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The comparison of gas tungsten arc welding and flux cored arc welding effects on dual phase steel

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Abstract

This work aims to investigate the effects of two welding techniques (gas tungsten arc welding (GTAW) with filler metal ER70S-3 and flux cored arc welding (FCAW) with filler metal E71T1C) on the microstructure and mechanical properties (including softening due to the conversion of martensite into tempered martensite) of DP steels with different martensite volume fractions ranging from 9 to 20%. Microstructure features and the constituents of base metals and heat affected zones of all weldments were examined and analyzed using an optical microscope and a scanning electron microscope integrated with energy-dispersive x-ray spectroscopy. Hardness, tensile, and v-notch impact toughness measurements were also carried out. Visual and radiographic inspection showed that both the FCAW and GTAW techniques produced sound weldments. However, DP steel weldments exhibited softening effects, which led to a decrease in joint efficiency. This decrease were related to transformation of the original martensite into tempered martensite. The results also revealed that the DP steel joint efficiencies are ranged from 85.9 to 87.7% using the FCAW process and ranged from 83.3 to 86% using the GTAW process. The impact toughness of the samples welded by FCAW is higher than the impact toughness of those welded by GTAW due to a higher percentage of acicular ferrite. This information should be valuable in the automotive and other industries, where DP steels are valued for their combination of high strength and ductility, which leads to weight savings and thus to reduced fuel consumption.

1. Introduction

Advanced high strength steel sheets are widely used in the automotive industry sector as their high strength per weight ratio which enable to reduce fuel consumption and carbon emissions. By 2020, a production of mid-size vehicles were expected using more than 20 types of new advanced high strength steels [1, 2]. Dual phase (DP) steel is an advanced high strength steel family in which a ferritic matrix contains islands of a hard martensitic second phase [3]. The martensite phase in DP steel defines the strength of steel, while ferrite phase allows for its ductile capacity. Increasing the volume fraction of the second phase increases the steel’s strength. DP steels were produced by rapid cooling of the austenite structure presents in α + γ regions into the martensite structure. Depending on the intercritical annealing conditions (holding temperature and holding time), different martensite volume fractions are obtained. The mechanical properties of DP steels depend on martensite volume fraction, martensite islands distribution in the ferrite phase, shape and grain sizes and partitioning of stress–strain between two phases [1, 2]. DP steel can be welded using a variety of fusion techniques, including resistance spot [3–7], laser beam [8–11], plasma arc [12–14], friction stir [15–18] and gas metal arc welding. Xia and Biro investigated the effects of heat input on heat affected zone (HAZ) softening [19], which cannot be avoided in DP steels. HAZ softening occurs in the subcritical HAZ, where tempering takes place and temperatures during the welding process remain at or below the Ac1 temperature [20, 21]. Biro et al concluded that HAZ softening of DP steel weldments by martensite tempering depends on the nucleation and growth of cementite [22]. Xu et al and Lakshminarayana et al found that the softer
The fusion zone formed in laser welding consists mainly of martensite, ferrite, and bainite; an almost fully martensite structure was observed, attributable to the faster cooling rate [23, 24]. Zhao et al studied how laser welding speed affects the microstructure and properties of DP steels of 600, 800, and 1000 MPa grades; they concluded that a linear relationship existed between the carbon equivalent and the hardness of the fusion zone [25]. Wang et al studied laser-welded joints of DP1000 steel, and concluded that they were softened by the tempering and softening of pre-existing martensite and by carbide precipitation [26, 27]. Resistance spot-welded DP1000 was studied by Chabok et al, who found that double pulse welding results in a softer HAZ [28]. Tiziani et al evaluated the effects of three types of welding (gas tungsten arc, plasma arc, and electron beam) on the properties of DP600 steel. They found a fusion zone microstructure containing a mixture of acicular, bainitic, and allotriomorphic ferrite; a zone with a coarse grain near the interface of the fusion and heat-affected zones; and a soft zone of tempered martensite [29]. Lee et al observed that the welded zone increases its size with heat input, tungsten inert gas welding exhibiting this effect more strongly than metal active gas welding, and laser welding more than either [30]. Khraisat et al [31] studied the influence of rolling...
direction on the weld structure and mechanical properties of a cold-rolled DP 1000 steel. Their results showed that, the degree of softening of the heat affected zone (HAZ) were found high in the sample welded parallel to the rolling direction because of the slower heat dissipation as confirmed by its microstructural products. The tensile strength or the hardness did not significantly decreased due to this softening. Ramazani et al. [32] investigated the gas metal arc welding (GMAW) process of high strength hot rolled dual phase sheet steel. The evolution of different diffusional transformational phases was simulated based on dilatometer experiments. The authors concluded that the martensite and ferrite transform into austenite during the heating cycle. The austenite grain grows after nucleation and decomposes into bainite phase or bainite and ferrite phases in the cooling cycle, depending on the heat input.

