A study into Investigation of the effect of the arc welding techniques on the mechanical properties of welded joints.

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ABSTRACT

The aim of the present work is to investigate the effect of the welding techniques such as SAW, SMAW, and GMAW on the mechanical properties of welded joints. Welding operations were carried out though controlled welding conditions. The welding techniques were examined through three zones such as base metal, HAZ and weld zone using optical microscope.

Mechanical properties were investigated using Universal Tensile Testing machine, and Vickers Hardness Testing Machine while the Impact test was performed using V-notch Impact Test Machine.

The results of the present work were indicated that the quality based on scope of work GMAW is preferred; for high productivity projects or thick joint SAW method. SMAW for impact based joints is preferred; and GMAW is preferred for high strength or hardness based joints.

KEYWARDS

Arc welding, Welding technique, Mechanical properties, microstructure.

INTRODUCTION

Welding is a process in which materials of the same properties or class are brought together and caused to joint through the formation of primary chemical bonds under the combined action of heat and pressure. The tendency for atoms to bond is the fundamental basis for welding. The definition of welding in ISO standard (1958) states; "welding is an operation in which continuity is obtained between parts for assembly, by various means" [1,2].

Presently welding is used extensively for fabrication of vastly different components including critical structures like boilers and

pressure vessels, ships, off-shore structures, bridges, storage tanks, pipelines, missile and rocket parts, nuclear reactors, fertilizer and chemical plants, earth moving equipment and automobile bodies etc. Welding is also used in heavy plate fabrication industries pipe and tube fabrication .

Three different Welding techniques (SAW, SMAW, and GMAW) were applied to steel grade DIN17100. Welding was carried out according to commercial practice under controlled welding conditions. For each welding technique three portions separately from base metal, HAZ and welded zone were examined microscopically on optical microscope while mechanical properties of each zone along with the hardness and impact test were carried out.

Submerged Arc Welding

In submerged arc welding (SAW) the arc and molten metal are shielded by an envelope of molten flux and layer of infused granular flux particles .When the arc is struck, the tip of the continuously feed electrode is submerged in the flux and the arc is therefore not visible. The weld is made without the intense radiation that characterizes an open arc process and with little fumes [3,4]. This welding process has these principles such as welding power source of 600 to 2000 A outputs, automatic wire feed devices, and tracking system to move the welding head or work piece**.** The welding power sources are normally connected to standard three-phase primary power lines when single phase power is required; it normally is drive from one phase of the three-phase line. Three-phase 220or 440 V and single–phase 440V system are normally used.

Gas Metal Arc Welding

Gas Metal Arc Welding (GMAW) is a welding process which joins metals by heating the metals to their melting point with an electric arc. The arc is between a continuous, consumable electrode wire and the metal being welded. The arc is shielded from contaminants in the atmosphere by a shielding gas [4,5].

Shielded Metal Arc Welding

Shielded metal arc welding means, it is one type of arc welding process. Where weld joint is produced by heating the work piece with an electrical

arc which is produced between shielded or coated electrode and work piece. In this welding process necessary filler metal is obtained from electrode. Coating or flux of electrode is used for shielding the melting metal from atmospheric harmful gas, maintaining arc stability, cleaning weld surface [6].

Welding Positions

Welding positions are indicated in Fig. 1 [7].

