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Investigation of The Effect of HAZ Width on Weld Metal Electrical Properties in Arc Welded Joints

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Abstract

This study was carried out in order to fill the gap in the literature and to increase the usability of welded joints as electrical connectors. For this purpose, shielded electrode metal arc welding and gas metal arc welding methods, which are frequently used in the industry, were used. In addition to mechanical tests such as microstructure, tensile and hardness of the joints made at different heat inputs, electrical conductivity tests were also performed and the results were evaluated together. According to the results obtained, electrical conductivity is lower in arc welding joint with shielded electrode, in other words, the weld metal has reduced conductivity. In the gas arc welding, the electrical conductivity five times more than in the electrode welding. In MAG welding, at the highest heat input 0.78 kJ/mm, 186.33 HV hardness was measured, while 191.33 HV hardness was measured at 0.60 kJ/mm, the lowest heat input. While 386.5 MPa tensile strength was obtained at 0.78 kJ/mm, 377 MPa tensile strength was measured at 0.60 kJ/mm heat input.

In SMAW, 163 HV hardness was obtained at the highest heat input as 1.47 kJ/mm, while the tensile strength of the weld metal was measured as 343.5 MPa and the electrical resistance was measured as 21.5 Ohm. The electrical resistance was measured as 11.86 Ohm, with a 384 MPa tensile strength and a 174 HV hardness at the lowest heat input 1.17 kJ/mm. It was determined that as the weld metal hardness increased, the electrical conductivity decreased.

The relation between the test findings and their interpretation are detailed in the study.

Keywords: Electrical conductivity, Gas metal arc welding, Heat affected zone, Shielded metal arc welding.

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1. Introduction

The invention and development of welding has been one of the most critical steps in the modernization of societies by providing metal production and development. The history of the welding dates back thousands of years and has led to important developments in many continents. When we came to the 19th century, the concept of today's welding technology began to emerge in line with the increasing human needs and with the help of developing technology. When we think about the welding, we often don't realize how this industry is affecting the world around us. The presence of the welding in household appliances, electronic devices and even medical devices that we use in our daily lives shows that it is an indispensable method [1]. Considering a large number of base materials such as steel and non-ferrous materials, semi-finished products of various thicknesses, device assemblies, welding filler materials and technological possibilities, a large number of welding processes are used [2]. In order to enhance the usage of welded joints in scholarly writing and engineering applications, many weld parameters have been investigated. Numerous studies have been conducted specifically to evaluate and enhance the mechanical characteristics of the welded material [3-6].

It is usual to develop properties such as strength and toughness of welded joints, which are frequently preferred in construction works, but studies on physical properties such as heat and electrical conductivity have been limited. Although copper and aluminum are the favored materials, studies on the change in electrical resistance after welding have been conducted [7,8]. No research has been found on the post-weld electrical characteristics of structural steels, which are mostly employed in industry, in contrast to these materials, which will be the first choice in terms of electrical conductivity. The electrical conductivity study of the materials welded by pressure welding was also looked into, but no link between the heat input and electrical conductivity as the research subject was anticipated was discovered [9].

In this study, different welding types and parameters were applied to S235 JR structural steels, which are used in many areas in industrial production, and the changes in electrical properties on the samples were investigated. The materials were cut by laser cutting method and then welded with MAG (metal active gas) and SMAW (shielded metal arc welding) welding methods. Firstly, visual inspection, tensile, hardness and microstructure tests were applied to the welded samples in order to analyze the welded area. Subsequently in order to determine how the microstructure, which changes with welding, affects the material, the electrical resistance was measured.

To summarize the electrical structure of the materials, electronic mobility, the crystalline structure of the existing phases, the presence of point defects like voids and interstitials, linear defects (dislocations), and surface defects (twins and grain boundaries) all have an impact on a material's conductivity. Grain size also affects σ0, due to the total length of grain boundaries per unit area [10,11]. Bautista stated that the intrinsic electrical conductivity, σ0, also depends significantly on the mechanical strain [11]. The electrical conductivity is, commonly, applied as a Non-Destructive Test (NDT) to assess the presence of small size superficial and sub-superficial defects, such as cracks, inclusions and pores, namely in welded joints [12]. However, background knowledge of material structure and electrical properties is required to analyze the results.

