American Journal of Mechanical Engineering, 2016, Vol. 4, No. 3, 92-98
Available online at http://pubs.sciepub.com/ajme/4/3/2

DOI:10.12691/ajme-4-3-2

An Investigation into Effect of Butt Welding Parameters on Weldment Mechanical Properties

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Abstract Butt Fusion is the most important welding technique used for joining materials of similar compositions and melting points, resulting in welded joints as strong as the materials itself. The principle of butt fusion is to heat the materials ends to a designated temperature under pressure for a specified amount of time, then the materials ends are fused together under pressure for a period of time. In the present work a set of experiments has been conducted on base material of steel 52-3N (DIN 17100) to study the effect of butt welding process variables on the temperature distributions, welding thermal cycles behavior, peak temperature and the cooling rate for the steel butt-welding joints in the multiple pass welding process by means of the practically measurements. Also the effect of heat input which presented by the welding process variables on the mechanical properties of the welded joints has been investigated to reach the optimum welding variables which give the optimum mechanical properties. It is observed through the experiments that the optimum mechanical properties can be achieved at interpass temperature of 200º, welding voltage of 35V and welding speed of 6 mm/sec.

Keywords: *Wire feed rate, Welding speed, Interpass temperature, Arc voltage, HAZ, Gas Metal Arc Welding (GMAW)*

Cite This Article: A. Hemaid, Tarik Tawfeek, and O. A. Gaheen, "**A**n Investigation into Effect of Butt Welding Parameters on Weldment Mechanical Properties." *American Journal of Mechanical Engineering*, vol. 4, no. 3 (2016): 92-98. doi: 10.12691/ajme-4-3-2.

1. Introduction

In the fusion welding processes, part edges or joint faying surfaces are heated to above the melting point for a pure material. All fusion welds contain a distinct fusion zone (FZ), as well as heat- affected zones (HAZ) and unaffected base material. In alloys, there is also a partially melted zone (PMZ) between the FZ and HAZ [1].

Thermal cycle of one weld pass where the high heat input gives low cooling rate and the low heat input gives high cooling rate. The cooling rate affects directly on the microstructure and the properties of the welded joint. The heat input depends on the welding voltage, current, and speed. The effect of varying the heat input, between 0.6 and 4.3 KJ/mm, on the microstructure and properties of manual metal arc deposits containing 0.6-18 Manganese (Mn) has been investigated in [2,3].

Reference [4] presented results of a study aimed to establish temperature distribution, distortion, and residual stress field developed during the welding process in welded aluminum plates. The material considered was of AL-2024-T3, commonly used for aircraft components. A numerical analysis of welding process using finite element method (FEM) was carried out. Numerical results were compared with experimental test, and good agreement is obtained.

Reference [5] studied the evolution of temperature and velocity field during gas tungsten arc spot welding of AISI 1005 steel by using a transient numerical model. The sensitivity of weldmetal microstructure and mechanical properties to variations in both heat input and weld dilution in submerged arc (SA) welding of micro alloyed steel was examined as in [6]. Weldments were prepared with weld metal dilutions of approximately 40% and 70% at heat input of 2.0, 3.3, 4.6, and 5.3 kJ/mm, using two commercial welding wires and a basic commercial flux. The high dilution welds, which were ordinary bead on – plate welds, resulted in microstructures that ranged from ferrite with aligned second phase at low heat input to acicular ferrite at high heat inputs. Special over- welding techniques were used to make the low dilution welds, allowing use of the same welding parameters as those for the high dilution welds.

Reference [7] described derivation of a control model for electrode melting and heat and mass transfer from the electrode to the workpiece in gas metal arc welding (GMAW). Specifically, a model is developed which allows electrode speed and welding speed to be calculated for given values of voltage and torch-to-base metal distance, as a function of the desired heat and mass input to the weldment. Heat input is given on a per unit weld length basis, and mass input is given in terms of transverse cross- sectional area added to the weld bead (termed reinforcement). The relationship to prior work is discussed.

A range of semiautomatic gas-shield arc welding consumables was selected as in [8], in order to assess their suitability for producing uphill groove welds in 30mm thick structural steel. In addition to 1.2mm diameter solid welding wire, 1.2mm diameter rutile and basic flux cored and metal cored welding wire were employed, all with Ar-20%CO2 shielding. A 2mm diameter self shielded flux cored welding wire was also included. All deposits contained nominally 1%Ni. Constant voltage power sources were used for the rutile and self-shield electrodes, and synergic pulsed power sources for the remainder. All welding was carried out without preheat, and with a maximum interpass temperature of 150ºC.

References [9,10,11] studied a three AWS Code, all weld-metal test assemblies were welded with an E11018-M electrode from a standard production batch, varying the welding parameters in such a way as to obtain three energy inputs: high heat input and high interpass temperature , medium heat input and medium interpass temperature, and low heat input and low interpass temperature. Mechanical properties and metallographic studies were performed in the as welded condition.

