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The effect of carbon content and submerged arc welding process on hardness of carbon steels

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Abstract
Like heat treatment processes, manufacturing methods that require heat input, such as welding process, can cause changes in material properties. This study aims to investigate the effect of carbon content and welding process on the hardness of welded carbon steels. For this purpose, samples of ultra-low carbon interstitial free, low carbon and medium carbon steels that have similar composition but different carbon content are used. All samples are heat treated to remove residual stresses remained during the manufacturing processes. Automated submerged arc technique is used to create a weld beam on plate despite a joining process. Rockwell B scale is used for hardness measurements. Results prove that steel carbon content and welding process have an effect on hardness around the weld beam.

***Keywords*:** Submerged arc welding; Carbon content; Hardness

1. INTRODUCTION

Hardness is a measure of the materials resistance to applied forces. Material properties, such as plasticity, yield strength, ductility, and toughness, have a relation with hardness. Their relations can be altered using heat treatment techniques. Different heat treatment processes have different effects on material properties. Full annealing provides softer steels with lower hardness and strength, but higher ductility. Normalized steels have higher strength and hardness than full annealed steels. Steels can be quenched by heating them to normalizing temperatures and then rapidly cooling. This process provides materials with higher yield strength [1] and hardness. Accordingly, it can be stated that hardness investigation after a manufacturing process can give hints about final properties of a material.

Welding of steel butt joints has a wide range of applications in the fabrication of industrial products including ships, offshore structures, steel bridges, aircrafts and pressure vessels. There are many advantages of welding process such as high joint efficiency, water and air tightness and low fabrication cost. However, among the advantages of this joining method, material properties can be changed because of heating followed by rapid cooling during the welding process.

Welding is a high-temperature process. Many authors investigated the effect of rapid heating and cooling cycles of welding process on the hardness of materials. Valesaco studied the effect of welding on local mechanical properties of stainless steels for concrete structures using universal hardness test [2]. Structure and hardness changes in welded joints of Hardox steels were investigated by Frydman [3]. Ziemian studied the effects of flashing and upset sequences on microstructure, hardness, and tensile properties of welded structural steel joints. ASTM-A529 carbon manganese steel was welded by flash butt welding [4]. Ultrafine grained plain low carbon steel formed by the martensitic process was welded by friction stir welding technique and hardness was measured [5]. Güral studied heat treatment in two phase regions and its effect on microstructure and mechanical strength after welding of low carbon steel [6]. Welding of 1010 steel was performed under controlled argon atmosphere. Acarer and Demir investigated mechanical and metallurgical properties of explosive welded aluminum-dual phase steel [7]. Incorporation of preheating and post heating effect on the mechanical properties of laser welding joints were investigated at mild steel and stainless steel by Abdullah and Siddiqui [8]. Klobcar investigated the ageing of mar-aging steel welds during aluminum alloy die casting [9]. Multi track laser surface melting roller steel is a thermal process. The ratio of overlapping during this process on hardness was studied by Li [10].

The relation between hardness and welding process is investigated in previous studies. However, none of these studies deals with the effect of carbon content and welding process on the hardness of carbon steels. In this study, the hardness of welded low alloy steels with different carbon is investigated using Rockwell B hardness scale.

2. METHODOLOGY

2.1. Sample Preparation and Welding

To investigate the effect of carbon content, samples with similar composition but different carbon content should be used. For this purpose, three different type of carbon steels are selected. Ultra-low-carbon interstitial free steel (IF steel) is issued as carbon free steel sample. Low carbon and medium carbon steels with carbon contents of 0.092 wt % and 0.478 wt % are other samples with low and medium carbon content respectively.

Three samples of each type of steel with dimensions of 280 × 200 × 10 mm are machined to create weld grooves as illustrated in Figure 1. The depth of the weld groove is determined to be 3 mm with an angle of 60^o. The width of the bottom part of the weld groove is issued as 2 mm. Weld grooves with a length of 93.3 mm, which is one-third of the length of base plates are located in the center of sample plates.

The welding process is performed with common parameters using a fully automated system. Submerged arc welding technique is a proper technique to this end which minimizes possible operator errors. Parameters of submerged arc welding process are given in Table 1. Dupont and Marder evaluated the effect of welding parameters and process type on arc and melting efficiency [11]. Authors compared various arc welding processes and determined efficiencies of those processes including submerged arc welding. The efficiency of the welding process is determined based on that study.