Hardness measurements are usually performed to evaluate the hardness field of a joint, directly correlated with the microstructure produced during welding. In the HAZ no plastic deformation of the material is observed, but the heat effect can induce small scale phase transformation, such as grain coarsening and precipitation [13]. Through the measurement of electronic mobility across a weld, electrical conductivity evaluation could be a rapid way to assess joint integrity while taking into account both the impact of the microstructure and flaws. Some existing studies aim to the development of this correlation [11], but limited information is available on the application of this technique. The purpose of these tests is to examine the effect of microstructural changes in the welded area (weld metal and HAZ) on the electrical conductivity, which is the physical property of the material. Thus, the welding parameters to be used in places that require electrical conductivity will be determined.

2. Material and Method

2.1 Material

In this study, S235JR quality low carbon steel (S235JR) was used as base metal. The mechanical and chemical properties of the material selected for these experiments are given in Table 1. The sample dimensions were determined as 230x150x5 mm according to ISO 15614 Specification and qualification of welding procedures for metallic materials, welding procedure test standard. SG2 wire in MAG welding and E 6013 rutile covered electrode in SMAW welding were used as filler material. Since the filler materials are a commercial product, no elemental analysis was applied.

Table 1. S235JR material properties

C %	Mn %	P %	S %	Cu %	Al %	Cr %	Ti %
0,09	0,53	0,018	0,011	0,008	0,037	0,025	0,002
Yield Strength (Mpa)			Tensile Strength (Mpa)			Elongation (%)	
285			388,1			40,1	

2.2. Welding

In order to give different heat inputs to the materials, the wire feed speeds in MAG welding and the current values in SMAW welding were changed. The welding parameters used in the experiments are given in Table 2 below.

Table 2. Welding parameters

Sample	Method	Shielded Gas / Electrode	Amper	Volt	Travel Speed (mm/min)	Wire feed speed (mm/min)	Heat Input (kJ/mm)
N1	MAG	$ArCO_2$	150-180	18	197,14	3,91	0,65-0,78
N2	MAG	$ArCO_2$	140-180	18	205,97	4,31	0,58-0,75
N3	MAG	$ArCO_2$	120-180	18	233,9	4,62	0,40-0,60
N4	SMAW	Rutile	150	25-30	146,81	-	1,22-1,47
N5	SMAW	Rutile	140	25-30	146,81	-	1,14-1,37
N6	SMAW	Rutile	120	25-30	146,81	-	0,90-1,17

The heat input at the welding was calculated with the formula given below.

$$\boldsymbol{Q} = \eta \frac{\mathbf{I.U}}{\mathbf{V}} \quad (1)$$

Where Q (kJ/mm) is heat input,η is thermal efficiency,I is current,U is voltage and V(mm/min) is welding speed respectively.

Welding length is 230 mm and welding times are kept constant in SMAW welding. Thermal efficiency taken as 0.8 for both welding methods.

3.Tests and Results

In this study, the effects of the changes in the mechanical and microstructural properties of the S235 JR materials, which are welded with MAG and SMAW methods, on the electrical conductivity of the material were investigated.