Reference [12] present the effect of heat input on the microstructure and mechanical properties of the heat affected zone of duplex steel. He studied the effect of the heat input on the microstructural changes and the impact properties. On the other hand, heat transfer calculations were absent, and its computer model. Also there is no temperature distribution in 3-D, thermal cycle in the 2-D, the NDTs for the welded joint, and empirical coloration.

Reference [13] presents an effect of the number of passes on the structure and properties of submerged arc welds of AISI type 316L stainless steel. He proof that as the number of passes increased, the hardness and tensile strength increased, while the ductility and toughness decreased.

The present work aims to study the effect of welding process variables (interpass temperature, welding power, welding speed, and welding position) on the temperature distributions, the welding thermal cycles behavior, peak temperature and the cooling rate for the steel butt-welding joints in the multiple pass welding process by means of the practically measurements

Also, it aims to study practically the effect of heat input which presented by the welding process variables on the mechanical properties (tensile strength, yield strength, surface hardness, and impact test) of the welded joints to reach the optimum welding variables which give the optimum mechanical properties.

2. Experimental Work

2.1. The Base Metal Specifications

According to the Egyptian Iron and Steel Co. Hadisolb [13] the base metal specifications used are shown in Table 1 and Table 2.

Table 1. The chemical compositions of the base metal

Steel Grade DIN 17100	C% max	Mn% Max	Si% Max	P% max	S% max	N% max
St. 52-3N	0.23	1.70	0.60	0.045	0.045	0.011

Table 2. The mechanical properties of the base metal

Steel Grade DIN 17100	Tensile Strength N/mm²	Upper Yield Point N/mm²	Elongation %
St. 52-3N	610	460	22%

2.2. The Electrode Specifications

According to the ESAB Welding Handbook [14] the used electrode specifications and classification are shown in Table 3, Table 4 and Table 5.

Table 3. Welding data ranges

Wire Classification DIN 8559	Welding Positions	Arc Voltage V	Current A	Wire feed m/min
SG3	1G & 3G	18-35	120-380	2.3-15

Table 4. The wire chemical compositions %

C%	Si%	Mn%
0.1	0.85	1.5

Table 5. The wire mechanical properties

Tensile Strength	Yield Stress	Elongation
620 N/mm²	470 N/mm²	25%

2.3. Preparation of the Welding Joints

Two plates of size 200x100 mm with thickness 10 mm, each with one of the edges chamfered by machining, were taken together to form a weld pad of size 200x200 mm with a S-V- groove joint, Figure 1, and Figure 2 shows the Single-V- groove weld, butt weld joint (B), and prequalified complete joint penetration (CJP) groove welded joint details. Table 1 dives all the data and specifications for the base metal.

The related steel strips were cut to size using band saw.

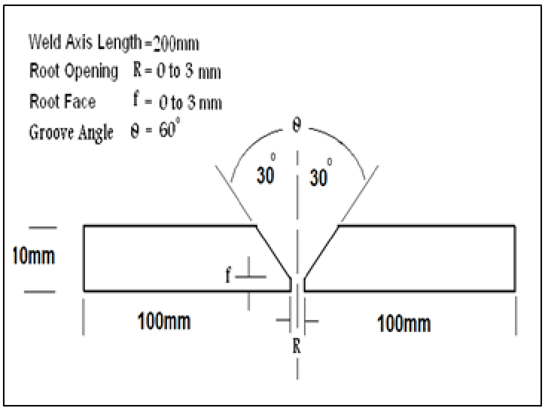

Figure 1. Welded joint details of S-V-groove butt weld (1G position) according to AWS code

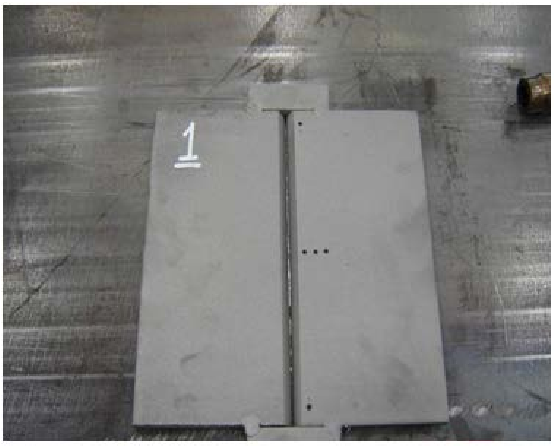

Figure 2. Prequalified CJP of S-V-groove butt weld for the present work

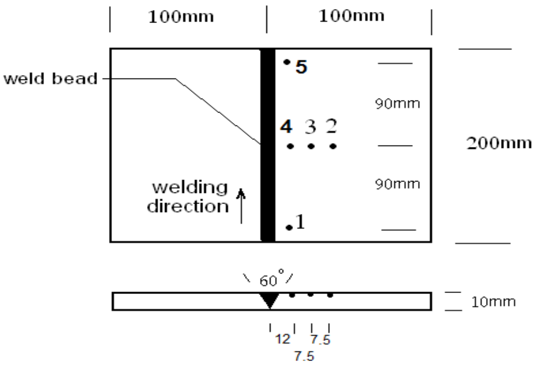

Figure 3. Thermocouples locations and distances between them for the present experimental work in the two-dimension