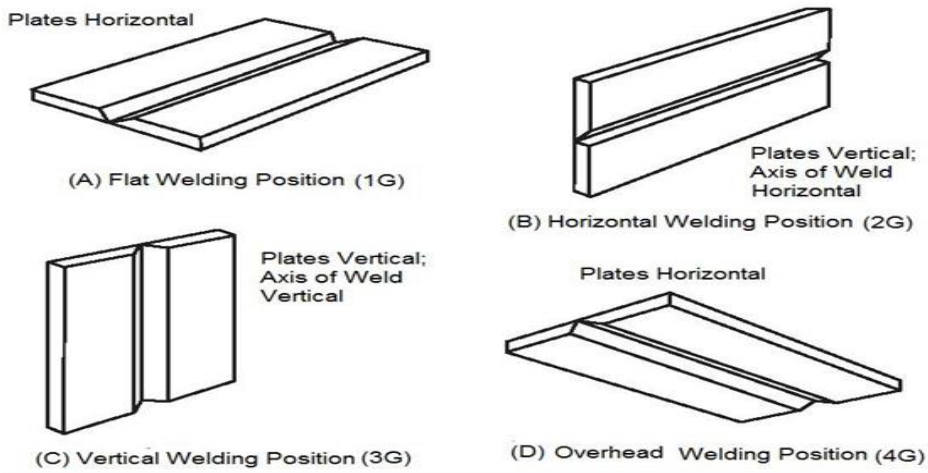


Fig. 1. Welding positions [7]

Non-Destructive Tests [NDT], is one part of the function of quality control and is complementary to other long established methods. By definition NDT is the testing of materials, for surface or internal flaws or metallurgical condition, without interfering in any way with the integrity of the material or its suitability for service [8].

NDTs includes magnetic particle testing (MT), Liquid Dye Penetrate testing (PT), Radiographic Testing (RT) and Ultrasonic Testing (UT). The purpose of NDTs is to serve as a backup to VI and to detect flaws and defects that are not visible. Nondestructive examination is not a replacement for an adequate program of VI, and should not be used as such [9].

Heat input and microstructure effect

In arc welding, energy is transferred from the welding electrode to the base metal by an electric arc. When the welder starts the arc, both the base metal and the filler metal are melted to create the weld. This melting

is possible because a sufficient amount of power (energy transferred per unit time) and energy density is supplied to the electrode [10].

Heat input is a relative measure of the energy transferred per unit length of weld. It is an important characteristic because, like preheat and inter pass temperature, it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and HAZ. Heat input is typically calculated as the ratio of the power (i.e., voltage x current) to the velocity of the heat source (i.e., the arc) as follows:

$$HI = \left(\frac{V * I * 60}{S * 1000}\right)\eta$$

Equ .1: Heat Input [10]

Where,

HI = heat input (kJ/in or kJ/mm); I = current (amps);
V = arc voltage (volts); S = travel speed (in/min or mm/min).
η = welding efficiency

Varying the heat input typically will affect the material properties in the weld. All of the mechanical properties show a monotonic relationship to heat input, that is, the mechanical property only increases or decreases with increasing heat input. Notch toughness, however, increases slightly and then drops significantly as heat input increases. The change in notch toughness is not just tied to the heat input, but is also significantly influenced by the weld bead size. As the bead size increases, which corresponds to a higher heat input, the notch toughness tends to decrease. In multiple-pass welds, a portion of the previous weld pass is refined, and the toughness improved, as the heat from each pass tempers the weld metal below it. If the beads are smaller, more grain refinement occurs, resulting in better notch toughness, all other factors being even [10,11].

EXPERIMENTAL WORK

Joint Geometry

The tested specimens were manufactured from steel plates of 250mm x 100mm .The two plates were fixed side to side to from 10mm, each plate edges was chamfered through angle of 30°using shaping machine. A weld pad of size 250mm x 200 mm with a S-V- groove joint as shown in Fig.2. The welding grooves were prepared according to the ANSI/AWS D1.1 [12] for Structural Welding Code Steel. Figs .2; and 3 shows the single-

V- groove butt weld joint, and prequalified complete joint penetration (CJP) groove welded joint details.

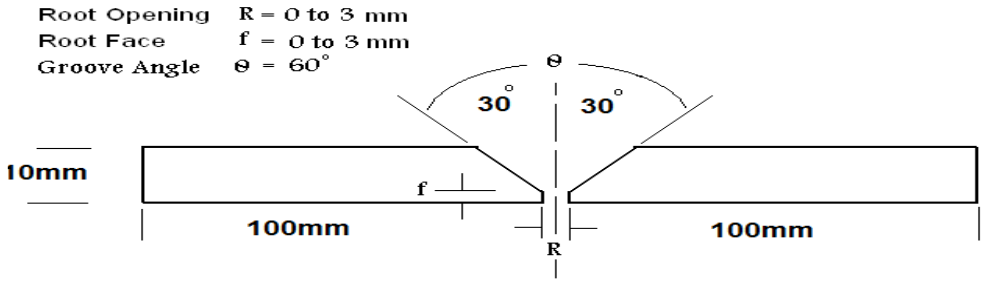


Fig .2. Welded joint details of S-V-groove butt joint (1G position) according to AWS [12]

Fig .3. Prequalified CJP of S-V-groove butt joint for the present work.