3.1. Visual Inspection

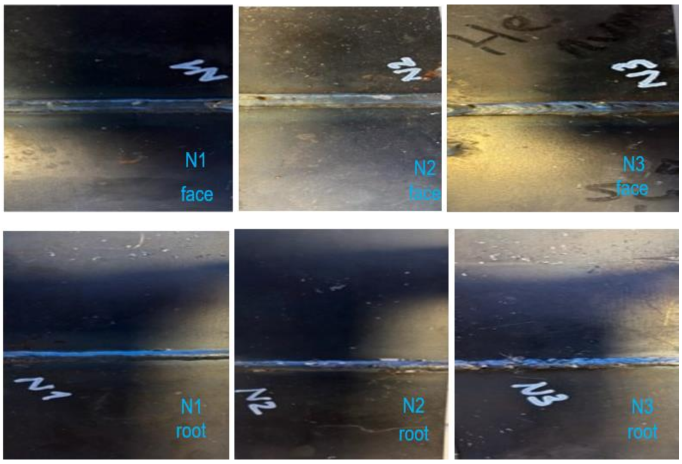

Fig.1 Visual inspection of MAG welded samples

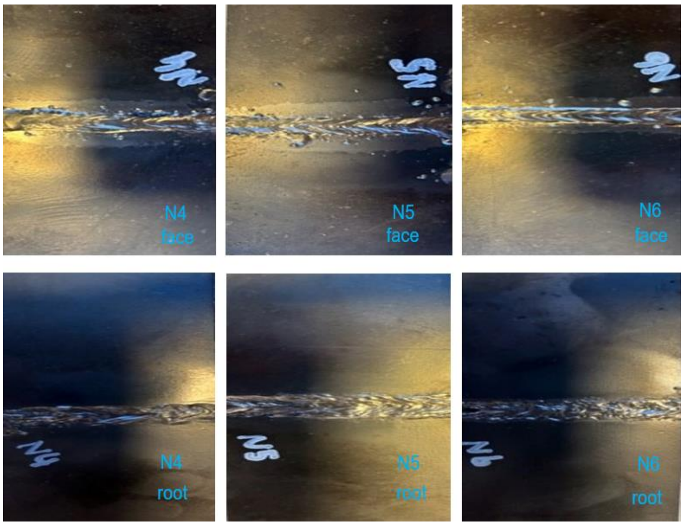

Fig.2 Visual inspection of SMAW welded samples

Visual inspection of MAG welded samples are given in Figure 1 above. As a result of visual inspection, no cracks were observed in the welding face area of the samples welded with the MAG welding method. Insufficient filler weld defect was detected in all of the samples, but when the samples were evaluated according to TS EN 5817 Class C, they remained within the acceptance limits. The root welding of all samples was evaluated as appropriate in the visual examinations.

Visual inspection of MAG welded samples are given in Figure 2. In consequence of the visual inspection of the samples welded with the SMAW, it was determined that partial burn throughs and spatter were formed in the N4, N5 and N6 samples and these defects were within the limits of the acceptance standard. In addition, in contrast to the samples welded by MAG welding, insufficiently filled weld (welding defect number 511) was observed in all of the samples, but it is in the acceptance limit when examined in accordance with the TS EN 5817 standard [14].

3.2. Microstructural Investigation

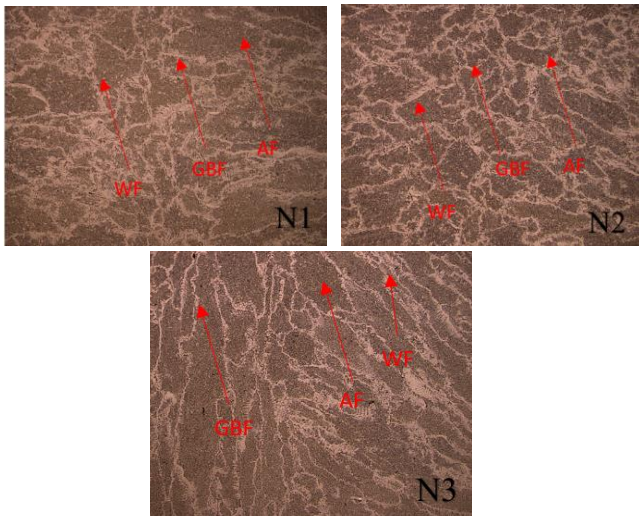

Fig.3 Microstructural examination of MAG welded samples

Microstructural examination of MAG welded samples are can be seen in Figure 3**.** When the weld metal microstructure photographs of the N1, N2 and N3 samples are examined, it is observed that the grain boundary ferrite, widmanstaten ferrite (WF) and acicular ferrite (AF) formations vary depending on the changing welding parameters. These phases are likely to occur in the welding of low-carbon materials and are the product of cooling under atmospheric conditions. In the N3 sample with the lowest heat input, the grain boundary ferrite networks (white colored areas) were observed to grow towards the last solidified weld center as fine and long grains, while in the N1 and N2 samples with high heat input, there was recovery in the oriented grains because the cooling rate was slow networks appear to be thickened.