Figure 3. OM (mag. 400×) and SEM of base metal microstructure: (a), (b) Specimen with 9% martensite, (c), (d) Specimen with 15% martensite, and (e), (f) Specimen with 20% martensite.
Hayat and Uzun [33] examined the microstructural evolution and mechanical properties of dual phase steel containing different contents of martensite volume fraction using GMAW with solid and flux-cored welding wires. They reported that the microstructure of the dual-phase steels joined with solid wire shows a martensitic phase in the weld metal, although the dual-phase steels joined with flux-cored wire exhibit ferrite phase in the weld metal. The tensile strength of the dual-phase steels joined with solid wire was tightly higher than that joined with flux-cored wire. So et al [34] investigated the weldability of alternative current pulse GMAW joints of 780 MPa dual-phase steel using a high-speed camera to follow-up the wire melting during the desired welding process. They concluded good relations among the welding current, electrode negative ratio, welding speed and bead shape parameters (bead width, height and penetration). The static tensile strength of GMAW lap joints of 1.5 mm uncoated dual phase 600 steels was studied [35]. The influence of wire feed rate and torch speed on the joint strength were investigated using a statistical approach via a two factor, two level, full factorial design of experiment. The results showed that the wire feed rate was the only significant factor on static tensile strength. The hardness dramatically decreased by 40% at the heat affected zone. In the present study, flux cored arc welding (FCAW) and gas tungsten arc welding (GTAW) are applied to the welding of DP steels with different martensite contents (9%, 15%, and 20% vol%). Electrodes of types E71T1C and ER70S-3 are used as fillers in FCAW and GTAW, respectively. The weldments are investigated by mechanical testing and metallographic examination using optical and scanning electron microscopy integrated with

**Figure 4.** EDX spectrum of base metal: (a) Specimen with 9% martensite, (b) Specimen with 15% martensite, and (c) Specimen with 20% martensite.

**Table 3.** Welding parameters of the desired welding techniques.

| Welding parameter       | FCAW | GTAW |
|-------------------------|------|------|
| Welding potential, Volts| 149  | 158  |
| Welding current, Amp.   | 160  | 168  |
| Welding speed, mm/min   | 418.2| 576.0|
| Heat input, kJ/mm       | 3.42 | 2.77 |
energy-dispersive x-ray (EDX) spectroscopy. The effect of the martensite volume on HAZ softening will also be considered.

2. Experimental work

2.1. Material

DP steel sheets containing 9%, 15%, and 20% (vol%) martensite were supplied by Ezz El-Dekheila Steel Company, Alexandria, Egypt. The desired DP steels were provided from a 3 mm thickness sheet by intercritical
annealing as shown in figure 1. Different martensite volume fraction DP steels were obtained depending on the holding time variation at 730 °C as a holding temperature. The chemical compositions and mechanical properties of the DP steels used are shown in tables 1 and 2, respectively.

2.2. Welding procedure
The DP steel sheets were be cut into dimensions of 300 × 400 mm to be ready for the welding processes. Two welding techniques were used to join twelve sheets of DP steel and produce six weldments. For each welding
technique, the experiments were repeated at least three times. The first technique was flux core arc welding (FCAW) using electrodes of type E71T-1C, shielding gas 100% CO2, and electrode diameter 1.2 mm. The second technique was gas tungsten arc welding (GTAW) using electrodes of type ER70S-3, shielding gas 99.9% argon, and electrode diameter 1.2 mm. The joints were prepared as shown in figure 2. The chemical and mechanical properties of electrode types E71T-1C and ER70S-3 are given in AWS A5.20 & AWS A5.18 respectively. The welding parameters of the two welding techniques are summarized in table 3. The heat input (E in kJ/mm) was calculated as follows [31]:

\[
E = \frac{U \times I \times 60}{V \times 1000}
\]

Where, U, I and V are the welding potential (in volts), current (in amperes) and speed (mm/min), respectively.

