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The effect of welding on reliability of mechanical properties of AISI 1020 and AISI 6150 steel materials

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ABSTRACT: Welding is one of the most important manufacturing and repair method of today's technology. Though it is known that it can reduced the mechanical properties of materials, it is a necessity in many areas and in some cases, it is preferred because of the efficient and fast manufacturing. The widespread use of welding has raised the problem of reliability of welded structure. It is important to carry on reliability analysis especially on critical welded constructions or some critical materials. In this study, two steel material (AISI 1020 and AISI 6150) which different weldability levels were selected. Gas metal arc welding (GMAW), Gas Tungsten arc welding (GTAW) and shielded metal arc welding (SMAW) were chosen as widespread industrial welding techniques. Welded and non-welded mechanical properties of these materials were examined taking into consideration the reliability, and effect of welding and welding methods were investigated. Reliability analyzes revealed that non-predictable mechanical properties and microstructures are main characteristic of welding process especially in some materials or methods.

KEYWORDS: Mechanical Properties; Microstructures; Reliability; Welding

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RESUMEN: *Efecto de la soldadura sobre la fiabilidad de las propiedades mecánicas en los materiales de acero AISI 1020 y AISI 6150.* La soldadura es uno de los métodos de fabricación y reparación más importantes de la tecnología actual. Aunque se sabe que puede reducir las propiedades mecánicas de los materiales, es una necesidad en muchas áreas y, en algunos casos, se prefiere debido a la fabricación eficiente y rápida. El uso generalizado de la soldadura ha planteado el problema de la fiabilidad de la estructura soldada. Es importante llevar a cabo análisis de confiabilidad, especialmente en construcciones soldadas críticas o algunos materiales críticos. En este estudio se seleccionaron dos materiales de acero (AISI 1020 y AISI 6150) los cuales se seleccionaron con diferentes niveles de soldabilidad. La soldadura por arco metálico con gas (GMAW), la soldadura por arco con gas tungsteno (GTAW) y la soldadura por arco metálico protegido (SMAW) se eligieron como técnicas de soldadura industrial generalizadas. Se examinaron las propiedades mecánicas soldadas y no soldadas de estos materiales teniendo en cuenta la fiabilidad y se investigó el efecto de la soldadura y los métodos de soldadura. Los análisis de confiabilidad revelaron que las propiedades mecánicas y microestructuras no predecibles son la característica principal del proceso de soldadura, especialmente en algunos materiales o métodos.

PALABRAS CLAVE: Microestructuras; Fiabilidad; Propiedades mecánicas; Soldadura

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1. INTRODUCTION

Joining processes provide that at least two components are combined; thereby more complicated or larger structures can be produced. Many joining techniques are used in various metal manufacturing and repair operations. Welding is one of the major metal manufacturing techniques and the characteristic of this technique is that the interatomic bonding within the base material or at least on the surface is occurred (Beddoes and Bibby, 1999). Welding processes divide into two major categories as fusion welding and solid-state welding. Fusion welding, in which two of the welding parts is melted, widely used for welding processes than solid-state welding, in which there is no melting of the base metals and no filler metal. Arc welding is most common industrial welding technique and it includes a group of welding process such as shielded metal arc welding, gas metal arc welding, flux-cored arc welding, submerged arc welding and gas Tungsten arc welding (Groover, 2007). Steel structures are widely used in engineering practices and the properties of steel structure depend mainly on its carbon content. The Weldability of steel gain importance in welding applications of steel structures and weldadability is determined by carbon equivalent (CE). Also, the microstructure of the heat affected zone (HAZ) plays an essential role in the mechanical properties of the weldment and HAZ is directly dependent on the welding method, (Odebiyi *et al.*, 2019). The conventional arc welding has two major families basis the type of electrode; consumable electrode arc welding and the non-consumable electrode arc welding. Both the types of processes have their own advantages and limitations (Sahasrabudhe and Raut, 2018).

Robotic welding systems have been used in different types of manufacturing. They can provide several benefits in welding applications. The most prominent advantages of robotic welding are precision and productivity (Tarn *et al.*, 2007). Beside of this, today, significant percentage of welding operations is still manual processes. Because of that, Inputs to the process have multiple origin and obtained welding characteristics are wide From this point of view, mechanical properties of welded product is related not only welding method or weldability of material but also welding parameters such as current, voltage and operators skill (Paul, 2014).

Reliability theory is the mathematical approach to solve reliability problems through statistical and stochastic means. The field of reliability covers a wide and diverse range of applied science (Klaassen and Van Peppen, 1990). Reliability and safety are important for machine and construction elements. The statistical measure of the probability that a mechanical element will not fail in use is called the reliability of that element. In the reliability method of design, it is important to make a judicious selection of materials, processes, and geometry so as to achieve a specific reliability value (Tahralı and Dikmen, 2004; Budynas and Nisbett, 2011). Very few studies have carried out reliability studies in welded structures. The results of these studies showed that welding parameters influence to reliability of mechanical properties of welded materials (Colombo *et al.*, 2019; Ku *et.al.*, 2019). The main purpose of this study was to investigate directly the effect of welding and different widespread welding methods on the reliability of mechanical properties of steel sheets unlike previous studies. For this purpose, in this study, a commercial welding enterprise has been determined, welding methods and parameters selected by that the company has already applied and by selecting two materials with different welding capabilities, it was aimed to observe the effect of welding on mechanical properties.