2.4. Welding Variables

Interpass temperature: The interpass temperature is the temperature immediately before each weld run after the first is deposited. The interpass temperatures were varied in the present work between 50 and 500°C.

Welding Power: The variation in the welding power was produced by the consumed voltage and current during the welding process. Figure 4-Figure 6 shows the power registered through the values of the volt and ampere on the screen of the welding machine in the GMAW process. The welding powers were varied in the present work between 2.6 to 9.9 k W.

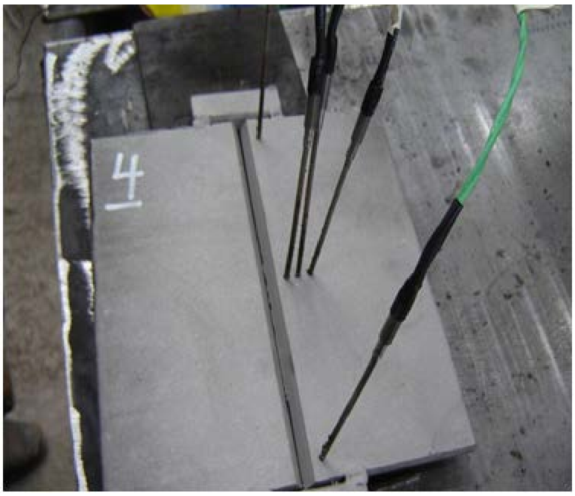

Figure 4. Thermocouples locations in the weld test plate practically in the two-dimension

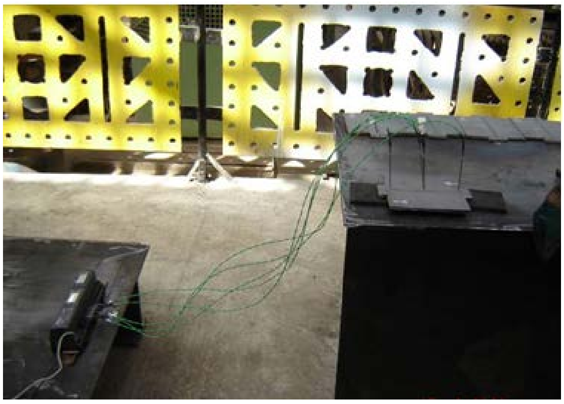

Figure 5. Thermocouples connections with the A/D C modules in the present experimental work

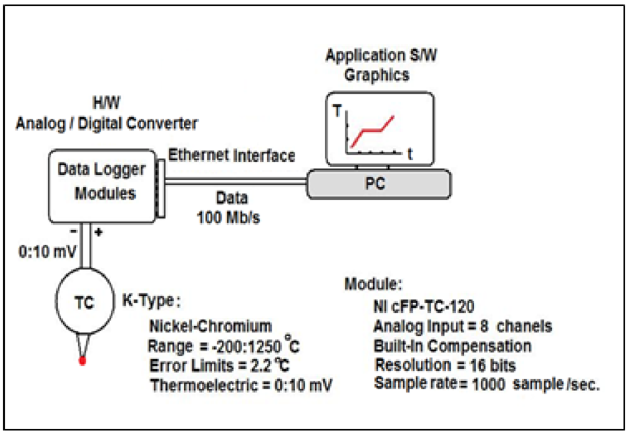

Figure 6. Ethernet interface for compact field point

Welding Speed:The welding speed or the travel speed of the welding arc is a function in the wire feed rate of the GMAW machine. The wire feed rate ranges affect on the arc speed directly and were varied in the present work between 3 to 9 mm/sec.

2.5. Temperature Measurement Technique

The welding thermal cycles were recorded with a computer based data acquisition system, using five K-type thermocouples calibrated with certification come from EAST company (2.5 mm in diameter, Nickel-Chromium, grade from -200 to 1250 ºC, standard error ±2.2°C above 0°C, and thermoelectric voltage 0:10 mill volts). The thermocouples are used to measure the temperature distribution during welding. The thermocouples were fixed in the plate to measure the temperature in the two-dimension (x-y plane) as shown in Figure 3 and Figure 4. The temperature were measured at distances 12, 19.5, and 27 mm from the weld centerline on one side plate only at the center plate, for the sensor numbers 4,3, and 2 respectively. And 12mm from the weld centerline for the sensor numbers 1, and 5 at the two edges of the plat at the top surface of the test plate.

