Comparison between GMAW, GTAW and FSW Techniques Based on Power Consumption and Joint Strength

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Abstract: Welding of steel sheets can be carried out by many techniques each one has its own advantages and limitations. Selection of one among these techniques to fabricate specific structure is very delicate and most of the time is based on personal experience. Fusion welding Techniques like GMAW, GTAW are extensively used in many applications in metal fabrication industry. Friction stir welding (FSW) is considered as one of promising solid state welding techniques based on power consumption and weld quality. The present work is a trial to validate this statement. GMAW, GTAW and FSW welding techniques were used to weld a sheet of 3 mm thickness of low carbon low alloy steel sheet with a length of 120 mm. The comparison which have been made to determine which one of these welding techniques consumes less energy and produce sound joint shows that FSW consumes less energy and produce bitter joint. The theoretical model used to predict the energy consumption by FSW gave reasonable prediction with an error of 5 percent compared with the experimental finding.
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Keywords: Low carbon low alloy, GMAW (Gas Metal Arc Welding), GTAW (Gas Tungsten Arc Welding), FSW (Friction Stir Welding).

Nomenclature: F: compressive force, P_f: power consumed in friction; μ: coefficient of friction; r_o: radius of tool shoulder (mm); h: height of tool pin (mm); ω: rotational speed of the tool (rev./min); P_P: power consumed in plastic deformation; σ_e: effective stress (power law stress); ϵ_e: effective strain (power law strain); r_i: radius of the pin (mm); v_o: welding speed (mm/min)

1-Introduction

GTAW is commonly used for welding thin sheets and sections of stainless steel and nonferrous light metals such as aluminum, magnesium, and copper alloys [1,2]. It is also used extensively in manufacturing of space vehicles, it is used frequently to weld small-diameter, thin-wall tubing and work pieces, to make root or first pass welds, for piping and to repair tools dies (especially components made of nonferrous such as aluminum and magnesium) [3, 4] and for critical welding operations like sealing spent nuclear fuel canisters before burial [5, 6]. GTAW welds are highly resistant to corrosion and cracking over long time periods.

Gas metal arc welding(GMAW) sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding, it is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used [7].

Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. The automobile industry in particular uses GMAW welding almost exclusively [8].

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a decade. Recently, friction stir processing (FSP) was developed for microstructural modification of metallic materials.

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys [9], [10]. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (Fig. 1).

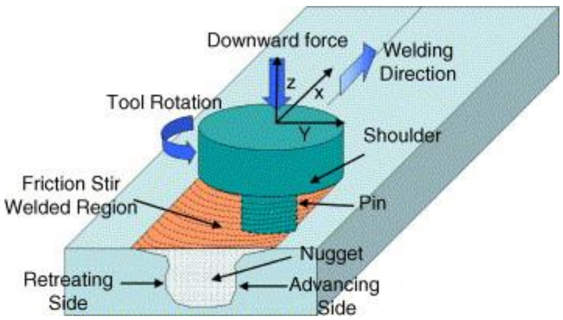

Fig. 1 Schematic drawing of friction stir welding.

As a result of this process a joint is produced in 'solid state'. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [11]. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains [12], [13], [14] and [15]. The fine microstructure in friction stir welds produces good mechanical properties.

The matter of cost in these 3 welding process is very critical, many research have been made to calculate the energy consumption and get its way to alter the parameters of these processes to reduce energy consumption consequently the cost will be reduced.

The present work used the GMAW, GTAW and FSW welding techniques to weld a sheet of 3 mm thickness of low carbon low alloy steel. A comparison had been made to see which one of these techniques is energy efficient.

2-Experimental work

2-1 Material

The material used in the present work is low carbon low alloy steel sheet of 3 mm thickness. Chemical analysis has been conducted on tested material by Spectrometer device (Spectrolab/ Germany). The results obtained are given in Table 1.

Table 1. Average values of chemical composition (weight %)

Element	C	Si	Mn	P	S	Cr	Mo	Ni
Wt %	0.0571	0.0470	0.561	0.0095	0.0016	0.0304	0.0062	0.0149
Element	Al	Co	Cu	V	W	Sn	Fe%	
Wt %	0.0346	0.0028	0.0271	0.0024	0.0050	0.0020	The Rest	

2-2 Welding process parameters:

The parameters used for GMAW&GTAW are given in Table 2. Welding process parameters for FSW is given in Table 3.