2. MATERIALS AND METHODS

2.1. Materials

Two types (AISI 1020 and AISI 6150) of steel sheets were used in the study. In order to examine the effect of welding on the reliability of mechanical properties, these metal sheet plates were used both welded and without welds. Beside of this, these steels were chosen at different weldability levels (Odebiyi *et al.*, 2019). Welding parameters were given in the following section. Spectral analyzes of the samples were performed before the experiments. The chemical compositions of steel sheets are shown in Table 1.

Specimens were machined from steel sheets and tensile test specimens prepared. Shape and dimensions of tensile specimens are shown in Fig. 1.

After machining, the specimens were normalized and mechanical tests of normalized specimens were done. Normalizing was accomplished at certain temperature above the transformation range and into the range of complete austenite according to Carbon content (900 °C for AISI 1020 and 850 °C for AISI 6150).

Table 1. Chemical composition of steel sheets

Material	C_{min}-C_{max}	Si_{min}-Si_{max}	Mn_{min}-Mn_{max}	P_{max}	S_{max}	Cr_{min}-Cr_{max}	V_{min}-V_{max}
AISI 1020	0.18-0.25	0.15-0.35	0.3-0.6	0.045	0.045	-	-
AISI 6150	0.47-0.55	0.15-0.4	0.7-1.1	0.035	0.035	0.9-1.2	0.1-0.2

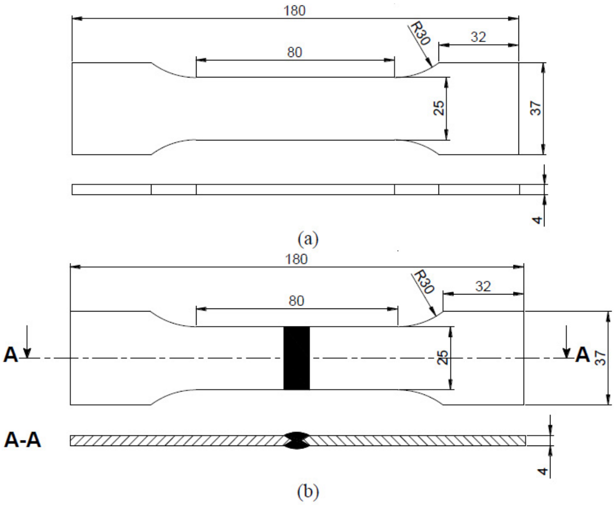

Figure 1. Schematic representation of tensile specimens: a) Non-welded specimen b) welded specimen.

2.2. Process parameters of welding

In order to observe the reliability of widespread welding applications in the industry, the welding process was applied manually. Welding parameters have been selected based on their current applications in mutual assessment with the organization operating on the welding sector. In addition, the studies in the literature were taken as a basis in the selection of welding parameters (Abbasi *et al.*, 2012; Ibrahim *et al.*, 2012; Odebiyi *et al.*, 2019) Gas Metal Arc Welding (GMAW. Gas metal arc welding (GMAW), Gas Tungsten arc welding (GTAW) and shielded metal arc welding (SMAW) were used to identify different welding methods to steel sheets. Welding parameters are shown in Table 2.

2.3. Mechanical tests and micro-structural investigation

Tensile and Vickers micro hardness tests were performed on the samples and microstructural investigations of samples were done. Tensile tests were performed on by using Autograph Shimadzu AG-IS 100 kN universal test machine according to ISO 4136:2012 (2012) standard. Vickers micro hardness values were measured with Future–Tech FM–700 micro hardness test machine by loading 100 g of force for 10 seconds. The results of the tensile experiments were evaluated with reliability analyses. Also micro structural investigation was done to relate obtained tensile and hardness results. Steel sheets were cut and specimens prepared following standard procedures for micro structural investigation. Samples were etched with Nital solution (3 vol. %NH_3 and 97 vol. % Alcohol). Nikon LV 100 optical microscope and Nikon SMZ 1000 stereo microscope were used for microstructural investigation.

2.4. Reliability analyses

In reliability analysis, distributions of random variables are determined, and reliability analyzes of the data obtained are performed through these distributions (Pham, 1994). The most widely used model for the distribution of a random variable is a Gauss (normal) distribution. When the number of random experiments increased, the probability distribution tends to have a normal distribution. Beside of this, Weibull distribution is one of the other most used distributions to model of many different physical systems as the parameters in the distribution provide a great deal of flexibility and ability to fit data

Table 2. Welding parameters

Welding Method	SMAW	GTAW	GMAW
Voltage	22 V	17.9 V	20.8 V
Current	140 A	165 A	179 A
Wire feeding rate	-	650 cm·min^{-1}	571.5 cm·min^{-1}
Welding Speed	25 cm·min^{-1}	20 cm·min^{-1}	20 cm·min^{-1}
Shielding Gas	-	Argon	Argon
Welding (Wire) Electrode	E42 3 B 42 H10	WTh20 (W 46 2 W3Si1)	G42 3CM G3Si1