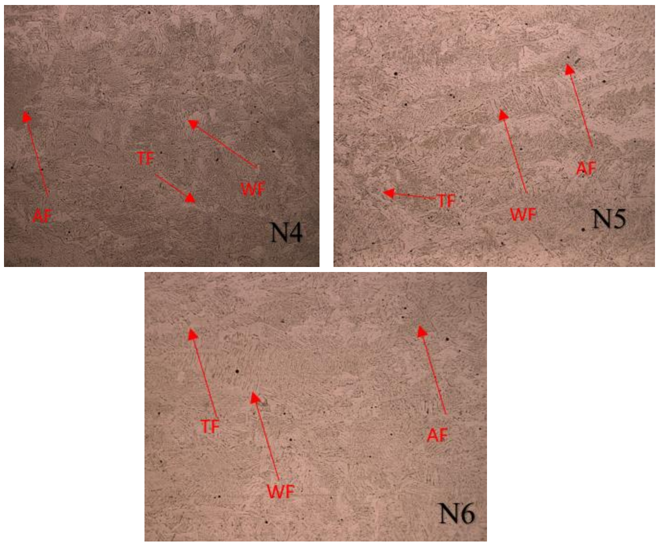

Fig.4 Microstructural examination of SMAW welded samples

Microstructural examination of SMAW welded samples are given in Figure 4 above. The cooling rate is very important in the formation of the final microstructure.

From this point of view, since the N4 sample with the highest heat input (1.47 kJ/mm) in this study shows slower cooling conditions, the grain boundary ferrite areas formed at the austenite grain boundaries during cooling are thicker, and this is seen both in the weld metal and in the HAZ region. When the N5 sample is examined (1.37 kJ/mm), it is clearly seen that the widmanstatten ferrite layers grow from the grain boundary ferrites into the austenite grains [15]. It is seen that the grain boundary ferrites in the N6 sample, which is welded with low heat input, are thin and long with rapid cooling. The widmanstatten phase, which nucleates at the austenite grain boundaries and expands into the austenite grains as the temperature decreases, has a longer structure than the other samples. N4 and N5 samples with high heat input have shorter and wider grain boundary ferrite phases, as expected, while widmanstatten ferrite phases have shorter structures [16].

3.3. Tensile Test

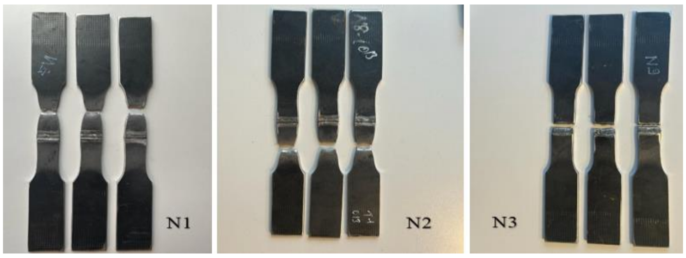

Fig.5 MAG welded samples' photographs after tensile test

In Figure 5, MAG welded samples' photographs are given. As a result of the tensile test of the joints welded with the MAG welding method, fracture is observed on the base material instead of the welding metal as it expected on N1 and N2 samples. In the N3 sample, it was observed that the fractures occurred in the HAZ region, where the transition regions of the base metal and weld metal formed a brittle core transition. The increase in the cooling rate due to the low heat input in the N3 sample was interpreted as brittle fracture accordingly.

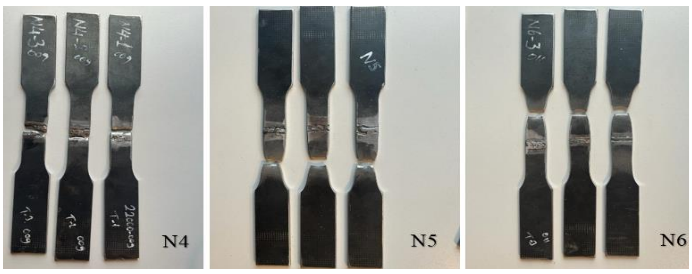

Fig.6 SMAW welded samples' photographs after tensile test

SMAW welded samples' photographs can be seen in Figure 6 above. It is seen that the N4 sample is fractured from the weld metal transition zone and the N5 and N6 samples are fractured by the base metal outside of HAZ. Since the heat input value of the N4 sample is higher than the N5 and N6 samples, burn through were observed in the joint area as mentioned in the visual inspection section, but these defects are in accordance with the TS EN 5817 standard. Although it is stated that it is within the acceptance limits, it is thought that they cause fractures to occur in the transition region due to the notch effect in the tensile test [3].