Table 2. The welding parameters for GMAW &GTAW.

Welding Parameter	GMAW	GTAW
Filler metal	AWS,A5.18,ER70S-6	AWS,A5.18,ER70S-6
Wire diameter, mm	1	1
Gas flow rate, L / min	12	12
Gas – flux	95%Argon, 2.5%CO_2,2.5%O_2	Argon (purity of 99.999%)
Current, Amps	170– 200	60- 80
Voltage, V	18- 20	15- 20
Polarity	= / +	= / -
Wire feed, m/min	4.5	- - -
Travel speed, m/min	0.162	0. 04
Joint type	BW	BW
Gap between two parts, mm	3	3

2-3 Mechanical Properties of Welded Joints

2-3-1 Tensile properties

Tension tests were conducted on specimens fabricated from as received sheet as well as GMAW, GTAW and FSW weldments.

Tension specimens were prepared using laser cutting technique according to ASTM E8M-04 standard [16].

Tension tests were performed using universal testing machine (Tinius Olsen-H100KU) with capacity of 100KN. Tests were conducted at room temperature and cross head displacement rate of 1 mm/min. Table 4 summarizes the tensile properties obtained from tension tests as well as the hardness tests for GMAW, GTAW and FSW.

Power law stress-strain curve was calculated by equation (1) after determining the parameters of power law model.

$$\sigma = K(\varepsilon_p)^n \quad \text{...............} \quad (1)$$

The parameters for the constitutive models of power law for as received material were as follow:-

K= 1040.02 MPa

n= 0.4013MPa

The stress-strain curve resulting from applying the power law model parameters for as received material was plotted as well as experimental curve for comparison in fig.2.

Table 3 The welding parameters of FSW

Welding Parameter	**FSW**
Tilt angle	3 degrees
Tool shoulder diameter	16 mm
Pin diameter	5 mm
Pin height	2.25 mm
Rotational speed	1600 rpm
Traverse speed	25 mm/min
Tool material	Carbide super V 80
Welding time	4.8 minutes

Table 4. Mechanical properties of the tested steels

	Ultimate Tensile MPa	Yield strength MPa	Elongation%	Hardness H_{V30} [17]	Hardness BHN	Calculated UTS UTS= 3.5 (BHN)
As received	418	350	25	143	125	437.5
GMAW	410	340	25	208.733	150.35	526.225
GTAW	420	370	25	207.33	129.5	453.25
FSW	377	290	27	170	135.25	473.375

Note the values tabulated in the table above is the average of 3 readings

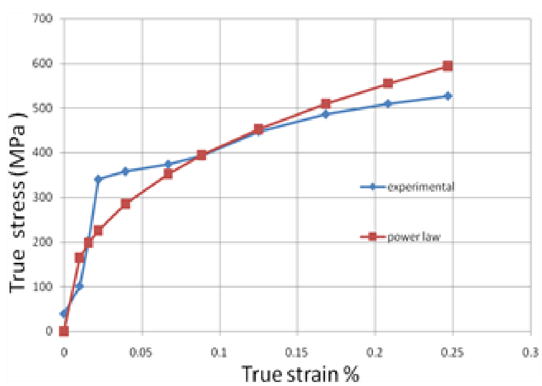

Fig. 2 Stress-strain curve resulting from applying the power law model parameters for as received material as well as experimental curve for comparison.

2-3-2 Micro hardness test of weldments

Micro hardness measurements were done on the specimen used for metallographic examination using the micro hardness tester with a load of 200 gram ($Hv_{0.2}$ kg) and diamond indenter were used for measurement.

The test was done according to BS. EN 1043-1 [17]. Fig.3 shows the results of micro hardness measurements.

It is shown that the micro hardness results for GTAW are little higher than GMAW and FSW which indicate better performance from strength and fracture toughness point of views.

The micro hardness results for FSW are little higher in weld zone than the heat affected zone (HAZ) and thermo mechanical affected zone (TMAZ) which indicate the effect of plastic deformation in the weld zone.

Calculating the UTS by the well Known Formula: UTS= 3.5 (BHN) we got the calculated UTS values for base material and successive welding processes we have seen that formula had given the best approximation to the experimental values in case of base metal and GTAW.