from various fields. (Horst, 2008; Montgomery and Runger, 2014). For instance the strength distribution curve for the ductile materials is described as Normal distribution, while that for the brittle material is Weibull distribution (André Meyers, 2009). In this study, reliability analysis of test results was done to observe welding on mechanical reliability of welded parts. In previous studies, it was seen from statistical distribution analysis of welded steel materials that, Gauss (Normal) distribution adequately describes most of the mechanical properties except for the hardness and toughness (Saoudi *et al.*, 2017) serial mechanical properties of 70 pipes, formed by spiral submerged arc welding of high strength low alloy steel (HSLA. Also there are some previous studies using the Weibull distribution in the reliability studies of the mechanical properties of welded samples included tensile tests (Colombo *et al.*, 2019; Ku *et al.*, 2019; Yang and Jiang, 2019). In reliability analysis of this study, Shapiro-Wilk normal distribution test was applied to all the test results. Tensile results were found to be suitable for normal distribution and hardness tests results were found to be not suitable as expected. Reliability analyses according to Weibull distribution were examined and compared. In addition, normal and cumulative distributions of Vickers hardness results were obtained with the acceptance of Gauss distribution in order to show the wide range and low reliability as a result of welding process. The equations of these distributions were given under below. Eq. (1) is Gauss distribution and Eq. (2) is Weibull distribution.

$$f(x) = \frac{1}{s_x.\sqrt{2\pi}} Exp\left[-\frac{\left(x-\bar{x}\right)^2}{2.s_x^{\;2}}\right] \qquad (1)$$

$$f(x) = \frac{b}{\theta}.\left(\frac{x}{\theta}\right)^{b-1}.\exp\left[-\left(\frac{x}{\theta}\right)^{b}\right] \qquad (2)$$

In equations, x: Random variable, : Average deviation of x, Sx: Standard deviation, b: Shape parameter of Weibull function, θ: Scale parameter of Weibull function, f(x): Distribution function of x, F(x) = ∫f(x).dx: Cumulative distribution function of x. The results of the experimental data and statistical analysis were included in the results and discussion section.

3. RESULTS AND DISCUSSION

3.1. Tensile test results

Tensile test results are given in Fig. 2. It can be seen in Fig. 2 that ultimate tensile strength of welded parts has a more widespread distribution. This is a sign that the welding process affects the reliability of the mechanical properties. With the welding process, the standard deviation increased, and this increased the range of data obtained.

It was also seen from Fig. 2 that tensile strengths of welded specimens were decreased. The decrease in the tensile strength of the samples is the result of the inhomogeneous welding microstructure (Yang and Jiang, 2019). Micro hardness test results and microstructural investigation also confirmed this thought. When evaluated in terms of optimum welding method for both steel materials; the welding method in which tensile strength decreases minimum was SMAW welding in AISI 1020 steel and GMAW welding in AISI 6150 steel. Shielded arc

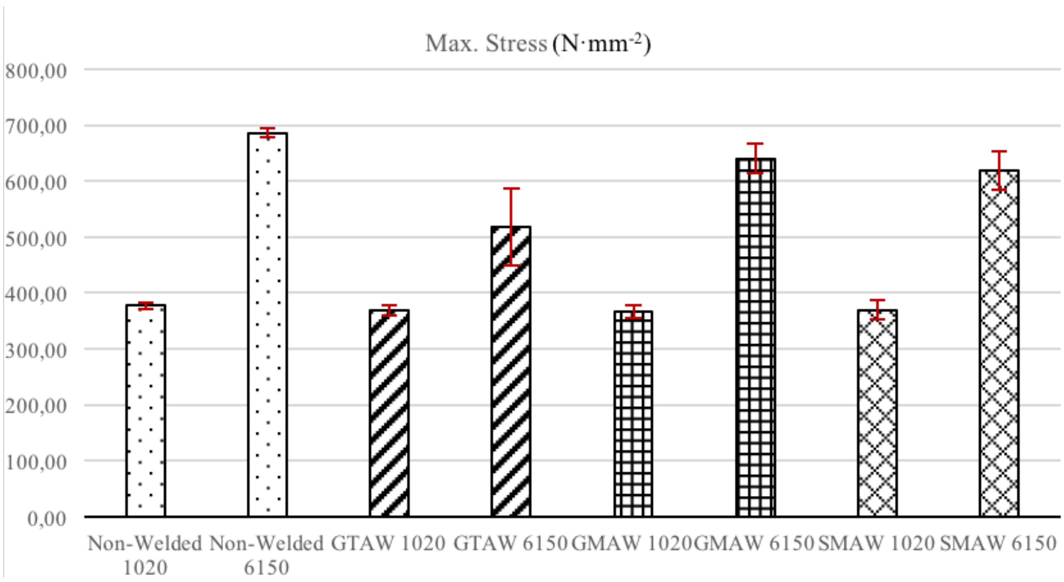

Figure 2. Tensile test results of AISI 1020 and AISI 6150 steel specimens.

welding is an important process which is widely used in industry sector for joining process etc. AISI 1020 is widely used by all industry especially in manufacturing sector. SMAW welding method is one of the widest welding method for this material (Shukla *et al.*, 2018). Consequently, it was seen the study that, as a perspective of tensile strength, the method is appropriately can be used for welding method of AISI 1020 steel.

AISI 6150 steel is a fine grained, highly abrasion-resistant chromium vanadium alloy steel, which has high strength, high fatigue strength and large hardenability. In recent years, AISI 6150 steel has been commonly used in many industries, particularly the automotive industry (Li *et al.*, 2013). AISI 6150 steel is extensively used in large-size damping springs for trains and vehicles (Çivi *et al.*, 2018; Zhang *et al.*, 2018). Despite such widespread use, there is limited study in the literature about welding methods of AISI 6150 steel, (Mendes *et al.*, 2013; Yalamaç *et al.*, 2016). Hardly any studies on tensile tests of welded AISI 6150 steel have been found. In this study, it has been seen that GMAW has given better results for this material with a slight difference. As known, the gas shield in SMAW is not clean enough especially for some materials. On the other side, GTAW and GMAW are very clean welding processes. The main advantage of GMAW over GTAW is the much higher deposition rate, which allows thicker workpieces to be welded at higher welding speeds. The skill to maintain a very short and yet stable arc in GTAW is not required (Kou, 2002). These reasons are thought to have an impact on the results obtained.