3.4. Hardness Test

In addition to the general belief that there is a relationship between hardness and mechanical properties, the effect of hardness on electrical resistance was investigated in this study. A previous study showed that increasing hardness increases the electrical resistance of the material [17]. Since the MAG and SMAW methods used in this study affect the cooling conditions of the weld metal, it is anticipated for the hardnesses to differ according to the methods. The hardnesses are lower than those of the samples welded with MAG welding because the slag layer on the weld seam and high heat input slow down the cooling rate in SMAW.

In MAG welding, the lack of any seam shielding accelerated cooling, raising the hardness values. In both methods, the highest hardnesses were measured in the weld metal. In the samples welded with different wire feeding speeds, slow cooling is thought to be effective in the low hardness in the N1 sample with the highest heat input, however, the hardness values increased proportionally in the N2 and N3 samples, whose heat input values decreased, respectively.

The lowest hardness value was measured in the N4 sample welded with the highest current value, as a result of the heat input increasing with the increasing current value and the correspondingly decreasing cooling rate. The results of all hardness tests are shown collectively in Figure 7 below.

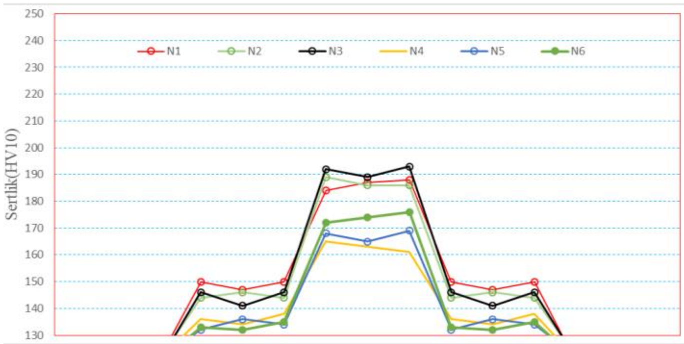

Fig.7 Hardness test results of SMAW and MAG welded samples

3.5. Electrical Resistance Test

It is known that material hardness has a resistance-increasing effect on the electrical conductivity of materials. Since the length L also impacts electrical conductivity, it is expected that resistance will rise as grain size, or the distance L, increases. In this regard, the high cooling rates of the samples welded with MAG welding improve the hardness of the weld metal and have the effect of reducing the HAZ distance when the impacts of welding procedures on the electrical resistance are analyzed.

In MAG welding, the electrical resistance was measured for three different heat inputs and the weld metal hardness was 186.33 HV in the N1 sample, which had the highest heat input, and the electrical resistance was measured as 1.06 Ohm, in the N2 coded sample with a medium heat input, the hardness was 187.0 HV, the electrical resistance is 2.5 Ohm and the N3 sample, which has the lowest heat input, measured 191.33 HV hardness and 5.71 Ohm electrical resistance. As can be observed, the electrical conductivity increases as the heat input decreases the hardness and raises the electrical resistance. In SMAW, the weld metal hardness of 163.0 HV, electrical resistance of 11.86 Ohms, 167.33 HV hardness and 17.82 Ohm of resistance in the N5 sample, which has the highest heat input, in the N4 sample with the lowest heat input, in the N6 sample with the lowest heat input. on the other hand, a hardness of 174.0 HV and a resistance of 21.50 Ohm were measured. The electrical resistance has greater values than both the MAG welded samples and the base metal, but the hardness values are lower than the MAG welded samples because the slag layer on the weld metal slows the weld metal's cooling rate in SMAW. These findings are explained by the fact that the electrical resistances are high due to SMAW's lower cooling rate and the ITAB's longer L length as a result of the high heat input. Electrical resistance test results of SMAW and MAG welded samples are given together in Figure 8 below.