The NI cFP- TC120 module built-in signal compensation (data logger or data acquisition) includes eight differential inputs for thermocouples, resolution of 16 bits resolution for high-accuracy measurements, sample rate 1000 sample/sec, and analog to digital conversion. It also provides cold –junction compensation using a thermistor embedded in the connector block.

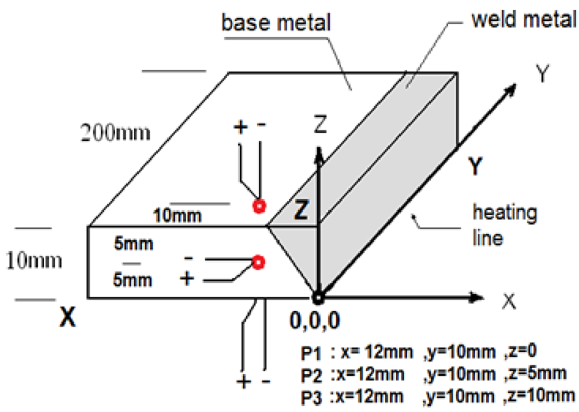

Figure 7. Thermocouples locations and distances between them for the present experimental work in the three-dimension at three points P1,P2, and P3

Figure 5 and Figure 6 show the ethernet interface for compact field point and the thermocouples module connection. The NI cFP- TC120 module which used in the measurements is come from EAST Company. Figure 7 and Figure 8 show the thermocouples locations in the plate used to measure the temperature in the three-dimension (x-y-z).

Figure 8. Thermocouples locations in the weld test plate practically in the three-dimension

2.6. Tension and Impact Test Specimens

The specimens of the tension and charpy V-notch impact tests are taken from the welded joints which are welded according to special conditions. These specimens are taken by machining according to ASTM code [15]. The locations of these specimens are shown in Figure 9.

The transverse weld specimens for tension and charpy V-notch impact test are used for evaluation of all welded joints with different welding variables. On the other hand, the longitudinal weld specimens for tension test are used only for evaluation the welded joints containing artificial porosity at different heat input conditions. The distractive tests are carried out in the Faculty of Engineering at Shoubra.

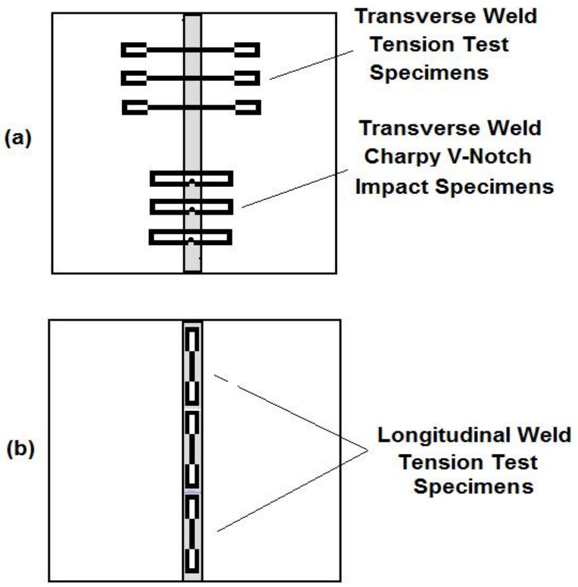

Figure 9. Locations of the tension and impact test specimen according to ASTM code

2.6.1. Tension Test Specimen

According to the ASTM code the tension test specimen dimensions are shown in Figure 10. The transverse weld specimens are used to study the effect of welding variables on the mechanical properties. On the other hand, the longitudinal weld specimens are used to study the effect of artificial porosity on the tensile and yield strength under multi thermal cycles.

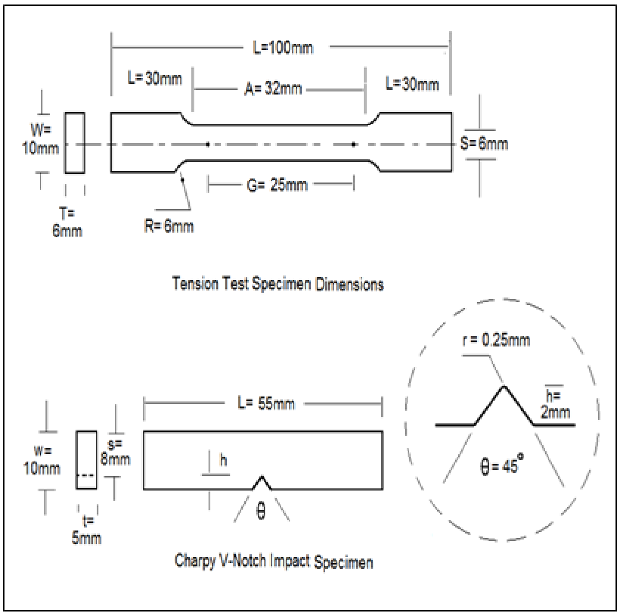

Figure 10. Dimensions of tension and impact test specimen according to ASTM code

2.6.2. Charpy V-Notch Impact Specimen

According to the ASTM code the charpy V-notch impact test specimen dimensions are shown in the Figure 10 also. These specimens are used to study the effect of welding variables on the mechanical properties.