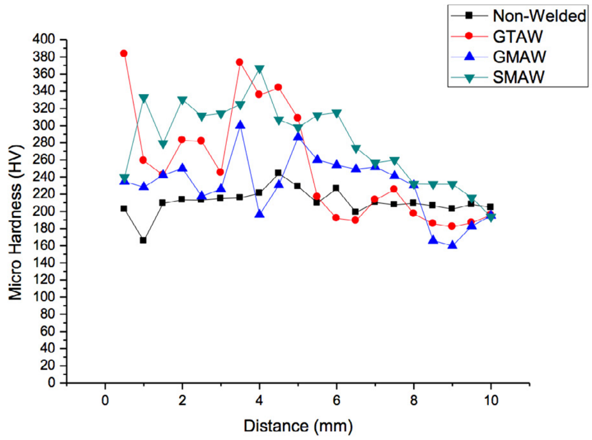

FIGURE 3. Vickers Microhardness Results of AISI 1020 specimens.

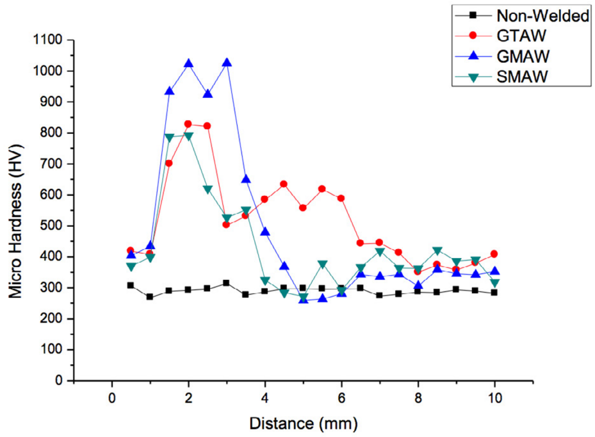

FIGURE 4. Vickers Microhardness Results of AISI 6150 HV specimens.

3.2. Vickers micro hardness test results

The microstructure hardness was measured from center of the welded zone to base material. The results were given in Fig. 3 and Fig. 4. It was seen the figures that, welding zone, heat-affected zone (HAZ) and base material have different hardness values as expected.

Comparing the base metal with the weld metal and the HAZ, a hardness increment was observed. It is estimated that the reason for this increase is martensite formation with reference to previous studies (Delgado *et al.*, 2016). Another point to be noted here is that the hardness level, which is almost the same in non-welded samples, contains large differences in the regions mentioned in welded samples. It is also seen that different welding methods have different effects on the samples in terms of hardness distribution. For instance, in AISI 1020 specimens, GTAW and GMAW welding methods provide great differences in hardness distributions while GMAW welding method provide different hardness distribution from other welding methods for AISI 6150 specimens. This shows that different welding methods directly affect the dimensions of the welding and HAZ region. When evaluated in terms of hardness results, it can be concluded that the SMAW method, whose distribution values for both materials do not differ greatly, is more suitable with reference to previous studies (Yalamaç *et al.*, 2016). However, tensile tests and microstructure analyzes should also be evaluated for the selection of the most suitable welding method.

3.3. Micro structural investigation

To understand the effects of the welding process, examining the microstructure of the main materials and welded joints is one of the important issues (Zdravecká and Slota, 2019). The results of microstructural analyses were given in Figs. 5-8. Figure 5 shows macro photographs of welded structures taken with a Stereo microscope. The discontinuity of the welded structure can be clearly seen in the