2.3. Weldments characterization

The welded specimen was visually inspected from both sides to check for surface discontinuities such as undercut, cracks, and porosity. The weldments were then radiographically inspected using Iridium-192 (Ir-192) with a strength of 65 Curies, and Kodak D7 radiographic film with an exposure time of 46 s. For metallographic examination, specimens were ground with 2000 grit emery paper and then polished with a 0.3 μm alumina
suspension. Optical metallography was carried out using an Olympus optical microscope (OM) equipped with a digital camera, model AXIOCAM MRC (Germany). Scanning metallography was carried out using a scanning electron microscope (SEM, FEI Inspect S50, The Netherlands) attached to an EDX unit. The tensile tests were carried out according to the ASTM-E8 standard at room temperature on a computerized universal testing machine (Instron model 4208 of 300 kN, United Kingdom) at a constant crosshead speed of 0.05 mm s\(^{-1}\). The bending test was performed according to ASTM E190–14. The impact test was performed on notched specimens according to ASTM E-23 at room temperature using a computerized universal testing machine (Instron model

### Table 5. Chemical composition the dual phase weld metal using GTAW.

| Weld metal–DP steel | Chemical composition, wt% |
|---------------------|---------------------------|
|                     | C  | Mn  | Si  | Ni  | Cr  |
| 9% Martensite       | 0.059 | 0.658 | 0.587 | 0.018 | 0.070 |
| 15% Martensite      | 0.035 | 0.940 | 0.290 | 0.019 | 0.252 |
| 20% Martensite      | 0.034 | 1.083 | 0.390 | 0.017 | 0.266 |

### Table 6. Acicular ferrite vol% in dual phase weld metal using FCAW and GTAW.

| DP steel | Acicular ferrite, vol% |
|----------|------------------------|
|          | Weld metal for FCAW    | Weld metal for GTAW |
| 9% Martensite | 40                  | 19                  |
| 15% Martensite | 43                  | 25                  |
| 20% Martensite | 51                  | 35                  |
4208 of 300 kN, United Kingdom). An impact testing machine, Type Zwick/Roell RKP 300/450 (Germany), was also used. Hardness measurements were carried out for all weldments according to ASTM E-384.

3. Results and discussion

Visual and radiographic inspection showed that the weldments produced were free from porosity, cracks, incomplete fusion, incomplete penetration, slag-tungsten, slag lines or inclusions, undercut, and other discontinuities.
### 3.1. Microstructure of base material

Dual phase steel consists of ferrite with martensite islands. Figures 3(a), (c), (e) shows the microstructure of DP steels containing 9%, 15%, and 20% martensite volume fractions, respectively. SEM images shown in figures 3(b), (d), (f) confirm that the martensite consists of lamellar substructures, as observed by Wang and Yang [26]. It is clear from the EXD spectra in figures 4(a)–(c) that the manganese content in steel increases with the martensite fraction.
3.2. Microstructure of weld metals
Figures 5(a)–(f) and 6(a)–(f) show the microstructure of weld metal for 9%, 15%, and 20% martensite volume fraction DP steels produced by the FCAW and GTAW processes, respectively using OM and SEM. Svensson showed that the microstructure of C-Mn weld metals consists of three types of ferrite (acicular, allotriomorphic, and Widmanstätten). The amount of acicular ferrite present depends on the amounts of carbon and manganese; in particular, it increases with manganese content [36]. EDX spectrum of weld metal produced by FCAW process are presented in figures 7(a)–(c). While those of weld metal produced by GTAW process are presented in figures 8(a)–(c). Tables 4 and 5 list the chemical composition of the weld metals, determined by using an arc spark analyzer. Svensson charts which determine quantitative description of the microstructure. The percentage of acicular ferrite in each weld metal was calculated and is given in table 6. It is known that acicular ferrite improves impact toughness and strength simultaneously [36].

3.3. Microstructure of heat affected zone
Figures 9(a)–(f) and 10(a)–(f) show the microstructure of the HAZ of 9%, 15% and 20% martensite volume fraction DP steels produced by the FCAW and GTAW processes, respectively, using OM and SEM. They show that tempered martensite was found, and that a part of the austenite was transformed into ferrite/bainite and martensite/austenite instead of pure martensite during the welding process, leading to softening. EDX spectrum of the HAZ of 9%, 15% and 20% martensite volume fraction DP steels produced by the FCAW and GTAW processes, respectively are shown in figures 11(a)–(c) and 12(a)–(c). It is shown that the aggregation of Mn and C by mean formation of carbides in the heat affected zones of three welded steels. Softening of the HAZ was observed and has been discussed elsewhere.