In the present work the presetting technique is used as shown in Fig .4. The advantage of presetting is that there are few or no residual stresses according to the AWS.

Fig .4. Techniques for preventing the distortion and the internal residual stresses [12]

Base Metal Specifications

According to the Egyptian Iron and Steel Code Hadidsolb [13] the base metal St52-3N specifications are shown in table 1 and 2.

Table 1: Chemical composition 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: Mechanical properties of the base metal

Steel Grade DIN 17100	Tensile Strength N/mm²	Upper Yield Point N/mm²	Elongation %
St. 52-3N	490-610	460	22%

Electrode Selection

According to the ESAB welding handbook [14] the selected electrodes were (E7018, Ø3) in SMAW, (SG2, Ø1.2) in GMAW and (S2, Ø2.4) in SAW.

Welding Stage

In the present work the GMAW, SMAW, SAW processes were conducted through the following conditions:-

1- A flat (1G) as shown in Fig .5.
2- Number of passes is three; and four
3- Prequalified complete joint penetration (CJP) groove welded.

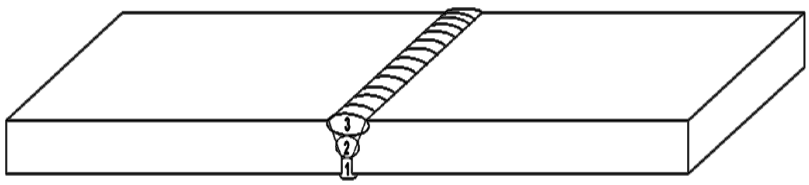


Fig .5: Flat welding position for experimental work

I- Welding Data Recorded

Table 3:The data recorded in case of three processes.

Item	$I_{ampers.}$	$V_{volt.}$	$T_{second.}$
SMAW	117	57.2	244
GMAW	180	26.7	100
SAW	373.4	29.3	59

II- Welding Data Calculated

Table 4: The data calculated in case of three processes.

Item	P_{Watt}	Smm/min	H.I
SMAW	6692.4	61.2	5.9
GMAW	4806	150	1.73
SAW	10940.62	253.8	2.327

Non-Destructive Tests

The welded specimens were Non- destructive tested using visual ultra-sonic and penetration testing were methods. Visual test was carried according to ASTM code [15], and the results showed that the welding process, the rate of electrode melts, the way the weld metal flows, sound and light of arc were improved quality. **Ultra-Sonic Test,** Particularly well-suited for detecting subsurface cracks, here a probe is scanned over the part surface in an attempt to detect a crack, and it is High frequency sound waves are introduced into a material and they are reflected back from surfaces or flaws. Reflected sound energy is displayed versus time, and inspector can visualize a cross section of the specimen showing the depth of features that reflect sound as shown in Fig.6. according to the AWS [16].

Fig .6. Ultra-sonic wave form [16]

Dye Penetrant Test, Penetration test is shown in Fig .7. which showed no surface defects. And according to ASTM code [15] the specimens is sound.

Fig .7. Penetration test

Destructive Tests

Tension test, impact test, and hardness test were done to identify the different mechanical properties. The specimens were taken according to ASTM code [15]. Tensile test is the most fundamental type of mechanical testing. A tensile test applies a load to a specimen past the yield point to failure. Tensile test results provide many mechanical properties such as Young's modulus, yield strength, tensile strength, elongation, deformation, reduction of area, and strain hardening behavior and the stress strain curve [15]. According to ASTM code [15] dimensions of tension test specimen is shown in Fig.8., study the effect of welding type on the tensile strength of the joint and on the different weld metals and the results at table 5.