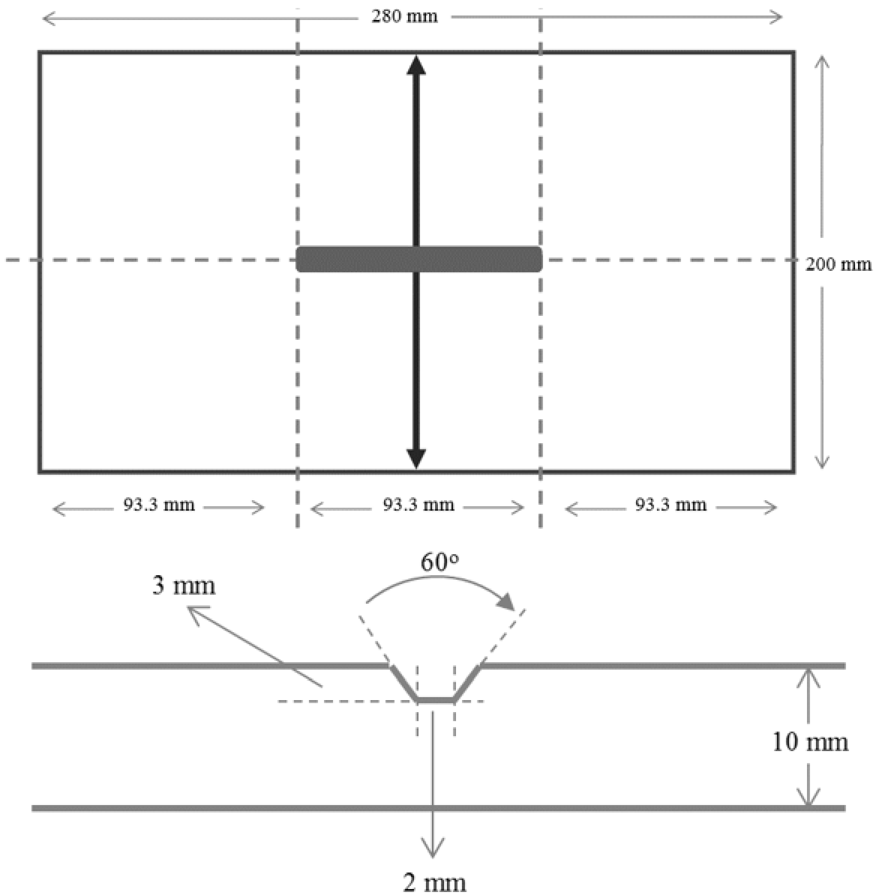

Figure 1. Illustration of sample geometry and hardness measurement section

In this study, the welding process is performed in TEKFEN Manufacturing and Engineering Co. lnc. Facility. AWS EM12K submerged arc wire is selected as filler material. Single pass weld beam is applied to fill each weld groove and then samples are left to cool in the stagnant air. Hardness measurements are performed after 24 hours following the welding process.

Table 1. Parameters for submerged arc welding process

Electric potential energy (Volt)	30
Electric current (Amp)	500
Efficiency (%)	84
Torch travel length (mm)	90
Time (s)	6.75

2.2. Hardness Measurements

Rockwell hardness test is a simple hardness measurement technique which can be used for a wide variety of materials such as carbon steels [12]. Short measurement time and digital readers allow gathering large amounts of data easily. These advantages differentiate that method from other hardness test methods such as Brinell or Vickers hardness testing. The depth of a prescribed load is determined and converted to a hardness value [13] which is inversely proportional to depth. Rockwell hardness test can be performed with a conical or a spherical indenter. The conical indenter is used for hard materials while spherical indenter is used for softer materials. Carbon steels used in this study are classified in the softer region so that spherical indenter is preferred.

Equation 1 [14] is used to calculate Rockwell hardness where HR is Rockwell hardness, N is numerical constant, h is remaining depth of penetration, and S is scale division. There are various Rockwell scales that are marked by additional capital letter to HR. HRA, HRB and HRE are selected according to indentation hardness of materials. HRB scale is used for soft and middle hardness steel, aluminum, and brass. Low alloy steels are classified as soft and middle hardness steels and accordingly, HRB scale is used in this study.

$$HR = N - h/s \qquad (1)$$

The width of weld beam is about 12 mm in all steel samples. Hardness measurements are performed along the measurement section which is normal to the weld zone. The purpose of this study is to investigate the effect of carbon content in carbon steels. Accordingly, measurements are performed on the base metals 6.5-7 mm away from weld beam center.

3. RESULTS

Hardness distribution in steels with carbon content less than 0.5 weight percent are investigated. Like the hardening process, the temperature of weld zone increases up to the melting point during application of weld arc and then decreases rapidly after the joining process. Results show that hardness increases because of welding process around the weld beam, and hardness variation after this process is affected by the carbon content of steel samples.

Hardness distribution in IF steel is given in Figure 2. Maximum hardness is observed around weld beam and it reaches a peak value between 70 and 75 HRB. A smooth decrease in hardness is observed. Results show that welding process causes an increase of hardness more than 25 HRB.