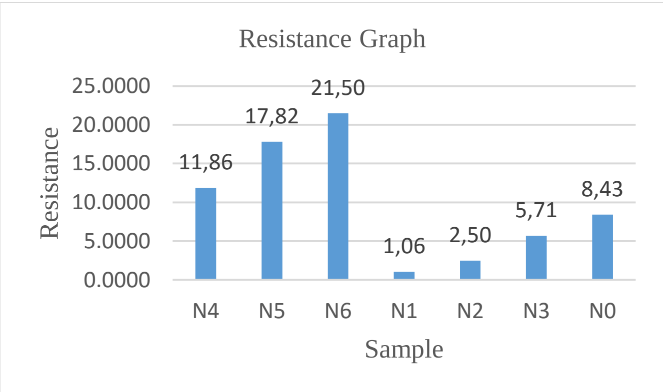

Fig.8 Electrical resistance test results of SMAW and MAG welded samples

4. Conclusion and Recommendations

In this study, which was carried out to investigate the effect of HAZ width on the electrical and mechanical properties of the weld metal in welded joints, welded joints were performed at three different heat inputs for both methods using MAG and SMAW welding methods, and the tensile, hardness values and electrical resistance values of these joints were measured, and the following results were obtained. A summary of all test results are shown in Table 3 below.

Table 3. Summary of test results

Sample	Welding Method	Heat input (kJ/mm)	HAZ hardness (HV)	Weld metal hardness (HV)	Electrical resistance (ohm)
N0	-	-	125,20		8,43
N1	MAG	0,65-0,78	149,00	186,33	1,06
N2	MAG	0,58-0,75	144,67	187,00	2,50
N3	MAG	0,40-0,60	144,33	191,33	5,71
N4	SMAW	1,22-1,47	136,00	163,00	11,86
N5	SMAW	1,14-1,37	134,00	167,33	17,82
N6	SMAW	0,90-1,17	133,33	174,00	21,50

1-) In MAG welding, at the highest heat input 0.78 kJ/mm, 186.33 HV hardness was measured, while 191.33 HV hardness was measured at 0.60 kJ/mm, the lowest heat input. Here, too, it is seen that the increase in the cooling rate with the decrease of the heat input leads to an increase in hardness and decreases the tensile strength. While 386.5 MPa tensile strength was obtained at 0.78 kJ/mm, 377 MPa tensile strength was measured at 0.60 kJ/mm heat input. When evaluated in terms of the effect of heat input on electrical conductivity, 1.06 Ohm electrical resistance was measured at 0.78 kJ/mm and 5.71 Ohm resistance was measured at 0.60 kJ/mm and this resulted in an increase in the electrical resistance depending on the cooling rate and the increase in the hardness of the weld metal.

2-) In SMAW, 163 HV hardness was obtained at the highest heat input as 1.47 kJ/mm, while the tensile strength of the weld metal was measured as 343.5 MPa and the electrical resistance was measured as 21.5 Ohm. The electrical resistance was measured as 11.86 Ohm, with a 384 MPa tensile strength and a 174 HV hardness at the lowest heat input 1.17 kJ/mm. Here, it is interpreted that the slowdown of the cooling rate at the highest heat input reduces the hardness of the weld metal, while increasing the width of the HAZ and increasing the length of L, that is, the HAZ, which is exposed to the electrical conductivity of the HAZ width, has a more significant effect than the hardness.

3-) As a result of this study, it is recommended to study the effects of both HAZ length and material types on electrical conductivity by conducting additional studies for different welding parameters and material types.

Nomenclature

HAZ	:	Heat affected zone
MAG	:	Metal active gas
SMAW	:	Shielded metal arc welding
MPa	:	unit vector of tensile test, megapascal
HV	:	Vickers hardness measurement method
kJ/mm	:	unit vector of heat input
WF	:	widmanstatten ferrite
AF	:	acicular ferrite
GBF	:	grain boundary ferrite

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Duygu Karaçay Karcı: Conceptualization, Writing – Original Draft**,**
Adem Kurt: Conceptualization, Validation, Supervision

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