Microstructural characterization and mechanical properties development with Ti, Cr, or Ni addition for low carbon steel butt joints

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Abstract. Welding is one of the most important industrial process, therefore many practical techniques are developed to obtain an efficient and cost effective welding for different kind of metals. In this research, the microstructural characterization and mechanical properties of welded joints using TIG welding were studied for 1020 AISI low carbon steel. Titanium, Chromium, or Nickel powder were added to the welded joint one at a time by paste it with paraffin wax in the form of a thin layer. The welds were conducted and tested, then results were compared with and without adding Ti, Cr, or Ni metal powder. The welding process was done at a constant DC current (200 Amps. and 20 Volts) using weld filler metal type ER70S-3. Tests results showed that the tensile strength of the welded joint without adding metal powders was approximately 2% higher than the tensile strength of the base metal. Additionally, the tensile strength enhanced by approximately 27%, 21%, and 2% for Titanium, Nickel, and Chromium metal powder addition to the welded joints respectively. The bending strength values for all welded joints were also higher than the base metal. Furthermore, the hardness values were increased in the welded zone for all specimens. This can be attributed to the difference in the behavior of each metal powder at high temperature. The obtained results provide an experimental reference for the development of a new welding technique. It can be used in practical welding applications to obtain the desired properties using a suitable metal powder or a combination of them.

Keywords: TIG Welding; Metal powders; Low carbon steel; Mechanical properties; Structural properties.

1. Introduction
Welding is one of the most important industrial process, therefore many practical techniques are developed to obtain an efficient and cost effective welding for different kind of metals [1]. TIG welding process is one of the common welds used in industry. The temperature is generated as a result of electrical arc between the Tungsten electrode and the workpiece. The inert gas, such as Argon, Helium, or Carbon dioxide, is used to protect weld joint from Nitrogen and Oxygen existed in the air [2, 3, 4]. Joints with thickness up to 6 mm can be welded by TIG; higher thickness requires certain improvements to the welding process which motivated authors to investigate such
improvements. This study investigating the addition of alloying elements (Ti, Cr, and Ni) to welding joint of 1020 AISI low carbon steel. Low Carbon Steel is used in 85% of the engineering applications as it can be used in the production of marine elements, transportation, oil pipes, bridges, and building structures. There are many factors affect the welding ability of low carbon steel such as chemical composition, physical properties, and heat treatments [5, 6, 7].

Many researchers investigated the addition of different weld metals. Oh et al. [8] used variation of boron and titanium additives to Gas-shielded flux cored A633 Gr C steel plate. Twenty-five experimental flux cored wires were used to produce variations in the concentration of titanium and boron of welded metal. Different current and travel speed were used in order to choose the best penetration in the root pass. The results showed that the impact of boron on increasing acicular ferrite in welded metal microstructures was very small without the addition of a sufficient amount of titanium. Additionally, the impact of titanium was also very small without sufficient amount of boron. Keehan et al. [9] used shielded metal arc welding to produce three weld metals with Ni of 6.6, 7.2 and 9.2 wt. %, while Mn was 0.6, 2.0 and 2.1 wt. %. Mechanical tests results showed that Ni reduction with Mn amount at 2 wt. % led to an increase in toughness. On the other hand, for higher contents of Mn, a harder and more brittle microstructure was formed mainly of martensitic. At lower contents of Mn a softer, tougher and easily tempered microstructure was formed with greater amounts of bainite. Keehan et al. [10] prepared three experimental weld metals of high strength steel with Ni at 7 wt. %, Mg at 0.5 wt. %, and with carbon content between 0.03 and 0.11 wt. %. Tests results showed that carbon additions were found to have a great effect on strength at minor expense to toughness, which can be attributed to the overall refinement of the microstructure. Lee and Lee [11] used three different welding wires with different Cr contents. They studied the microstructure and mechanical properties of low carbon steel welds and found that welding wire with higher Cr content increased the proportion of acicular ferrite. This led to the improvement in the strength and toughness of welds. Lee et al. [12] analyzed microscopically the microstructures existed in the HAZ of three high strength low alloy steel (HSLA). Further. Effects of various microstructural features on critical crack tip opening displacement (CTOD) were studied by conducting weld thermal cycle simulation tests and by evaluating CTOD values of thermally simulated HAZ specimens. It was concluded that the addition of Mn or Ni affects microstructures of the simulated HAZ specimens and consequent critical CTOD values. In other words, Ni fostered the formation of acicular ferrite in the coarse-grained HAZ, while it prevented the formation of granular bainite, and thus the addition of Ni resulted in very high critical CTOD value 0.30 mm. However, Ni lowered the critical CTOD to 0.22 mm in the inter-critically heated HAZ because it fostered the formation of martensite-austenite. Mao et al. [13] investigated the effect of four metal powder flux-cored wires with Ni addition on the microstructure and toughness in low-carbon bainitic weld metal. The test results showed that more martensite transformation happens with Ni content increasing as well as the ductile-brittle transition temperature declines with added Ni. Another study by Mao et al. [14] was done for Q345 steel with different Ni contents wires. Obtained results were similer to what found in previous study [13]. The present study investigates the feasibility of a new welding technique where Ti, Cr, and Ni metal powder was added separately to the welding joint by pasting a thin layer mixed with paraffin wax. Based on the above survy and for authors’ best knowledge, the current welding approach considered as a new technique since no researcher has used it previously. It’s an efficient and cost effective approach, on the contrary to other approaches where the addition of metal powders is done by changing composition of the welding rod (wire) or welded metal which is very costly. The evolution of microstructural and mechanical properties as a result of powders addition were tested.
2. Experimental Procedures
The base metal used in the present work was 1020 AISI low carbon steel plate with a dimensions of 150mm×120mm×6 mm. A single 45° V-type groove was done, see Ref. 15, as shown in Fig. 1 and 2. The chemical composition of the base metal is shown in Table 1.