We have noticed also in the figure 3, the values of micro hardness are matched with the values of hardness in a great manner.

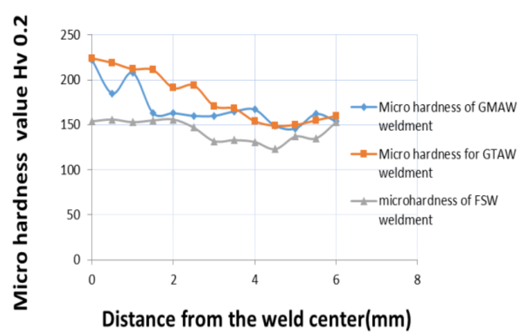

Fig. 3 Micro hardness results of GMAW, GTAW and FSW weldments respectively for purpose of comparison

2-4 Measuring the electric Power for welding processes

2-4-1 Electric Power for GMAW and GTAW

Equipment used to measure the voltage and amperage in case of GMAW and GTAW welding are avometer and clip ampere respectively. Three readings were taken and the power consumed was calculated for every case. The average values were calculated.

2-4-2 Measuring power used for FSW

The equipment used to measure the voltage and amperage in case of FSW welding are avometer and clip ampere respectively. Figure (4) shows the equipment used and the measuring setup.

The electrical characteristics (Voltage and Current) when the machine is idle (the tool rotated without any contact to the work piece) and when the machine is working (the tool rotated and travel along the welding line of the work piece) were monitored and measured.

Fig.4 Avometer and clip ampere which had been used to measure voltage and amperage used in FSW welding.

3-Experimental Results

In case of fusion welding processes (GMAW, GTAW) the readings of the volts and amperages had been recorded automatically from the control panel of the welding machine and checked by using avometer and clip ampere on the chord coming from the power supply.

In case of FSW the readings of the volts and amperages had been recorded in idle situation and in working situation, the three reading of these voltages and amperage had been averaged.

The power consumed of fusion and non-fusion welding processes had been calculated mathematically and theoretically to judge the power consumption in each case.

Fusion welding power consumption can be calculated using the following equation:

Power consumption = $((V*I)/1000)*(T/60)*(1/E)$ --(2)

Where:

V is the voltage in volts

I is the current in Amps

T is the welding time in minutes

E is the efficiency of the welding machine

NB.

E=0.6 (for welding transformer)

E=0.25 (for welding generator) [18]

3-1 Power consumption based on measurements

The results of the measured parameters are given in Table 5.

Power consumed in case of FSW is 31.4Whr which proofs that too small energy is needed to execute the welding process when it is compared with the other techniques.

Table 5. Results of Voltage and Ampere Readings

Measured Parameter	GMAW	GTAW	Milling Machine, Idle Condition	Milling Machine, Loaded Condition
Voltage (V)	**19**	**17.5**	**380**	**380**
Current (I)	**185**	**70**	**5.1**	**5.7**
Weld line length (mm)	**120**	**120**	**120**	**120**
Traveling speed (m/min)	**0.162**	**0.04**	**0.025**	**0.025**
Welding time (min)	**0.74**	**3**	**4.8**	**4.8**
Power Consumed (Whr)	72.3 Whr	102 Whr	258.4Whr	288.8Whr Power consumed in welding = 288.8-258.4=31.4

3-2 Prediction of Power Consumption by Energy Model for FSW

All previous studies assumes that the heat generated due to friction of the pin shoulder on the work pieces surface is dominant and the heat generated due to the plastic deformation within the work piece and the friction of the pin with the material is negligible. However other models [19-21] consider the heat generated from both the friction of the pin shoulder and plastic flow. Power consumption in FSW has been calculated by Eq,(3) according to Samir and El Domiaty [19].