3. Results and Discussions

Input Variables and Their Limits

The independently controllable input parameters affecting the tensile strength were arc voltage (V), wire feed rate (F), welding speed (S), and interpass temperature (T). Trial runs were carried out by varying one of the input parameters while keeping the rest at constant values. The input variables and their limits in coding form are given in Table 6.

Table 6. welding conditions and their limits

Welding Parameters	Units	Sym	Limits in code form				
			-2	-1	0	+1	+2
Arc voltage	Volts	V	20	25	30	35	40
Wire feed rate	m/min	F	3	5	7	9	11
Welding speed	mm/sec	S	2	4	6	8	10
Interpass temperature	ºC	T	100	200	300	400	500

3.1. Experimental Data

The selected design matrix shown in Table 7 is a five-levels for each factor. All welding variables at their intermediate level (0).

Table 7. Design matrix and their response

Input Variables				Coded Variables				Responses
WFR	Volt	Speed	Temp	F	V	S	T	σ_T =(10 N/mm2)
3	30	6	300	-2	0	0	0	56.266
5	30	6	300	-1	0	0	0	52.066
7	30	6	300	0	0	0	0	48.866
9	30	6	300	1	0	0	0	54.9
11	30	6	300	2	0	0	0	54.566
7	20	6	300	0	-2	0	0	45
7	25	6	300	0	-1	0	0	48.466
7	30	6	300	0	0	0	0	47.6
7	35	6	300	0	1	0	0	57.666
7	40	6	300	0	2	0	0	48.933
7	30	2	300	0	0	-2	0	49.033
7	30	4	300	0	0	-1	0	48.7
7	30	6	300	0	0	0	0	50.733
7	30	8	300	0	0	1	0	48.866
7	30	10	300	0	0	2	0	44.933
7	30	6	100	0	0	0	-2	49.266
7	30	6	200	0	0	0	-1	51.866
7	30	6	300	0	0	0	0	50.5
7	30	6	400	0	0	0	1	49.166
7	30	6	500	0	0	0	2	48

3.2. Effect of Wire Feed Rate and Welding Voltage

The empirical correlation is useful in prediction of the tensile strength at different welding variables. Figure (11-1), (11-2), (11-3), (11-4), (11-5) show the predicted effect of the wire feed rate of the welding electrode at 3m/min, 5m/min, 7m/min, 9m/min, and 11m/min on the tensile strength of the joint before welding at different welding voltage of 20V, 25V, 30V, 35V, and 40V and at welding speed of 2mm/sec, 4mm/sec, 6mm/sec, 8mm/sec, and 10mm/sec, and interpass temperature of 100ºC, 200ºC, 300ºC, 400ºC, and 500ºC . The result shows that the tensile strength decreases with the increasing of the wire feed rate, welding speed, and interpass temperature at any constant value of welding voltage. On the other hand, the tensile strength increases with welding voltage increases also at any value of the wire feed rate, welding speed, and interpass temperature.

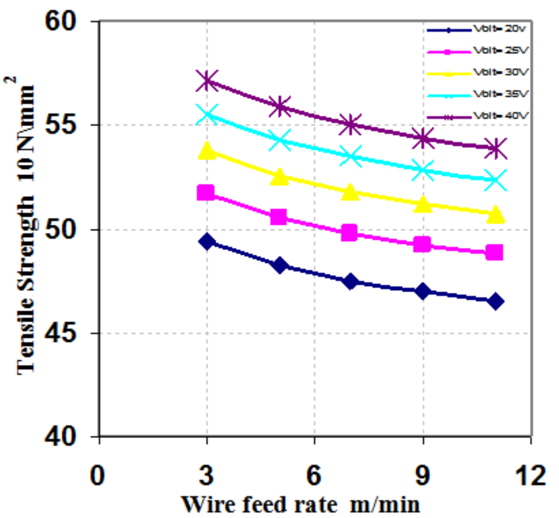

Figure 11-1. Effect of wire feed rate and welding voltage on the tensile strength at S=2mm/sec, and T=100 ºC