![Figure 1. A schematic representation of a V-type butt joint (Ref. 15).](image1)

![Figure 2. The V-type butt joint.](image2)

Three metal powders were adopted (Ti, Cr, and Ni) as an additive to the welding joint by paste it as a thin layer of about 5 wt. % mixed with paraffin wax. Welding of samples in horizontal position was done using a fixed welding parameters (A voltage of 20 Volts, and a current of 200 Amps.) with ER70S-3 wire diameter of 3 mm as the filler metal using JASIC TIG300 welding machine. The heat generated during the welding process approaches to 2.4 kJ, see Ref. 15 and 16 for more details. The chemical composition of ER70S-3 welding wire is listed in Table 2. Fig. 3 shows the V-type butt joint formed after welding by multi-pass welding.

Tensile, bending, micro hardness, and microstructure tests specimens were cut perpendicular to the weld direction. Test specimens were classified and named as listed in Table 3.
Figure 3. V-type butt joint after welding.

Table 1. The chemical composition of AISI 1020 (weight %) by ARL spectrometer.

| Elements wt. % | C  | Si  | Mn  | Ni  | Mo  | Cu  | Co  | Al  | Ti  | S  | P  |
|----------------|----|-----|-----|-----|-----|-----|-----|-----|-----|----|----|
| Value          | 0.2| 0.009| 0.5 | 0.04| 0.005| 0.44| 0.009| 0.009| 0.009| 0.05| 0.04|

Table 2. The chemical composition of ER70S-3 welding wire.

| Element wt% | C  | Si  | Mn  | S  | Cu | P  | Fe  |
|-------------|----|-----|-----|----|----|----|-----|
| Value       | 0.07| 0.52| 1.19| 0.022| 0.4| 0.012| Rem.|

Table 3. Classification of the test specimens.

| Specimens | Condition                        |
|-----------|----------------------------------|
| A         | As received (Based metal)        |
| B         | Welded without additives.        |
| C         | Welded with Cr in the welding joint. |
| D         | Welded with Ni in the welding joint. |
| E         | Welded with Ti in the welding joint. |

3. Results and Discussions

3.1. Microstructure Test

The microstructure test specimens were cut from the welds and grinded by emery paper of SiC with grits (240, 500, 800, and 1000). After that, the specimens were polished using diamond paste of size (0.2μm), unusual polishing cloth and lubricant. Etching process was done using etching Nital solution composed of 98% Alcohol and 2% HNO₃ acid. After the etching process was completed, the specimens were washed and dried by water and alcohol. Microstructural characterization of specimens were performed by an optical microscope equipped with a camera and connected to a computer. Fig. 4 illustrates the microstructures of test specimens.
3.2. Micro hardness and macro hardness tests

The Vickers micro hardness with 200g load was applied for 15 sec to measure the micro hardness for all specimens on a cross section perpendicular to the welding line. Fig. 5 shows hardness values vs. distance of the weld metals, and table 4 shows some of the Vickers hardness results.

Figure 4. Microstructures of test specimens at magnification (400X).
3.3. Tensile Tests
Specimens for tensile tests were cut from the base and welded plate by water jet machine according to the ASTM17500 specifications with dimensions shown in Fig. 6 and Fig. 7. The tensile tests were performed by smart machine with preload of 500 kg and cross head speed of 2 mm/min. Results are illustrated in table 5 and Fig. 8.

