss of impact energy inT-680 may have been caused by the high temperature of stress relieving, which results in over-tempering of A517 steel (with a tempered martensitic structure). The impact test with the undesirable microstructural changes that led to the loss of ideal properties in A517 steel compared to its primary state (AW) can be explained along the same lines as was in the case of hardness and tensile testing of T-680. The fractographic images of the impact tested base metals are shown in Fig. 7.

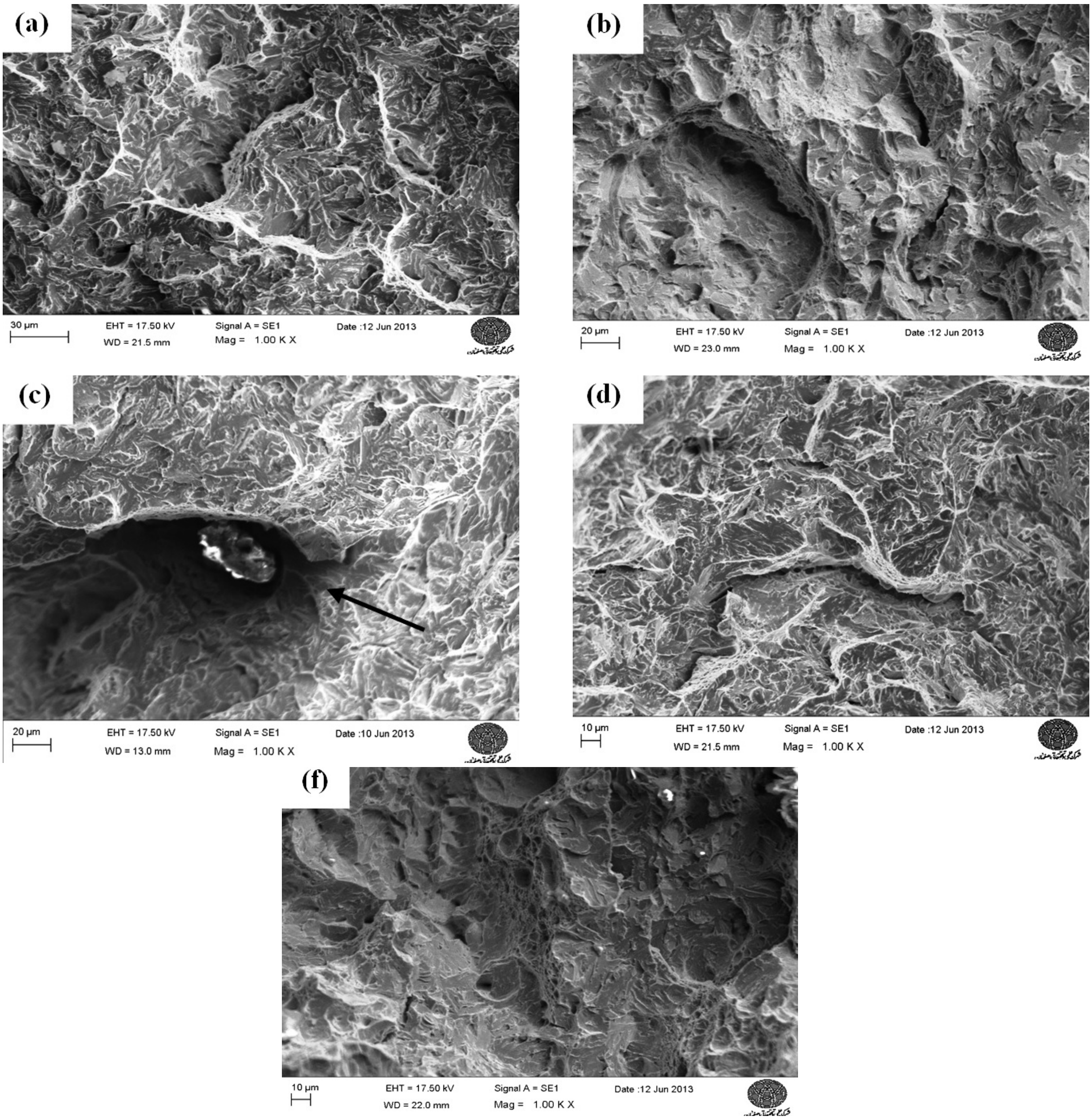

Fig. 7. SEM images from fracture surfaces of base metal of samples: (a) T-480, (b) T-560, (c) T-620, (d) T-680 and (e) AW.

Comparison of these images reveals that the fractured surface of T-680 (which, according to Fig. 6, has the highest impact energy in its base metal compared to other specimens) contains more and finer dimples, indicating a higher percentage of ductile form of fracture. The arrow in Fig. 7c shows an impurity at the fracture surface of the base metal of T-620. The Energy Dispersive X-Ray Analysis (EDAX) for this impurity is shown in Fig. 8.