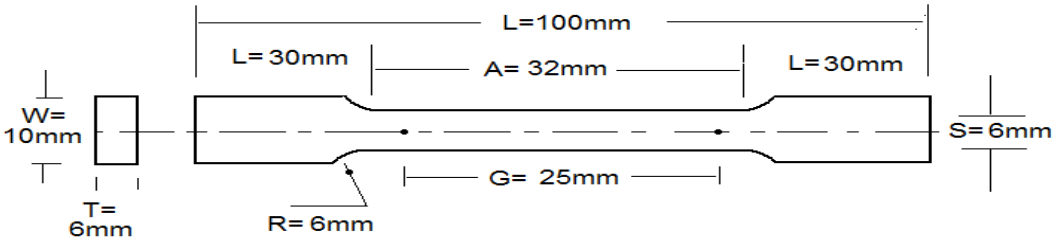


Fig .8. Dimensions of tension test specimen according to ASTM[15].

❖ **Tensile strength Test Results**

Table 5 Ultimate Tensile Strength Test Results

Specimen No.	SMAW (KN)	GMAW (KN)	SAW (KN)
1	23.7	28.55	29.7
2	27.8	29.6	26.35
3	24.4	26.3	28
Y.T.S Weld Metal	20.75	20	23.2
U.T.S Weld Metal	27.5	27.3	30.1

Impact Test, To study the effect of welding type on the joint toughness the impact tests were applied on a welded specimen. The welding specimens were manufactured according to ASTM code [24], while the dimensions are shown in the Fig.9.The results of impact tests are shown in table 6.

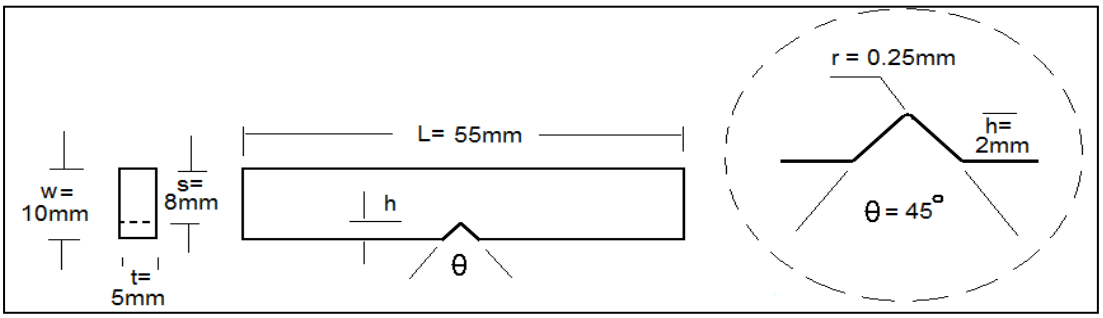


Fig .9. Dimensions of impact test specimen according to ASTM [15]

Table 6 : Impact test result

Specimen No.	SMAW	GMAW	SAW	Unit
1	102	112	102	Degree

	97	70	97	Joule
2	106	123	104	Degree
	86	42	92	Joule
3	104	109	120.5	Degree
	92	78	47	Joule

Hardness Test, A hardness tests were conducted using welded joint specimens. The specimens were manufactured according to ASTM code [15].The specimen dimensions are shown in the Fig.10, and location of hardness test specimen is shown in the Fig.11. The hardness test results are shown in table 7.

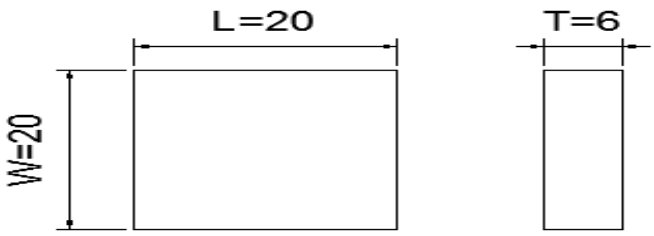


Fig .10. Dimensions of hardness test specimen according to ASTM [15]