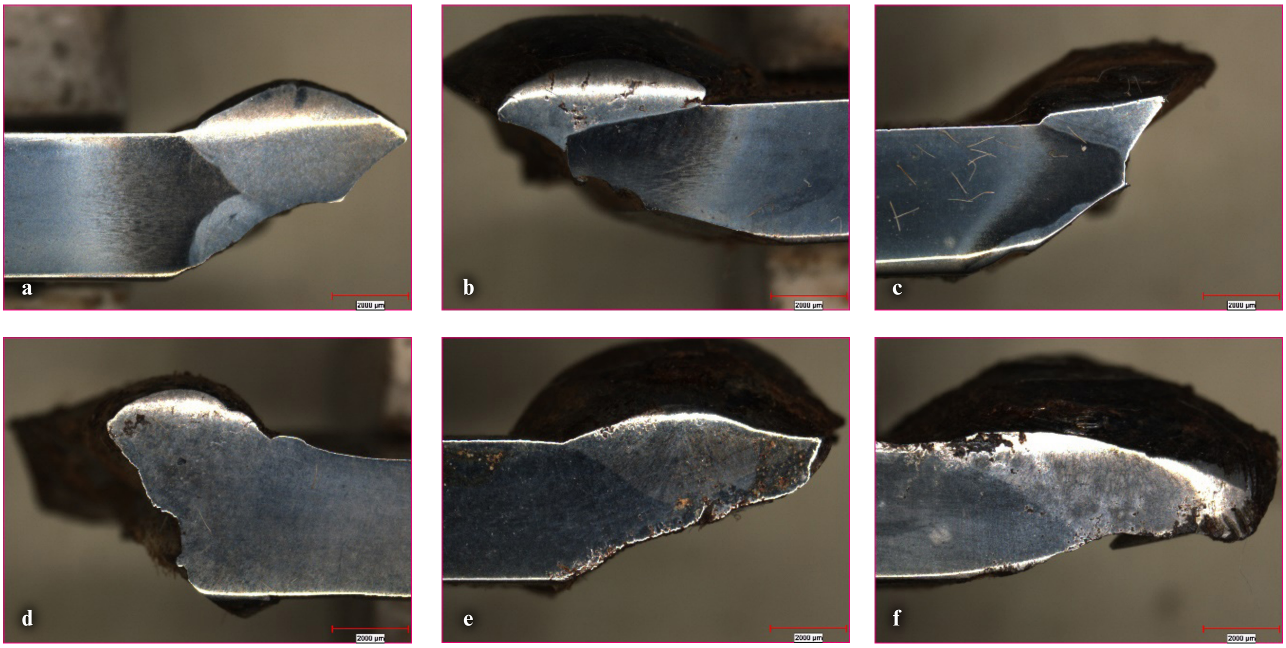

Figure 5. Stereo Images of Specimens: a) AISI 1020 GTAW welding, b) AISI 1020 GMAW welding, c) AISI 1020 SMAW welding, d) AISI 6150 GTAW welding, e) AISI 6150 GMAW welding, and f) AISI 6150 SMAW welding.

photographs. It can be commended that, heat input made for the welding would create a microscopically heat affected region.

Figures 6, 7 and 8 show microstructural photographs of non-welded and welded structures taken with optical microscope.

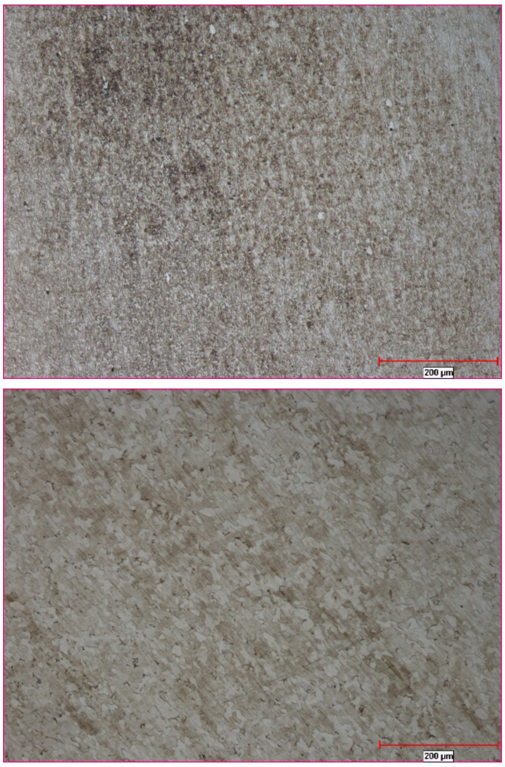

Figure 6. Microstructural Images of non-welded specimens a) AISI 1020 b) AISI 6150.

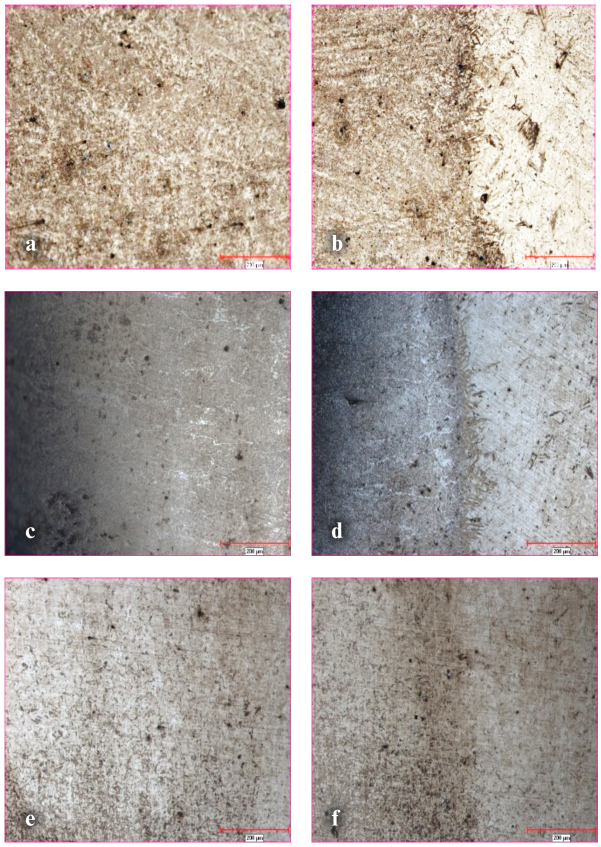

Figure 7. Microstructural Images of AISI 1020 Specimens: a) GTAW welding metal, b) GTAW HAZ, c) GMAW welding metal, d) GMAW HAZ, e) SMAW welding metal, and f) SMAW HAZ