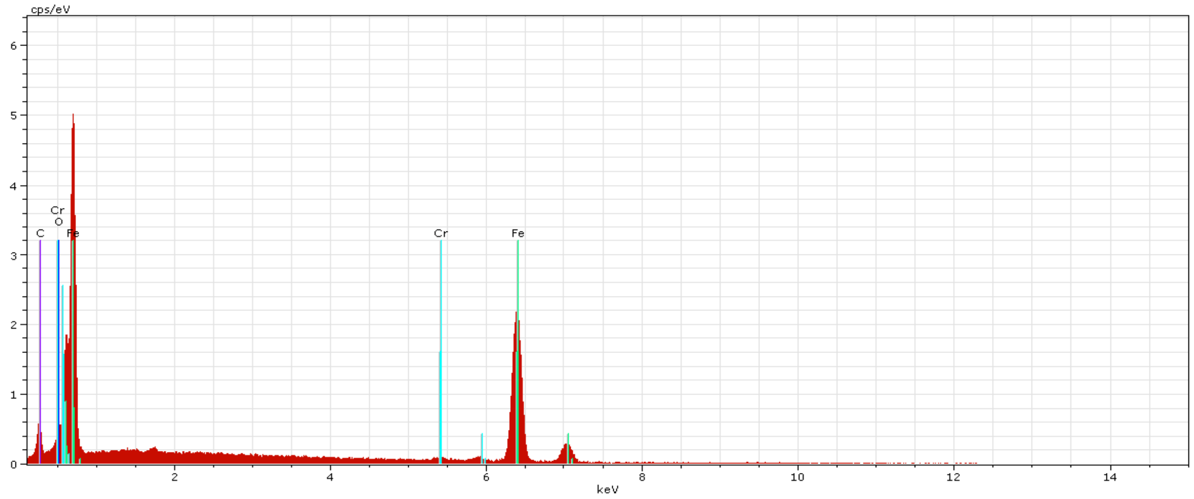

Fig. 8. EDS analysis related to impurity shown in Fig.7 (c) from fracture surface of base metal of sample T-620.

In this impurity, high temperature stress relieving (620°C) probably caused the supersaturated carbon to move out of the high carbon martensitic structure and to form carbides with the alloying elements of steel; consequently, this alloying carbide might have initiated and propagated cracks to reduce the absorbed impact energy of the metal. It is clear from Fig. 8 that the main elements of this impurity are Fe, Cr, and C.

It is, therefore, likely that stress relieving led to the formation of chromium carbide or complex carbide (consisting of iron and chromium) in the A517 steel weldments. Pimenta et al. [10] investigated the effects of long-time post weld heat treatments on the mechanical properties of A516 Gr70 carbon-manganese pressure vessel steel. According to their results, PWHT reduced the impact energy of the base metal in welded joints, a finding that agrees well with the results of the present study. Comparison of the impact energies of weld metals in T-480, T-560, T-620, and T-680 with that of AW in Fig. 6 shows that the toughness of the stress-relieved samples reduced by 36, 30, 33, and 11%, respectively, as a result of stress relieving. The reduced toughness in the base metals of the stress-relieved specimens is probably caused by exposure to the relatively high temperature ranges during stress relieving, which led to the formation of a continuous carbide network at the grain boundaries of the weld metal with the acicular ferrite microstructure, ultimately resulting in the tempering embrittlement. On the other hand, the impact energy of the weld metal is lower than that of HAZ in all the specimens except for T-680. The lower fracture toughness of the weld metal compared to that of the HAZ can be justified on the basis of the nature of the metal in this area which is similar to castings in which higher inclusions from the coated electrodes maybe entrapped in the weld pool due to the rapid cooling after welding. There are, therefore, more preferential sites for the initiation and propagation of cracks in the weld metal than are in the HAZ, leading to lower impact energies in these areas. On the other hand, based on published reports on the distribution of residual stresses, maximum residual tensile stresses due to welding occurs in the weld metal, which may be another reason for the lower impact energy in this area compared to HAZ [11].

4. Conclusions

Based on the results of this study, the following conclusions may be drawn:

- Stress relieving heat treatment makes no considerable change in the microstructure of the different weld areas (WM, BM and HAZ).

- Increasing the temperature of the stress relieving heat treatment leads to more reductions in hardness of different weld areas.

- Stress relieving reduces the tensile strength of the A517 quenched and tempered steel weldments and strength reduction increases with increasing the stress relieving temperature.

- As a result of stress relief at 480, 560, 620, and 680°C for 75 minutes, the impact energy of the weld metal reduces (as compared to the welding metal of a non-stress relieved specimen).

- Stress relieving at 480, 560, and 620°C, reduces the impact energy (or fracture toughness) of the base metal (compared to that of the base metal of a non-stress relieved specimen), and these reductions are small and almost equal (about 8%).

- Compared to the HAZ of AW, stress relief at 480, 560, and 620°C reduces the impact energy of HAZs by about 8%, 29%, and 32%, respectively.

- It is concluded that stress relieving at 560°C, among the applied cycles at different temperatures, leads to better mechanical properties.

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