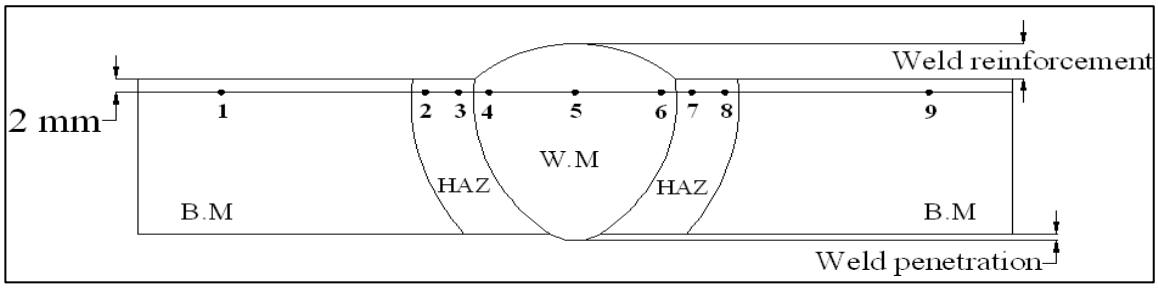


Fig .11. locations of hardness test [15]

Table 7: Hardness Test Results

No.	$SMAW_{HV10}$	$GMAW_{HV10}$	SAW_{HV10}
1	184	178	186
2	187	190	198
3	191	188	194
4	208	216	212
5	213	245	225
6	211	207	214
7	192	191	196
8	190	189	185
9	188	183	179

Microstructure Test

The microstructure tests were conducted through grinding the welded specimens to get obvious welding zones. The welding specimen was cut to get a small test specimen with obvious welding zones [Base Metal-HAZ-Weld Metal]. Grinding paper of different degrees used were 120, 240, 400, 600, and800 then a polishing paper of 1500 used with alumina to get a very shiny and scratch less surface. Finally acidic solution called tenal used to itch the specimen to get obvious grain boundaries. In case of microstructure itching was done lightly to obvious grain boundaries only. The polished specimens were microscopy examined using magnifications of 100X, 200X, and 500X. The results were shown in Figs. 15 to 23

Macrostructure Test

The same steps of microstructure specimen preparation were used and the microstructure photos were taken using a lens of 10X magnification.

Results and Discussions

Welding Power (P) (watt) of SAW Process.

$$\mathbf{P = I * V} \qquad [17]$$

Where

I: current [Ampere], V: voltage [volt]

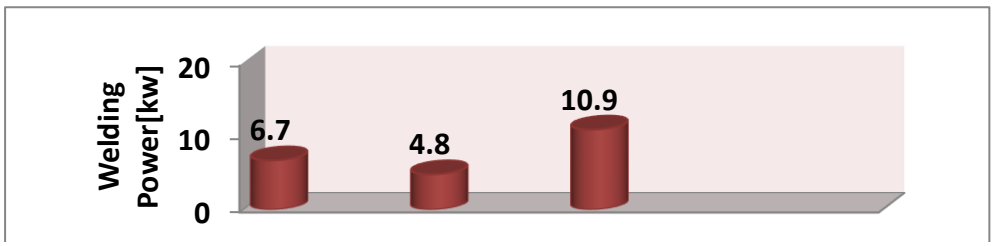


Fig .12. Power Consumed Values in [KW]

The automation of welding process needs high power to get good melting and filling processes. In GMAW process a semi-automatic mechanism consumes power lower than manual and automatic as in GMAW process. Filling process is supported by labor hand and filler metal flow rate automatic mechanism while only labor hand is used to support melting and filling process in SMAW so; it was founded that power consumed in SAW is higher than that of SMAW while GMAW is the least consumed power value.

Travel Speed

$$\mathbf{S = \frac{Weld\ distance\ [mm]}{Arcing\ Time\ [min]}}$$ Equ.3: Travel speed(S) [mm/min][18]