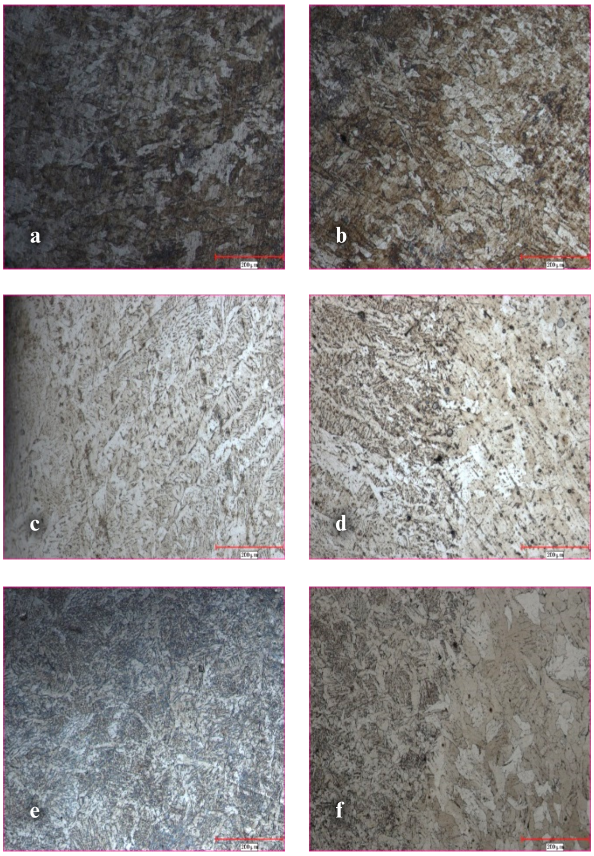

Figure 8. Microstructural Images of AISI 6150 Specimens: a) GTAW welding metal, b) GTAW HAZ, c) GMAW welding metal, d) GMAW HAZ, e) SMAW welding metal, f) SMAW HAZ.

Hardness distributions (Figs. 3-4) were directly related to microstructure photographs (Figs. 6-8) as expected. The relatively homogeneous microstructure in the non-welded material provided a uniform distribution of hardness. Microstructural differences in the welding metal and in the heat affected zone are directly related to the standard deviation obtained with the high hardness distribution. As a result of the microstructural investigation it was seen that, In AISI 1020 steel; considering the weld penetration, heat effect of the welding and welding seam, SMAW is the most suitable method. On the other hand, in the microstructure studies for AISI 6150 steel, it was observed that the better microstructure conditions that will provide better strength values are formed by GMAW welding.

3.4. Reliability analysis

The distribution of tensile and hardness test results under consideration of normal distribution were given in Figs. 9-10. Left side of the figures show obtained tensile (maximum strength) and hardness values and right side show the cumulative distribution of tensile and hardness values.

The reliability analysis of the data obtained in the material tests is of great importance in both the test accuracy and the evaluation of the material manufacturing parameters (Çivi *et al.*, 2014; Çömez *et al.*, 2019; Gül *et al.*, 2019) iron based powder metal parts (3% Cu, 0.5% Graphite and 1% Kenolube lubricant by weight. It can clearly be seen from Figs.

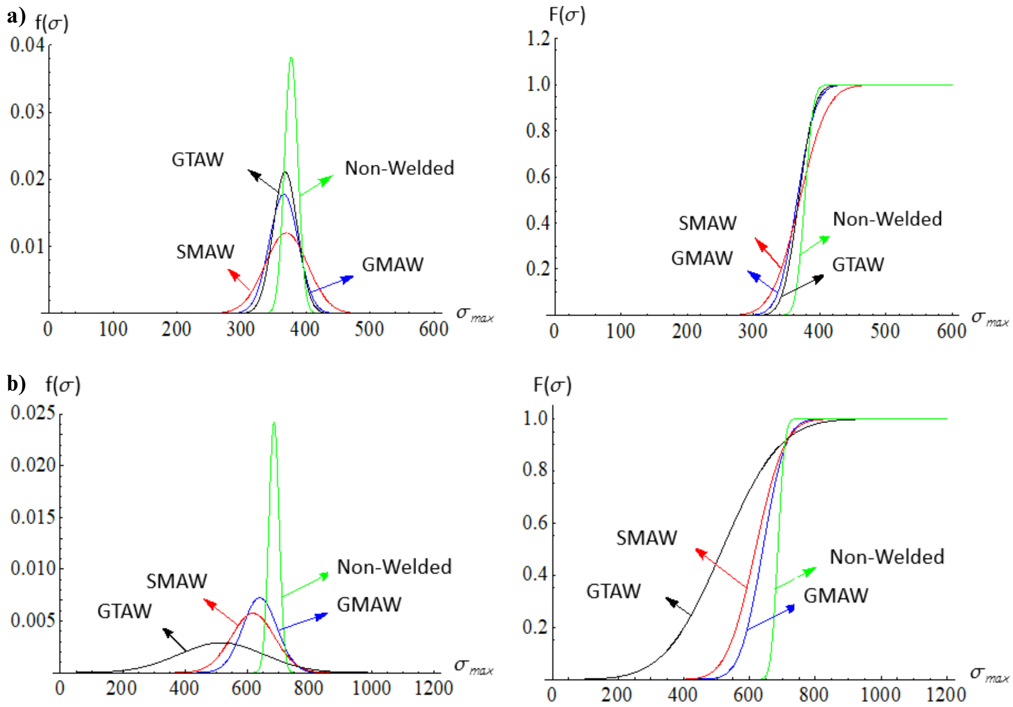

Figure 9. Normal and cumulative distribution of tensile (max. stress) test values: a) AISI 1020 materials, and b) AISI 6150 materials.