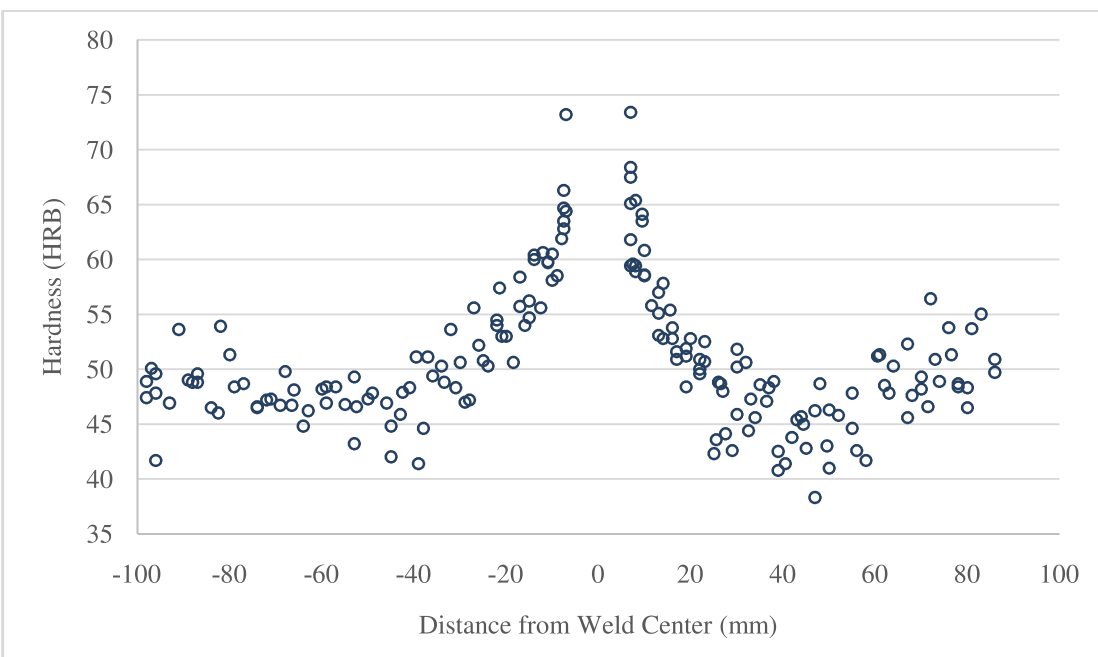

Figure 2. Hardness distribution in IF steel after welding process

Low carbon steel has a different hardness distribution when compared to IF steel as illustrated in Figure 3. A sharp increase in hardness is observed around the weld beam. Maximum hardness value is changed between 90 - 95 HRB. As it is expected, that value is higher than that of IF steel. Hardness increased more than 30 HRB after the welding process.

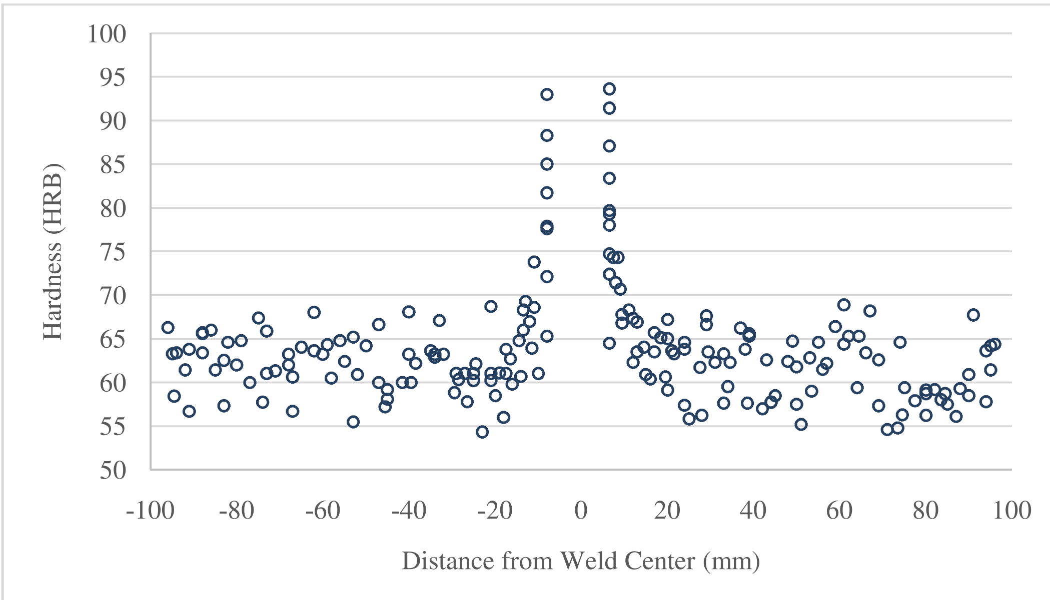

Figure 3. Hardness distribution in low carbon steel after welding process

Like low carbon steel, a sharp increase of hardness around the weld beam is observed in medium carbon steel. Hardness distribution is similar to low carbon steels. The peak value of hardness is highest when compared to other steel types. Maximum hardness of medium carbon steel is higher than 115 HRBas illustrated in Figure 4.