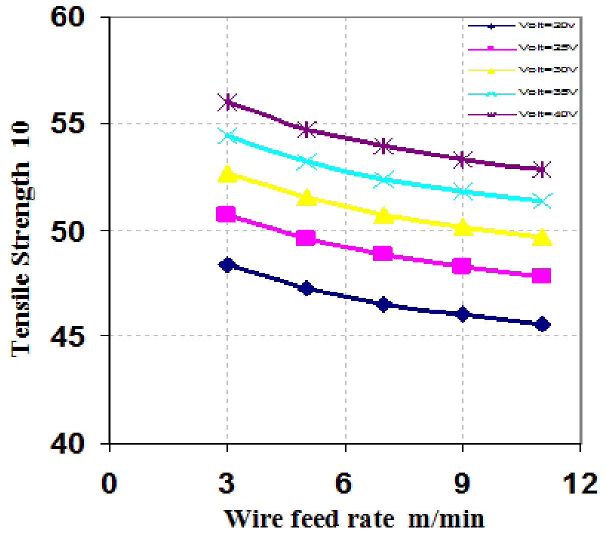

Figure 11-2. Effect of wire feed rate and welding voltage on the tensile strength at S=4mm/sec, and T=200 ºC

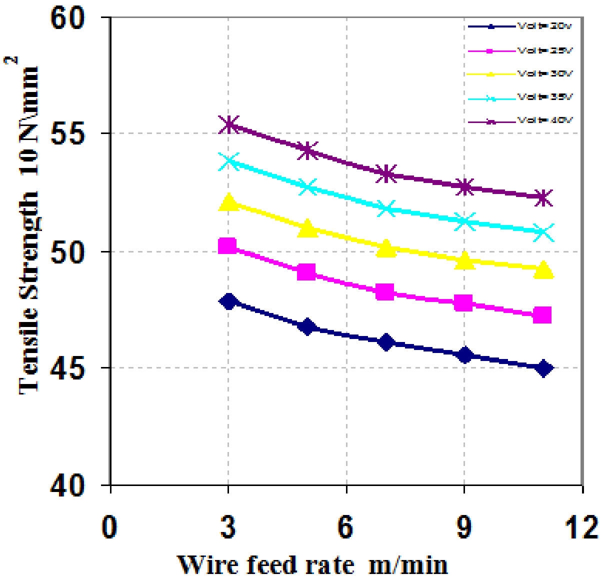

Figure 11-3. Effect of wire feed rate and welding voltage on the tensile strength at S=6mm/sec, and T=300 ºC

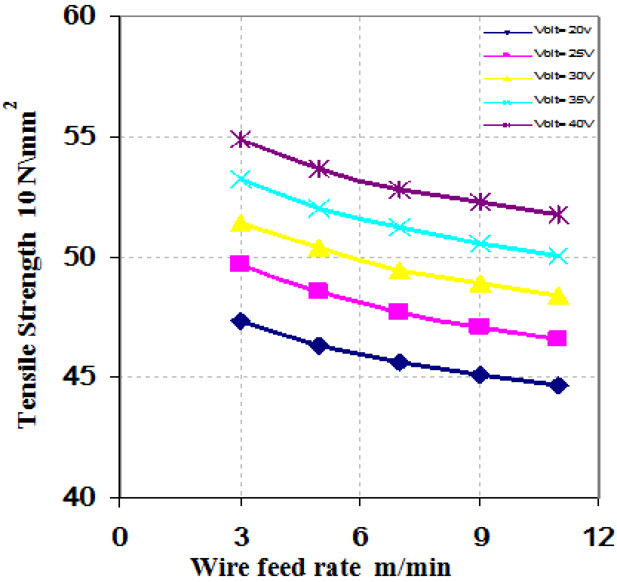

Figure 11-4. Effect of wire feed rate and welding voltage on the tensile strength at S=8mm/sec, and T=400 ºC

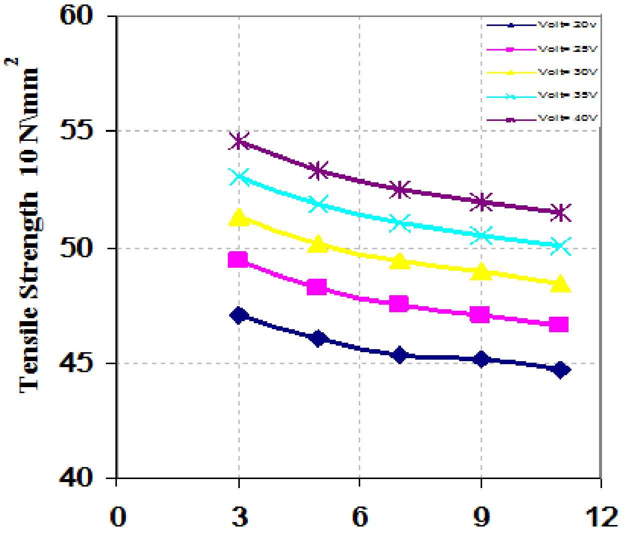

Figure 11-5. Effect of wire feed rate and welding voltage on the tensile strength at S=10mm/sec, and T=500 ºC