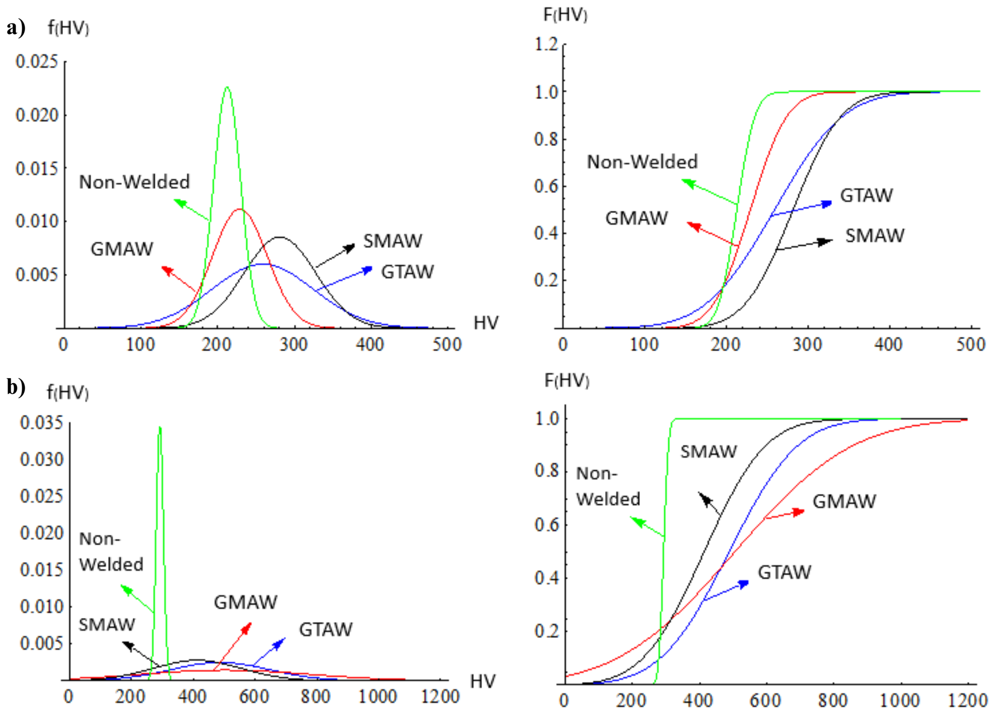

Figure 10. Normal and cumulative distribution of micro Vickers test values a) AISI 1020 materials, and b) AISI 6150 materials.

9-10 that, the distribution exhibited a narrow gap on non-welded specimens while it exhibited wide gap after welding. And also, in 1020 steel, which is low hardenability steel because of its low carbon content, the hardness distribution does not show a wide range after welding, while the hardness range is very wide as expected in 6150 steel (Mendes *et al.*, 2013; Maharjan *et al.*, 2020). Narrow distributions refer to high reliability values. When the standard deviations and the range of values obtained increase, the probability of an obtained value of reflecting the entire cluster decreases, so the reliability values decrease.

It was seen from the previous studies that, both Weibull and Normal distribution can be used as statistical distribution of tensile strength of welded and non-welded materials. However, Weibull distribution can be used especially in a small number of experiments, since it is a more flexible distribution and can also meet the normal distribution in some cases. In this study, tensile test results were found suitable for normal distribution, but Vickers test results were found not suitable as expected. Because of this, Weibull distribution was used to carry on reliability analyses of Vickers hardness results. Curves of the Vickers hardness test results are also shown in the Figs. 11-12.

When Vickers hardness results are examined, it was seen that the hardness distribution can be provided by the Weibull distribution due to microstructural differences in different parts of the welded structure in parallel with previous studies in the literature (Saoudi *et al.*, 2017) serial mechanical properties of 70 pipes, formed by spiral submerged arc welding of high strength low alloy steel (HSLA).

As a result of the all tests and analyzes, it was seen that all the mechanical properties values of the welded samples were decreased after welding process. Welding method is a commonly used joining and repair method in construction structures. When we evaluate in terms of optimum welding method for these two steel materials; the welding method in which tensile strength decreases the least is SMAW in 1020 steel and GMAW in 6150 steel. According to non-welded samples, HAZ and base metal difference and regional hardening occurred in welded samples with the effect of heat. For instance, in the AISI 6150 steel, the hardening is 289 HV in the non-welded sample and 488 HV in the MIG welded sample. As a result, SMAW in AISI 1020 steel; It has been found to be the best method in terms of welding penetration, welding heat effect, welding seam image and arc welding application cost. Considering all these factors for AISI 6150 steel, GMAW is the best welding method regarding the conditions in this study and the data obtained.