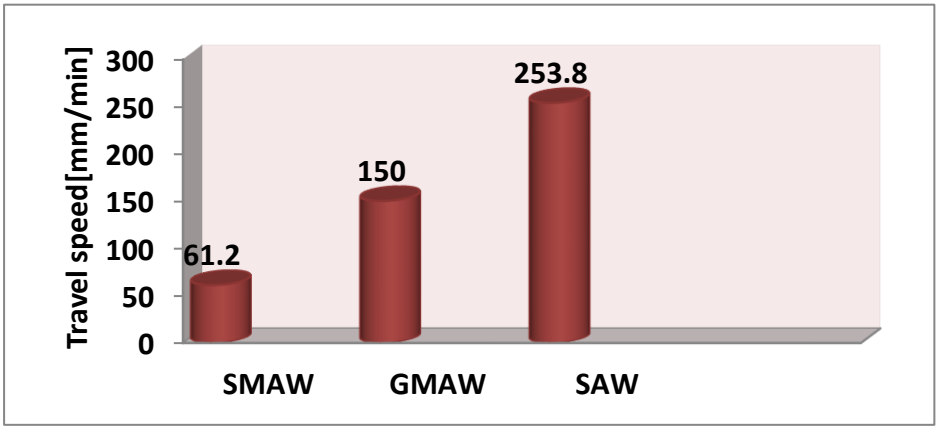


Figure .13. Travel speed in [mm/min]

Figure 13 shows that the mechanism used mainly effects on the travel speed. Values that effect on productivity and obviously effect on power required to support filling process, also effect on heat input; so it effect on microstructure and mechanical properties. So travel speed is a very affective welding parameter that gives interpretation of automation requirement question.

Heat Input [HI]

Equation 1 shows the effective parameters to estimate HI, which are power consumed [I*V] and travel speed of welding process and Welding Process Efficiency (η = 90%) . Figure 13 shows that the travel speed most effective parameter on HI than power. As obvious in SAW process the higher travel speed with higher welding power consumed leads to low HI value but in SMAW a moderate welding power consumed and low travel speed, and so that; as a result the heat input is very high. In GMAW process, a moderate power consumed and moderate travel speed that gave the lowest HI as shown in Fig.14.

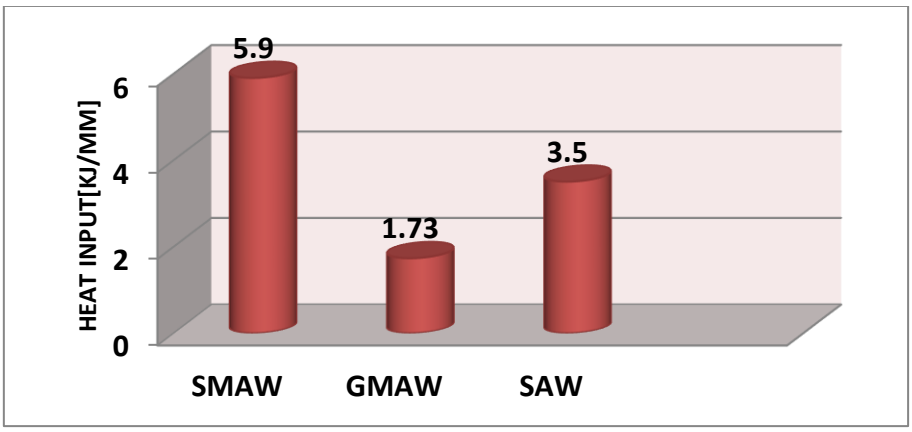


Fig .13. Heat Input in [KJ/mm]

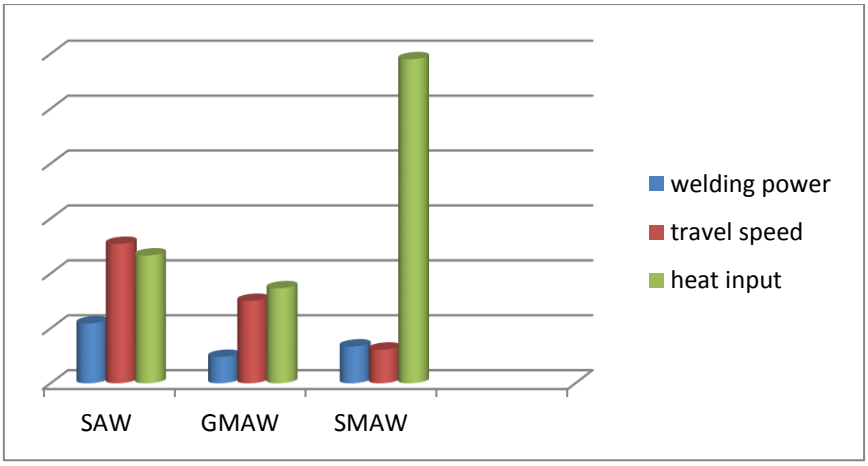


Fig .14. The Effect of Welding Power and Travel Speed on Heat Input

Microstructure

Base Metal Microstructure

Figures 15 to 17 show the microstructure of the base metal. The microstructure is mainly consisted of ferrite and pearlite.