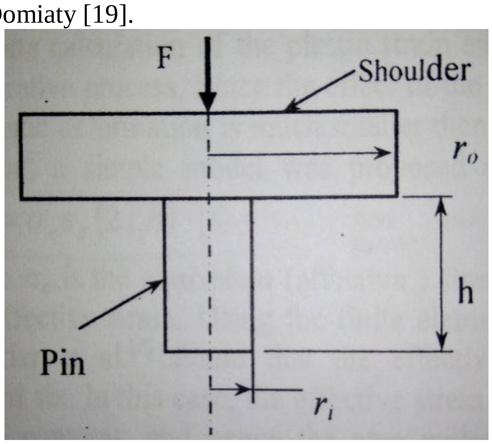

Fig.5 Geometry of the FSW tool

$$P=2\mu F\,[(1/3)*r_o+((r_i^2)/(r_o^2))*h]\,\omega + \sigma_e\,\epsilon_e(r_i h)v_o \quad \text{------------ (3)}$$

Given that:

r_i =2.5 mm, r_o= 8mm, h= 2.25 mm,ω = 1600 rpm, v_o=25 mm/min, σ_y=394.923 MPa

σ_u=594.311MPa, μ=0.5,$\sigma_{avg}=(\sigma_y+\sigma_u)/2$

= (394.923+594.311)/2= 494.617 MPa

$F=\sigma A=494.617*((3.14*(2.5^2))/4)$

= 2426.71465625N

σ_e is the effective stress (power law stress)

σ_e = 600 MPa

ϵ_e is the effective strain (power law strain)= 6

Substituting all the above parameters into equation (3),

Power consumption is estimated as:

P_l= 2350204.53125 joule /hour

where

To convert the power in joules /hour to power in joules/second we can use the formula

1joule /hour=0.0003 joule/second

Where joule /second = watt

Hence

P_{total}= 705.061359375joule /second

P total= 705.061359375watt

or

P = 56.4 Whr

3-3 Calculation of effective strain in FSW using volume constancy concept

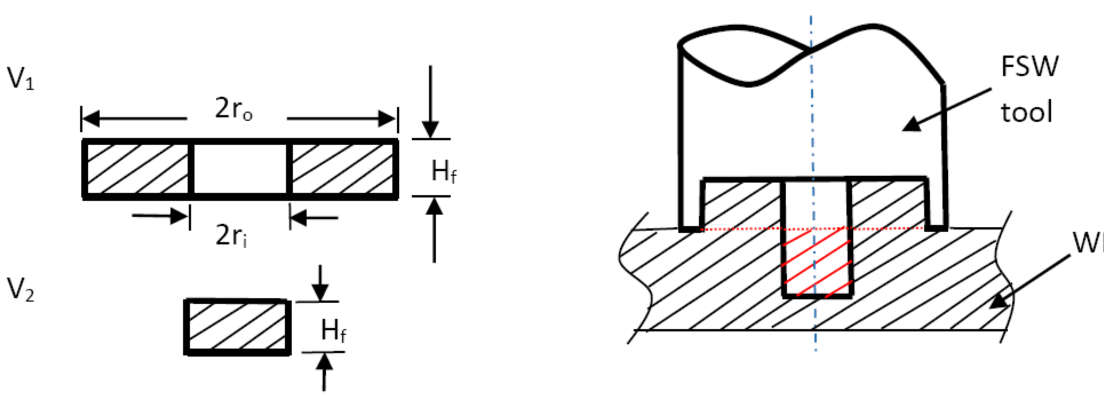

Fig 6 Schematic for clarifying Volume constancy concept of FSW

Volume constancy concept states that the volume of the displaced metal which comes out of the work piece into the area under the shoulder of FSW tool(V_1) is equal the volume of the pin which plunged into the work piece(V_2).

$V_1=V_2$

$(4\Pi/4) * (r_o^2-r_i^2) * H_f = (4\Pi/4)\, r_i^2 * H_o$

$H_f = (r_i^2 * H_o)/ (r_o^2-r_i^2)$ ---------------------- (4)

Given that H_o =2.25 mm the height of FSW tool pin

H_f =0.24 mm

ϵ_e (the effective strain) =ln (H_o/ H_f) = ln (2.25/0.24)= ln (9.375) =2.24

Substituting this modified value into Eq.(3) it is possible to obtain modified value for power consumption as following:

P_l=11789386.65/(0.08*60) joule /hour

or

P total= 59 Whr

Figure (7) give a comparison between welding techniques based on power consumption which measured experimentally and also the predicted theoretically (19-21).

