Influence of Ti addition on fracture behaviour of HSLA steel using TIG melting technique

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Abstract. The welding process is a critical stage in the production of structural parts and the microstructure and mechanical properties of the welded joints must be appropriate in order to guarantee the reliability and durability of the components. The fracture toughness behaviour, which accounts for the residual strength of the component in the presence of flaws or cracks, is one of the most important properties to be evaluated in terms of microstructure and mechanical properties. In this present study, the surface of high strength low alloy (HSLA) steel was surface modified with the preplacement of pure Titanium (Ti) powder using a tungsten inert gas (TIG) arc heat source, at 100 ampere current with a voltage 30 V and a constant traversing speed of 1.0 mm/s using Argon shielded gas. The effect of preplaced Ti powder on the strength and toughness properties of the modified HSLA steel surface was investigated. The results indicated that the tensile and yield strength of HSLA steel decreased by ~12% and ~14%, respectively. While the impact toughness increased by ~33% and the ductility decreased by ~50%. The fractography analysis results by scanning electron microscopy (SEM) were also presented in this paper.

1. Introduction

High-strength, low-alloy (HSLA) steels are aimed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are designed to meet specific mechanical properties, such as yield strength greater than 275 MPa [1, 2]. Due to the high strength-to-weight ratio, HSLA steels are widely employed as a suitable material for oil and gas pipelines, chemical, petrochemical and marine applications [3]. However, owing to their low toughness and low strength due to welding process, their potential application is restricted. The welding process is a critical stage in the production of structural parts and the microstructure and mechanical properties of the welded joints must be appropriate in order to guarantee the reliability and durability of the components. The fracture toughness, which accounts for the residual strength of the component in the presence of flaws or cracks, is one of the most important properties to be evaluated [4]. One of the ways to overcome the problem is to modify the welding area on the substrate material.
by melting microalloying elements (Ti, V, Nb) via high energy input. Since then, research works showed improvement in surface hardness under this processing technique [5, 6]. On the other hand, the modified surfaces may affect the strength and toughness of particular material properties. Mechanical properties of HSLA steels are strongly connected to their microstructure obtained after welding that are generally performed in order to achieve a good hardness and/or tensile strength with sufficient ductility [7].

The development of surface alloying by adding a Ti powder into a molten alloy pool created by surface melting using TIG torch has been actively researched to obtain superior wear and corrosion resistance of low alloy steel [7-9]. The TIG torch with adequate power density is scanned over the material which melts a thin layer of the substrate surface by absorbing heat energy from the torch in a short time interval; the melt matrix interface moves toward the substrate at a rate which depends on the scanning speed and creates a melt pool. Upon solidification, the solidified layer creates a metallurgical bond with the substrate material [10]. Very stable Ti-rich carbonitrides can constrict austenite grain coarsening during austenitization. Small Ti additions may increase toughness and it was found to have significant influence on refinement of grains and increase of ferrite/pearlite ratio. Ti is the only micro-alloy Carbo-nitride that is stable at the high temperature attained in the HAZ during welding [11]. Increasing the titanium level in the range 0.01%-0.03% improving the toughness, particularly when the nitrogen and oxygen levels approach stoichiometry. However, if the titanium and nitrogen levels were sufficiently high to permit formation of TiN during solidification, then the resultant particles could act as crack nuclei which increase fracture transition temperature. It is well known that Ti, Nb, and V carbonitrides dissolve during the heating cycle of fusion welding, and precipitate if the cooling rate is slow enough [12]. It follows that the effect of any microalloying addition on HAZ toughness properties depends markedly on the heat input used (on the thermal cycle enabling particle solution, possible re-precipitation and subsequent hardening), and on the effect of soluble titanium on the phase transformations occurring during cooling after welding [13]. In another study the better combination of microstructure and impact properties was obtained in the range of 0.02–0.05% titanium by increasing the formation of acicular ferrite in the microstructure [14].

There is a little publication focusing on the effect of the surface modification technique by melting using TIG torch on the mechanical behavior of HSLA steel. Therefore, in the present work, HSLA steel was evaluated with Ti addition using TIG torch to modify the surface. Samples were taken from the chosen steel in order to provide information on the fracture toughness and mechanical behavior of the welding zone. The mechanical properties characterization was performed by means of tensile test and impact toughness. The obtained results provide a support for understanding on how the surface modification process affect the materials properties. The fractography analysis results by scanning electron microscopy (SEM) were also presented in this paper.

2. Experimental

A 10 mm thick HSLA steel plate with chemical composition containing 0.08% C was used as substrate material for this investigation and the chemical composition of the used HSLA steel is presented in Table 1. The specimen with the dimensions of 250 mm × 200 mm were cut out from the plate by using CNC machine. Tensile and impact samples were prepared according to ASTM E8-M-04 and ASTM E 23-11, respectively. The sample surface was abraded with SiC paper and degreased using acetone. The 45 μm size titanium powder of 99.97% purity was used as a preplacement and the amount was 1 mg per mm² area of the specimen surface. The Ti powder was first made into a pasty mass by mixing with PVA (polyvinyl acetate) binder and then placed on the substrate surfaces. The use of binder was mainly to prevent the powder from blowing away during melting operation under the flow of shielding gas [15]. The Ti powder preplaced specimen was then dried in an oven at 60 °C for 1h to remove moisture.
### Table 1. Chemical Composition of the HSLA steel (wt. %)

|   | C     | Si    | Mn    | P    | S    | Cr    | Ni    | Cu    | Mo    | V    | Al    | Ti    | Nb    | Fe    |
|---|-------|-------|-------|------|------|-------|-------|-------|-------|------|-------|-------|-------|-------|
|   | 0.08  | 0.17  | 1.41  | 0.014| 0.0017| 0.024 | 0.016 | 0.011 | 0.003 | 0.022| 0.032 | 0.015 | 0.019 | Bal.  |

A Miller TIG torch source attached with a semi-automatic traversing arm was used for melting purpose. The direct current electrode negative (DCEN) mode was used and a 3.2 mm diameter tungsten electrode was used to strike an arc between the electrode and the workpiece in pure Argon atmosphere with a gas flow rate of 20 L/min to prevent excessive oxidation. The arc was produced using a current of 100 A and voltage of 30 V. The glazing of the preplaced powder layer was done under the torch at a constant electrode traverse speed of 1.5 mm/s. The optimum parameters of TIG torch technique was chosen from elsewhere [6].