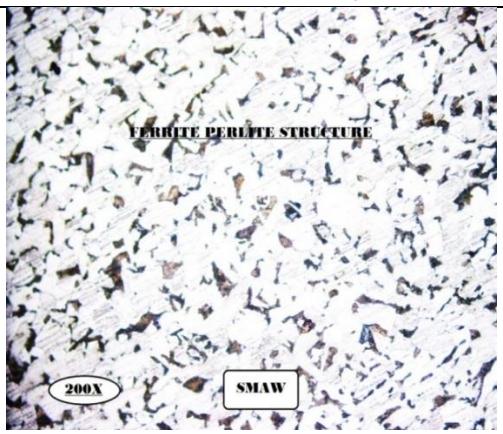


Fig.15. Base Metal Microstructure In Case Of Shielded Metal Arc Welding

Fig.16 Base Metal Microstructure In Case Of Gas Metal Arc Welding

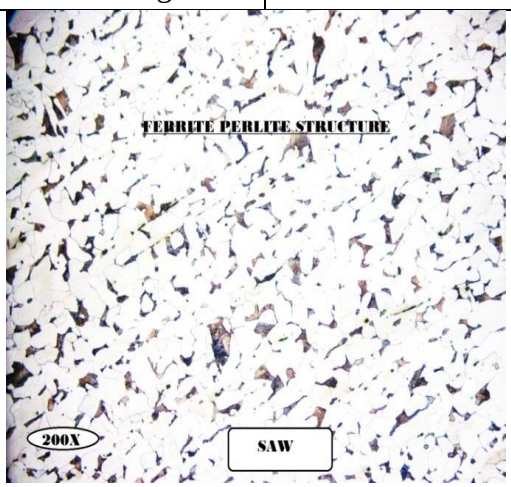


Fig.17. Base Metal Microstructure In Case Of Submerged Arc Welding

Heat affected zone Microstructure

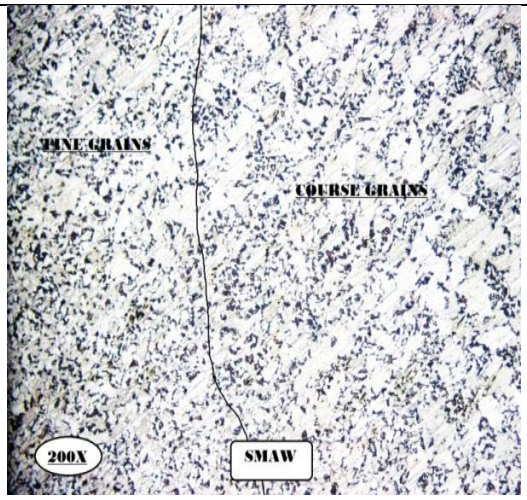


Fig.18. Heat Affected Zone Microstructure In Case Of Shielded Metal Arc Welding

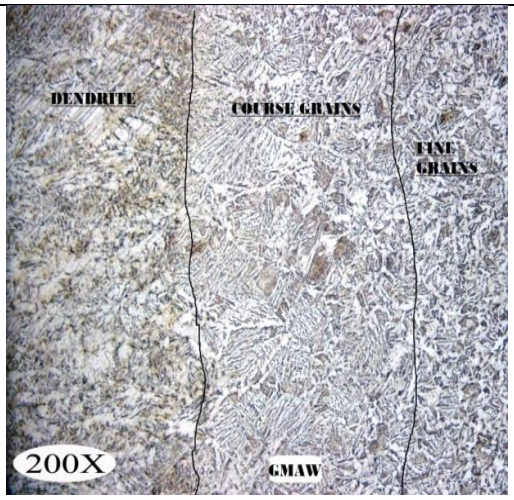


Fig.19. Heat Affected Zone Microstructure In Case Of Gas Metal Arc Welding

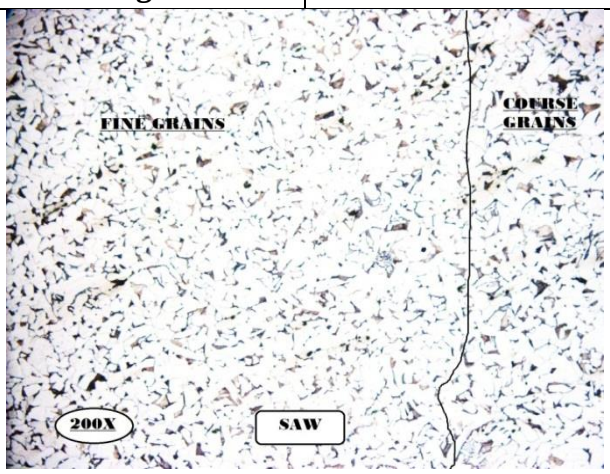


Fig.20. Heat Affected Zone Microstructure In Case Of Submerged Arc Welding

Figure 18 shows two different regions of ferrite pearlite microstructure. The right one has a large area and coarser grains than left one. That is due to high heat input which leds to high cooling rate which finally affected on the resulted grains to be coarse grains. As the microstructure is far from the weld zone it became finer due to low HI and fast cooling rate.