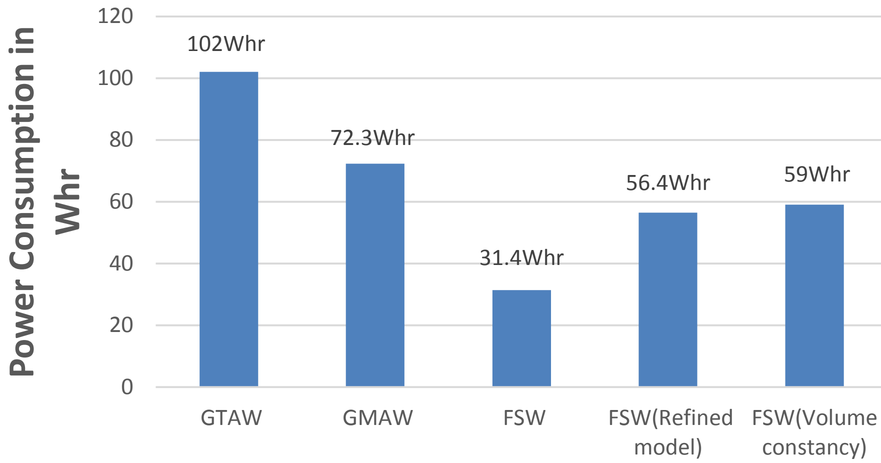

Fig.7 Power consumed comparizon chart

4 - Results and Discussion

Microstructure examinations (Fig.8) for GTAW, GMAW and FSW weldments demonstrate that all techniques gave sound weld with no micro cracking or any weld defect. Also the results of micro hardness measurements of the three weldments show good strength compared with the parent material.

The GTAW weld zone shows ferrite pearlite matrix with high percent of pearlite, GMAW weld zone shows ferrite pearlite matrix with high percent of ferrite and the FSW weld zone (Nugget) shows equiaxed fine grains structure, they have micro hardness values 224 $Hv_{0.2}$, 222 $Hv_{0.2}$ and 154$Hv_{0.2}$ respectively at weld center.

The readings of micro-hardness of the three welding processes interpret the values of power consumed in each case, the higher the values of micro-hardness the higher the power consumed in each welding process.

The power consumed in GTAW and GMAW were 102, 72.3 Whr, however the power consumed in the case of FSW is ranging from 31.4 to 59 Whr. These results proves that FSW technique has the lowest energy consumption.

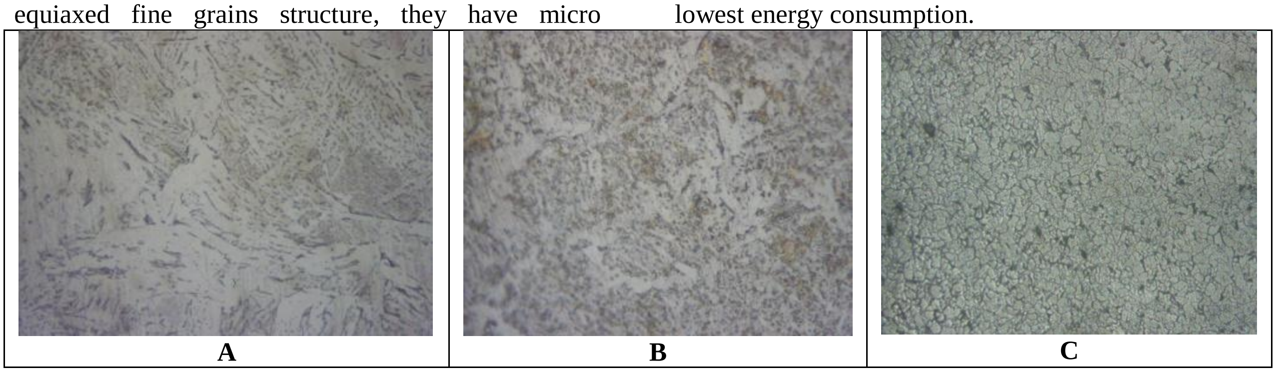

Fig.8 Microstructure of GTAW, GMAW and FSW weldments (magnification of 500X) A- GTAW weld metal, B- GMAW weld metal, C- FSW nugget

5 - Conclusion

Low carbon low alloy steel sheet of 3 mm thickness is welded successfully by GMAW, GTAW and FSW. FSW has the lowest value of power consumption to fulfill a sound weldment compared with GMAW and GTAW.

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