The Ti preplaced HSLA steel was tested using tensile testing machine in order to determine the tensile strength ($\sigma_{uts}$), yield strength ($\sigma_y$), as well as percent of elongation (E %). The tensile test is done at room temperature on Instor-5582 universal testing machine at a crosshead speed 2.5mm/min (three specimens were tested and the average value was presented). Also, the 10mm X10mm X 55 mm Charpy impact specimens were prepared to evaluate the impact toughness using INSTRON Charpy testing machine with 400J capacity at 25 °C. Impact energies were recorded and fracture surface was studied by using SEM.

### 3. Results and discussion

The results are presented and discussed in the following sections in terms of tensile properties, impact toughness, and fractography.

#### 3.1 Tensile properties

The tensile test results of HSLA steel with and without Ti addition is presented in Fig. 1. Fig 2 and Table 2. Modified HSLA steel showed that the tensile strength was decreased by ~12%, the yield strength decreased by ~14%, and also ductility reduced compared to as-received HSLA steel evaluated in this work by ~50. It shows a significant variation in the tensile properties due to the influence of Ti addition using TIG melting technique that change the chemical composition and microstructural morphology [16].

![Fig. 1. Stress – Strain curve for as received HSLA steel](image1)

![Fig. 2. Stress – Strain curve for modified HSLA steel with Ti addition.](image2)
Table 2. Tensile test results.

| Steel                        | $\sigma_y$ (MPa) | $\sigma_{uts}$ (MPa) | E (%) |
|------------------------------|------------------|----------------------|-------|
| As received HSLA steel       | 370              | 445                  | 42    |
| Modified HSLA steel with Ti addition | 320              | 390                  | 21    |

3.2 Impact toughness

The Charpy impact test result is shown in Table 3. The general behavior is that the absorbed impact toughness corresponding to modified HSLA steel with Ti addition is higher compared to as-received HSLA steel. A significant increase in the impact toughness occurred for the test conducted which showed ~33%. It is also remarkable that though decrease in the tensile properties of the modified HSLA steel, but toughness properties of this steel was increased significantly which is required for pipeline applications. Improvement in HSLA steel toughness was obtained by the addition of Ti on the surface which produce new microstructural feature through the formation of intermetallic compound. Similar observation was done by other researchers [17].

Table 3. Charpy impact toughness test results

| Sample No. | 1   | 2   | 3   | Average |
|------------|-----|-----|-----|---------|
| Impact toughness of received HSAL steel (J) | 88  | 85  | 83  | 85      |
| Impact toughness of Ti addition HSAL steel (J) | 100 | 115 | 125 | 113     |

3.3 Fractography

Further SEM examination on the fracture surfaces was conducted closely to the notch area and at the middle area especially in the TIG torch melting zone and base metal fractured surfaces. These impact tested specimens of base metal and welded zone were analyzed using a scanning electron microscope and EDX. It shows that the morphology of fracture surface of Charpy impact notch samples mainly consists of quasi-cleavage facets in the region of TIG torch melting zone. In addition, some river-like lines on quasi-cleavage facets and some cracks are also observed as shown in Fig. 4. However, the base metal shows that numerous dimples, which indicating a better deformation with higher ductility as indicated in Fig. 3.

Fig. 3. SEM image of fractured surfaces of impact samples of base metal.

Fig. 4. SEM image of fractured surfaces of impact samples of TIG melting zone.
The EDX elemental analysis of the three zones (base metal, fusion line and TIG torch welding zone) is shown in Fig. 5. It shows dissolution of preplaced Ti powder in HSLA steel whereby the melting of Ti depends on the energy input and the Ti content. In HSLA steels, crack initiation and propagation are dependent on the type and distribution of the brittle phase, as well as the characteristics of the matrix microstructure, inclusion particles, particularly the grain size. Figure 6 indicate the location of cleavage fracture mechanism was transgranular leading to brittle fracture, and the location of ductile mechanism was intergranular decohesion for both samples, impact and tensile fractures.

Fig. 5. EDX analysis traces of Ti added HSLA steel taken from the fracture surfaces; a) Base metal, b) Fusion line and c) Weld zone.

Fig. 6. SEM fractographs of Ti added HSLA steel; a) Tensile fracture, and b) Impact fracture

4. Conclusion

The following conclusion can be drawn from the present study:

1. The additional of 1mg/mm² Ti powder in HSLA steel has a significant influence on the mechanical properties and impact toughness representing lower strength and higher toughness.
2. The impact toughness was improved by 33%, however, ultimate tensile strength was decreased by 12% with the addition of Ti under TIG torch melting technique.
3. Improvement in toughness was obtained due to new microstructural feature through the formation of intermetallic compound.
4. Fractography observations revealed that the fracture characteristics were most likely brittle fracture in welding area, base metal exhibited ductile fracture resulting higher impact toughness for the modified HSLA steel.
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