4. CONCLUSIONS

In this study, reliabilities of widespread welding processes were analyzed in detail. Mechanical properties and microstructural characteristics of welded and non-welded materials were compared. Welding process brings about microstructural differences which cause hardness distributions and uncertain

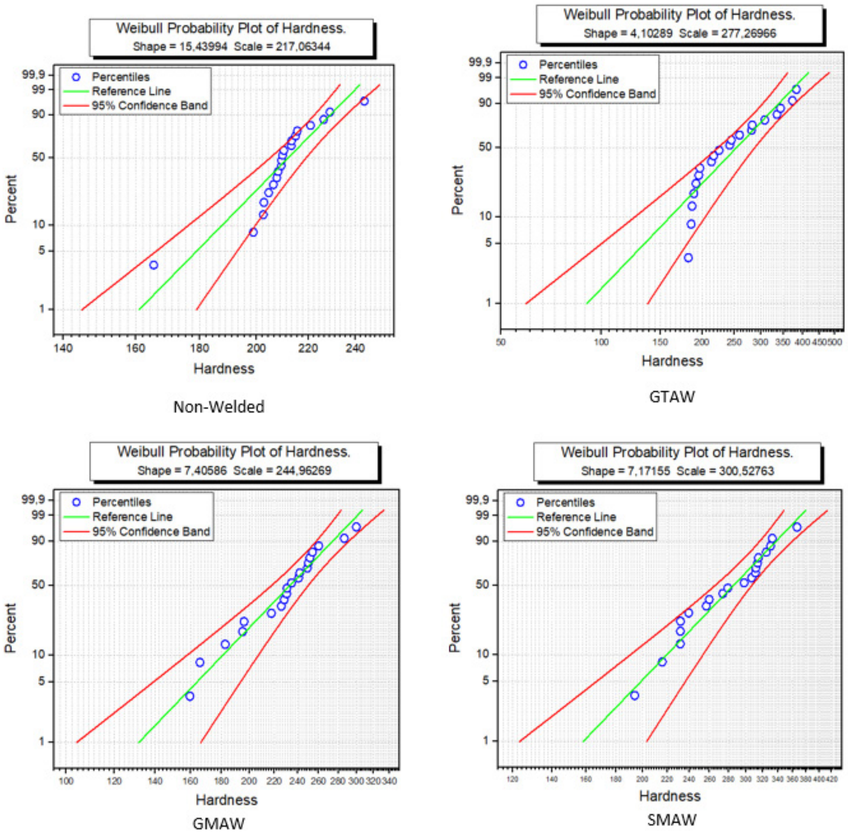

Figure 11. Weibull distribution of Vickers hardness values (HV) of AISI 1020 material.

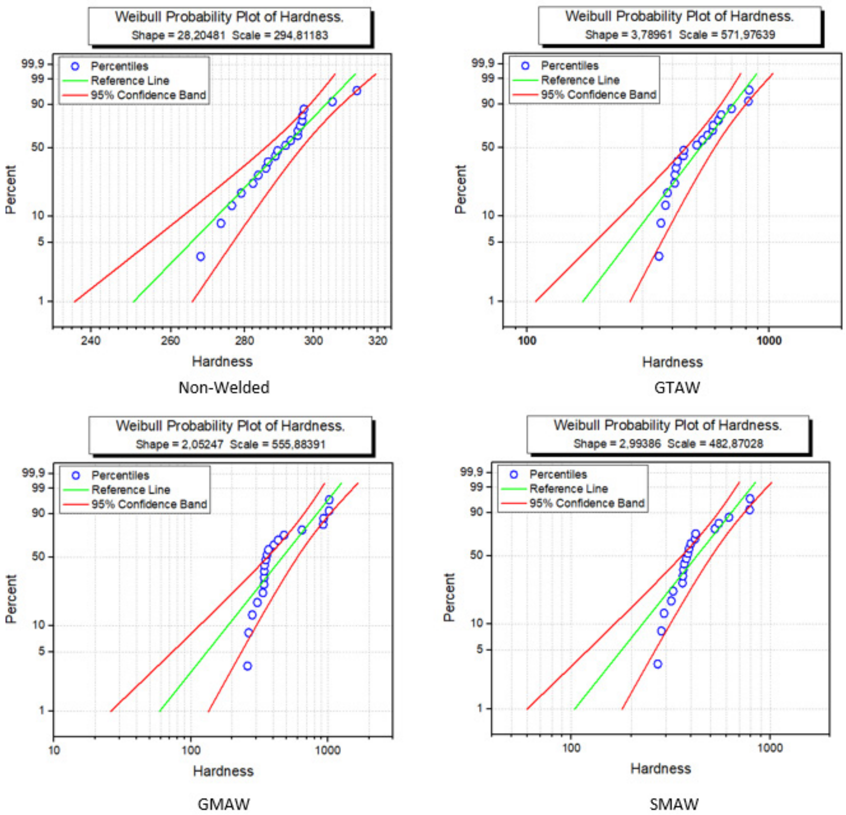

Figure 12. Weibull distribution of Vickers hardness values (HV) of AISI 6150 material.

mechanical strength as a result of segregation on welded structure. It has been observed that different welding methods and weldability levels significantly affect the reliability of mechanical properties.

As a result of this study, it has been shown that normal distribution can be used in the evaluation of tensile strength values of welded steel materials instead of the Weibull distribution, which is widely used due to its flexibility. As the number of data analyzed was increased, it was observed that tensile strength values were compatible with normal distribution. However, normal distribution is not suitable for hardness evaluations. In the statistical evaluation of the hardness values of the welded structures, it was seen that each structure should be examined under separately. Certain distributions should be used for only comparison.

Welded manufacturing is indispensable as a manufacturing method due to economy and efficiency factors. However, the fact that the mechanical properties of the structures obtained depend on many parameters such as welding method, welding material, welding parameters, is a very important risk that welded construction designers should consider. This risk can be reduced with reliability analyzes to be performed, at least, critical parts on welded constructions. In addition, energy usage could be evaluated together with mechanical properties and reliability analysis in the selection of welding methods and parameters in future studies.

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