![Tensile test specimen](image)

**Figure 6.** Tensile test specimen according to the ASTM17500 specifications.

| Specimens Symbol | A   | B   | C   | D   | E   |
|------------------|-----|-----|-----|-----|-----|
| Vickers Hardens Kg /mm² | 282 | 286 | 292 | 287 | 296 |

**Table 4.** Some of the macro hardness results.

![Hardness values vs. distance of the weld metals](image)

**Figure 5.** Hardness values vs. distance of the weld metals.
3.4. Bending Test

The bending test specimens were cut according to ASTM (E 190-92) as shown in Fig. 9 and 10. Universal testing machine with 100 kN at a speed of 3.5 mm / min was used. Three-points method was used to perform the tests where the sample is placed horizontally across two supports and then a force applied on the top of the welding line to deform the sample into a (U) shape, see Fig. 11. Results are illustrated in Table 6 and Fig.12.

Table 5. Tensile tests results.

| Specimens Symbol | $\sigma_Y$ Mpa | $\sigma_U$ Mpa | $\sigma_F$ Mpa | Elongation %$\varepsilon$ |
|------------------|----------------|----------------|----------------|--------------------------|
| A                | 210            | 380            | 280            | 25                      |
| B                | 341            | 387            | 305            | 34                      |
| C                | 262            | 386            | 300            | 35                      |
| D                | 358            | 458            | 373            | 33                      |
| E                | 314            | 483            | 369            | 23                      |
Figure 9. Bending test specimen.

Figure 10. Bending test specimens for all welded joints.

Figure 11. Three-points bending test machine.
Figure 12. Stress – Strain curves for bending tests.

Table 6. Bending tests results.

| Specimens Symbol | $\sigma_L$ Mpa | $\sigma_U$ Mpa | $\sigma_E$ Mpa | Elongation $\varepsilon$ |
|------------------|----------------|----------------|----------------|------------------------|
| A                | 132            | 162            | 123            | 36                     |
| B                | 326            | 447            | 368            | 36                     |
| C                | 169            | 262            | 232            | 30                     |
| D                | 217            | 357b           | 250            | 34                     |
| E                | 214            | 250            | 196            | 36                     |

4. Discussion

Based on the tests results discussed in Sec. 3, it was found that the current welding approach influences the weld appearance, penetration and strength. Fig. 4 clearly shows the microstructural behavior of the welded metal at different metal powder additives (Ti, Cr, and Ni). There is no defects such as holes were observed in the macrographs. It is noticed in the micrographs that the particulates are scattered all over the weld zone. However, the grain size decreased in the weld zone as well as in the heat effected zone (HAZ). It is suggested that metal powder additives, especially Ni and Ti, play a vital role in enhancing the grain size and arrangement which coincides well with what was found in most recent researches [12, 13, 14]. On the contrary, Cr addition led to increase in the grain size and hence affect its microstructure and mechanical properties which was also proven by other researchers [11]. In addition, the heat developed during the welding process was sufficient to cause plasticization of the metal and cause finer grain size. Further, the weld zone is characterized by a small grain size and it’s very obvious in specimen D. This observation indicates that Ni additive was very effective to increase the deformation and hence break the newly generated grains.

Fig. 5 suggests that the micro hardness of specimen E was the highest. Also, the micro hardness is lower in weld zone in all specimens in comparison to the base metal. This behavior can be explained by the increase in heat during the welding process and hence the degree of plastic deformation as in specimens E and D. Nevertheless, the macro hardness results show that specimen
E gave the highest result due to refinement in grain size which was effected by welding parameters and alloying elements. Typical stress – strain curve for all the specimens are shown in Fig. 8. Ultimate tensile stress were 380, 387, 386, 458, and 483 MPa for specimens A, B, C, D, and E respectively. It is obvious that the decrease in grain size has a significant effect on tensile properties as in specimen E, and D. Compared to the base metal, the tensile strength enhanced approximately by 2 %, 2 %, 21 %, and 27 % for specimens B, C, D, and E respectively. The three points bending test curves for all the specimens are shown in Fig 12. The results suggest that TIG welding is a very effective way to increase the bending strength in the weld zone, as it can be seen clearly with the specimen B. It can also be seen from the figure that with decrease in grain size, bending strength increases slightly. That can be attributed to the effect of high plastic deformation due to high heat generated in weld zone as mentioned earlier. Furthermore, tensile strength values for the specimens were very high and that affect the bending strength as well.

5. Conclusions

- It was seen that using metal powder additives generate fine grain structure in weld zone which contribute to an increase in hardness.
- Decrease in grain size has a significant effect on tensile and bending properties. This behavior is very evident in specimen C, D, and E with Cr, Ni, and Ti addition respectively.
- The tensile strength enhanced by approximately 2% for the welded joints in comparison with base metal as a result of well-chosen welding parameters.
- A maximum tensile strength of 483 MPa (specimen E) was obtained for the welded joint with the Ti metal powder addition. The tensile strength values enhanced by 2 %, 2 %, 21 %, and 27 % for specimens B, C, D, and E respectively.
- The obtained results provide an experimental reference for the development of a new welding technique. The new technique can be used in practical welding applications to obtain the desired properties using a suitable metal powder or a combination of them.

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