Martensitic transformation is a common hardening mechanism for steels. During this process, the steel is heated to a temperature that causes a phase change from ferrite into austenite. In other words, BCC (body centered cubic) crystal structure of iron changes to FCC (face centered cubic) crystal structure. The austenitic form allows dissolution of a high percent of carbon. Rapid cooling prevents return to BCC crystal structure and the final crystal structure becomes BCT (body centered tetragonal). This martensitic form is extremely hard because of prevention of slip dislocation. Accordingly, carbon content has an effect on the hardening process. Similarly, rapid heating and cooling cycles during the welding process cause martensitic transformation and hardening around the weld beam. Results proved that increasing carbon content increases the effect of martensitic transformation.

The welding process causes the formation of residual stresses within and around the weld beam. The relation between hardness and residual stress was investigated in various studies [15 - 17]. These studies showed that hardness increases with increasing carbon content. Bulk residual stresses observed in previous studies [18, 19, 20] and hardness distributions around the weld beam show similarities. Therefore, it can be stated that hardness and residual stress in the weld zone are proportional to each other.

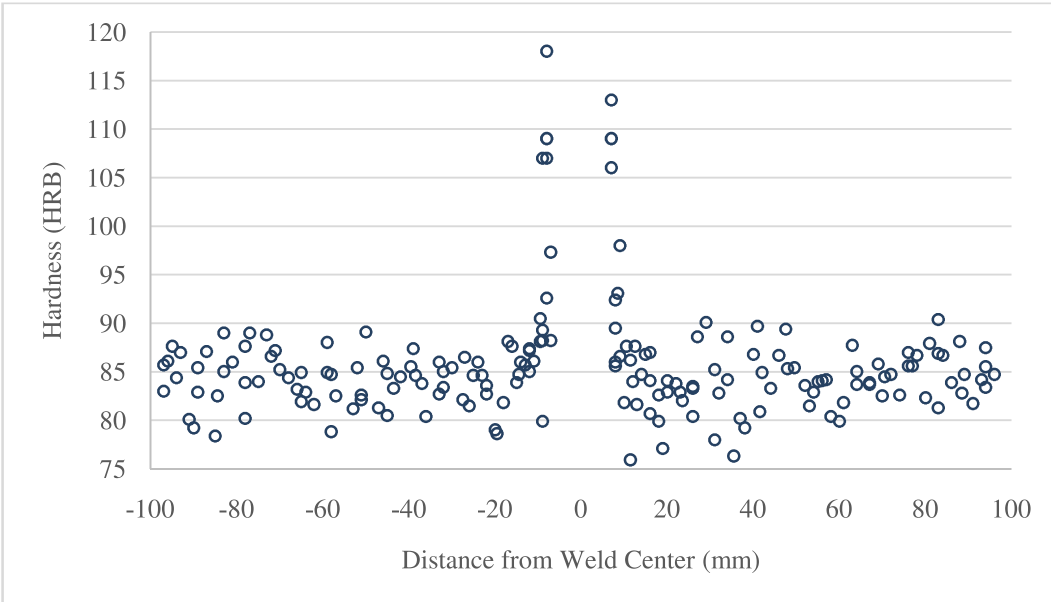

Figure 4. Hardness distribution in medium carbon steel after welding process

The maximum hardness of samples after the welding process are given in Table 2. Results show that welding process has effect on the hardness of materials and it varies related to the carbon content. Percent of hardness increase is also a distinctive result related to carbon content which gets higher when the carbon percent decreases.

Table 2. Initial and final hardness values with percent of hardness increase

Carbon Content (wt %)	Initial Hardness (HRB)	Max Hardness After Welding (HRB)	Percent of Hardness Increase
0	46	74	60.7
0.092	64	94	46.9
0.478	86	118	37.2

4. CONCLUSION

Results proved that welding process influences the hardness. Rapid heating and cooling periods cause the formation of a locally hardened zone around the weld beam. This study showed that carbon content of low alloy steels also influences the formation of that locally hardened zone. Hardness around weld beam increases and magnitude of this increase is related to carbon content.

Hardness is a property which is proportional to other material properties. Investigation on hardness provides information about variations in other properties of materials. The increase of hardness increases strength, but ductility decreases with increasing hardness which can form a brittle zone around the weld beam. In addition, it is observed that hardness distribution has similarities with bulk residual stress distribution in welded materials. It can be stated that hardness data can be used to have an idea about properties and stress state of materials.

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