3.3. Effect of Welding Speed And Welding Voltage

The empirical correlation is useful in the prediction of the tensile strength at different welding variables. Figure (12-1), Figure (12-2), Figure (12-3), Figure (12-4), Figure (12-5) show the predicted effect of the welding voltage of the welding electrode voltage of 20V, 25V, 30V, 35V, and 40V on the tensile strength of the joint before welding at different welding speed of 2mm/sec, 4mm/sec, 6mm/sec, 8mm/sec, and 10mm/sec at wire feed rate of the welding electrode of 3m/min, 5m/min, 7m/min, 9m/min, and 11m/min, and interpass temperature of 100ºC, 200ºC, 300ºC, 400ºC, and 500ºCthe result show that with the increasing in the welding voltage the tensile strength increases also. On the other hand, the tensile strength decreases with increasing in the welding speed, wire feed rate, and interpass temperature at any constant value of the welding voltage.

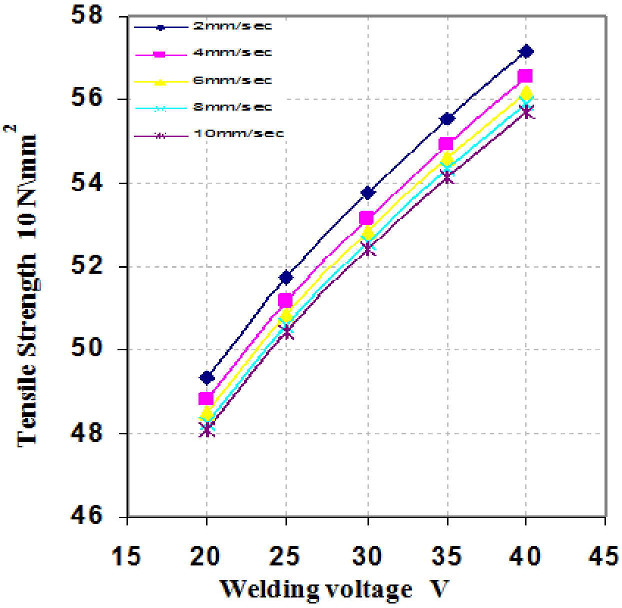

Figure 12-1. Effect of welding voltage and welding speed on the tensile strength at WFR=3m, a/min, and T=100 ºC

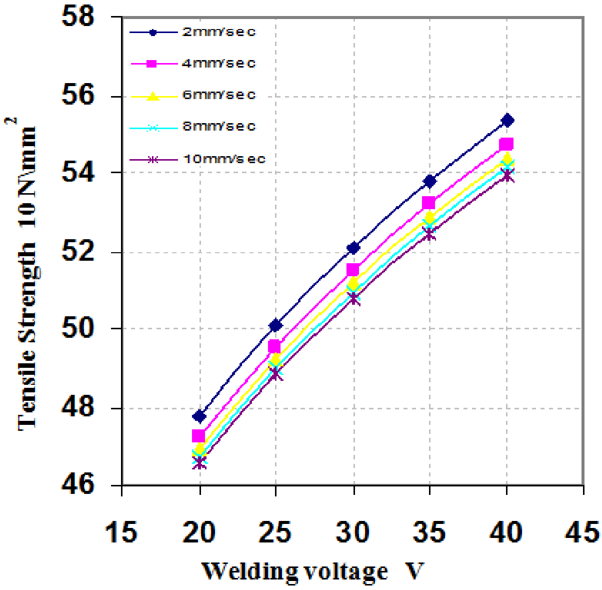

Figure 12-2. Effect of welding voltage and welding speed on the tensile strength at WFR=5m/min, and T=200 ºC

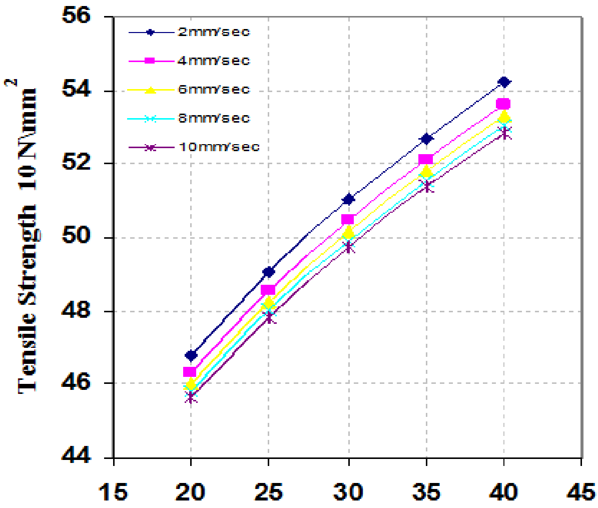

Figure 12-3. Effect of welding voltage and welding speed on the tensile strength at WFR=7m/min, and T=300 ºC