3.4. Mechanical testing results
Table 7 indicates the mechanical properties of the six weldments. Stress—strain curves of the DP steel weldments were represented in figure 13. It is clear that there is some decrease in the tensile strength and yield stress $\sigma_{0.2}$ of welded materials when compared with base materials. This could be attributed to the softening in
It was also observed that fractures of tension specimens were in HAZs where the hardness of the welded joint is minimal. The range of values of ultimate tensile strength (UTS) for joints welded with FCAW was found to be higher than for those welded with GTAW. The bending tests of the weldments revealed no cracks or fractures in the welded areas. This indicates that the welded areas possess a reasonable degree of ductility and toughness.

The impact test at 25 °C showed that the impact toughness of the samples welded by FCAW is higher than that of those welded by GTAW (table 8). This could be related to the higher content of acicular ferrite, as mentioned by Svensson, who linked acicular ferrite to increased impact toughness [36]. The volume fraction of acicular ferrite in WM increased by both heat input (3.42 kJ mm⁻¹ in FCAW versus 2.77 kJ mm⁻¹ in GTAW; see table 3) and/or acicular ferrite volume fraction (see table 6). High volume fraction of acicular improves the impact toughness because of increased proportion of high angle grain boundaries and interlocking structure.

Vickers microhardness (HV) measurements were performed on the weldment area for the samples welded by FCAW (table 9) and GTAW (table 10) to determine the presence of soft zones. In general, the sub-critical area of the HAZ will soften during arc welding of DP steel sheets; this is typically referred to as HAZ softening. HAZ...
Figure 13. Stress-strain curves of DP steel joints by (a) FCAW and (b) GTAW.

Table 8. Impact value measurements for samples welded by FCAW and GTAW.

| DP steel  | Impact value, J |  |  |
|-----------|-----------------|---|---|
|           | FCAW process    | GTAW process |   |
| 9% Martensite | 58.5            | 36.3        |   |
| 15% Martensite | 60.3            | 43.5        |   |
| 20% Martensite | 69.0            | 57.0        |   |

Table 9. Hardness value measurements for weldments of FCAW process.

| DP steel  | Hardness vickers |  |  |
|-----------|------------------|---|---|
|           | Base metal | HAZ | Weld zone |   |
| 9% Martensite | 184.2 | 141.5 | 170.5 |   |
| 15% Martensite | 198.0 | 151.5 | 196.5 |   |
| 20% Martensite | 222.6 | 165.5 | 207.0 |   |

Table 10. Hardness value measurements for weldments of GTAW process.

| DP steel  | Hardness vickers |  |  |
|-----------|------------------|---|---|
|           | Base metal | HAZ | Weld zone |   |
| 9% Martensite | 184.2 | 163.1 | 176.6 |   |
| 15% Martensite | 198.0 | 162.8 | 196.5 |   |
| 20% Martensite | 222.6 | 163.7 | 202.7 |   |
softening, the reduction in hardness for all heat-affected zones relative to the original hardness of the base material, is related to the tempering of the pre-existing martensite in the sub-critical areas of the HAZ. The extent of HAZ softening was found to be proportional to the welding heat input, martensite volume fraction and steel chemistry. Figure 14 shows that, as the martensite volume fraction increases, so does the amount of softening. These results are in good agreement of those of Xia and Biro [19].

4. Conclusions

Dual phase steels with different martensite volume fractions (9, 15 and 20%) were successfully welded using both gas tungsten arc welding with filler metal ER70S-3 and flux cored arc welding with filler metal E71T1C. The following points were established:

- Welding of dual phase steel reduces the joint efficiency. The joint efficiencies using the FCAW process on DP steels containing 9, 15, and 20 vol% martensite are 87.7, 86.3, and 85.9%, respectively; using the GTAW process, they are 86.0, 85.4, and 83.3%.

- The presence of martensite in addition to tempered martensite in the HAZ of welded DP steel results in a higher joint efficiency with the FCAW process than with the GTAW process.

- The impact toughness of the samples welded by FCAW is higher than the impact toughness of those welded by GTAW. This is due to a higher percentage of acicular ferrite.

- The softening of DP steel weldments produced by GTAW and FCAW could be related to the decomposition of the martensite islands into islands of softer tempered martensite in the HAZ, where fracture tends to occur.

- The softening of DP steel weldments produced by GTAW and FCAW increases with the percentage of martensite.

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