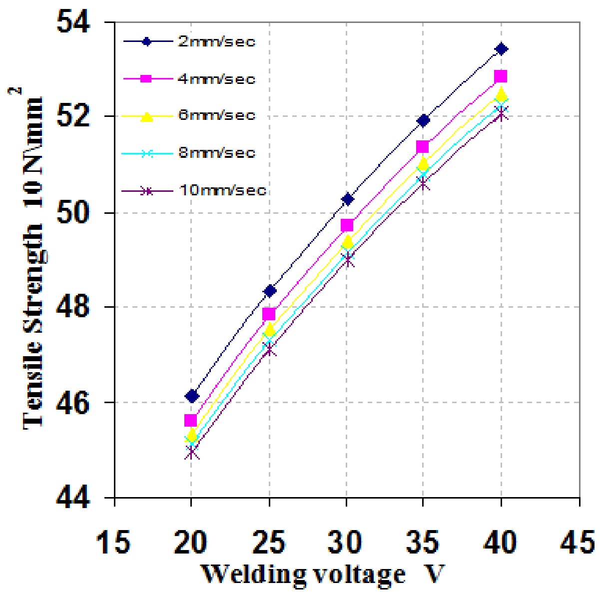

Figure 12-4. Effect of welding voltage and welding speed on the tensile strength at WFR=9m/min, and T=400 ºC

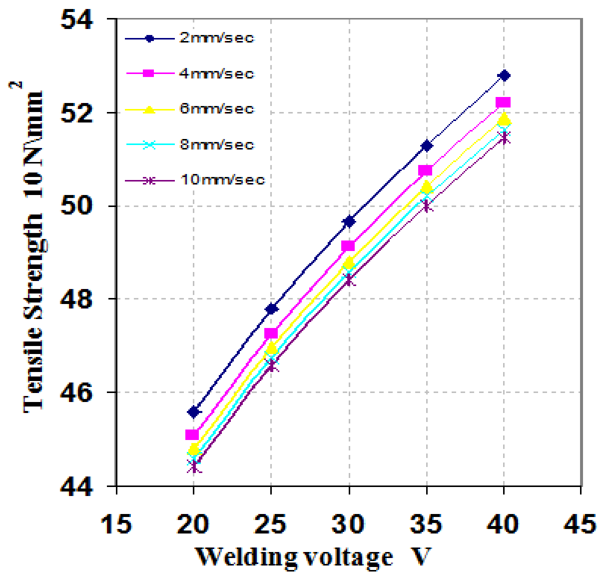

Figure 12-5. Effect of welding voltage and welding speed on the tensile strength at WFR=11m/min, and T=500 ºC

4. Conclusons

The results of studying the effect of welding parameters (interpass temperature, welding power, welding speed, and welding position) which presented in the heat input on the temperature distribution in three-dimension, and two-dimension, and the mechanical properties of the steel welded joints by GMAW came out with the following conclusions.

- Increasing the heat input in the welding process by the welding variables leaded to a welding joint which has less mechanical prosperities than the base metal prosperities.

- Increasing the heat input in the welding process by the welding variables increase the heat accumulation during the welding process, increases the peak temperature in the thermal cycles, and decreases the cooling rate.

-The error due to two-dimensional approximation in the heat transfer analysis of welding process thermal cycle is 10.7% for the first and second pass, and 27% for the third pass.

- Through the welding variables values which give the optimum mechanical properties, it is easy to predict the quality of the joint by following these values during the welding process.

- The optimum mechanical properties take place at interpass temperature of 200º.

- The optimum mechanical properties take place at welding voltage of 35V.

- The best mechanical properties take place at welding speed of 6 mm/sec.

- The optimum mechanical properties take place at welding position of 3G-up and 1G.

- Although the artificial porosity in the welded joint was accepted, the tensile and yield strengths of the welded joint decreased with the increasing in the welding heat input.

- Through the experimental data which taken by the destructive tests the predicted tensile strength can be obtained from the following empirical equation within the application limits;

$$\sigma_U = 29.48 * F^{-0.045} V^{0.212} * S^{-0.0158} * T^{-0.013}$$

$$\varepsilon_{avr} = 4.9\%$$

- For the steel plates of 10mm thickness the two-dimensional temperature distributions may be good approximation instead of the three-dimensional for the temperature distribution.

- For the steel structure field it prefer the gap between weld pass within 50sec it means for the long welding joint it must be use more than one welding machine to keep the time gap be constant.

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