In case of lowest heat input in GMAW process; Fig.19 shows ferrite pearlite microstructure with fine grains "compared with those in SMAW or SAW" at right and middle regions where low heat input in this case prevented the occurrence of grain growth.

In case of SAW heat input wasn't the highest one, so it caused grain growth but not large like in case of SMAW and not very small like in case of GMAW. Ferrite pearlite microstructures shown in Fig.20 have

coarse grains region at right side and big fine grains region at left side due to the moderate applied HI.

Weld metal Microstructure

Figures 21 to 23 show the microstructure of deposited weld metal which was typically dendritic structure.

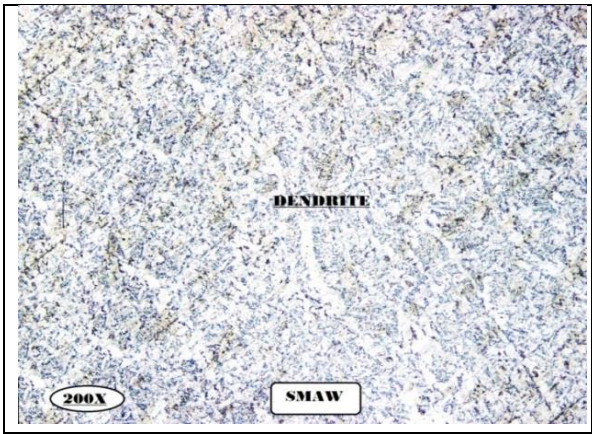


Fig.21.Weld Metal Microstructure In Case Of Shielded Metal Arc Welding

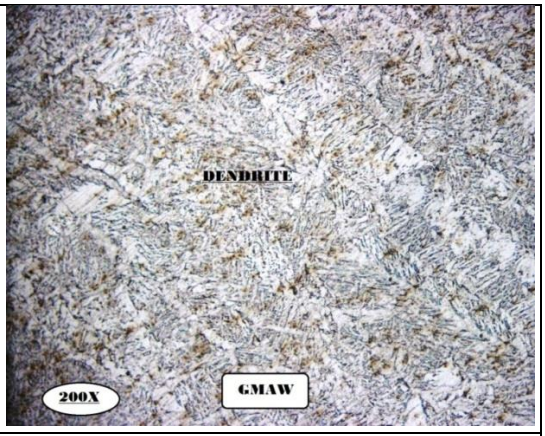


Fig.22. Weld Metal Microstructure In Case Of Gas Metal Arc Welding

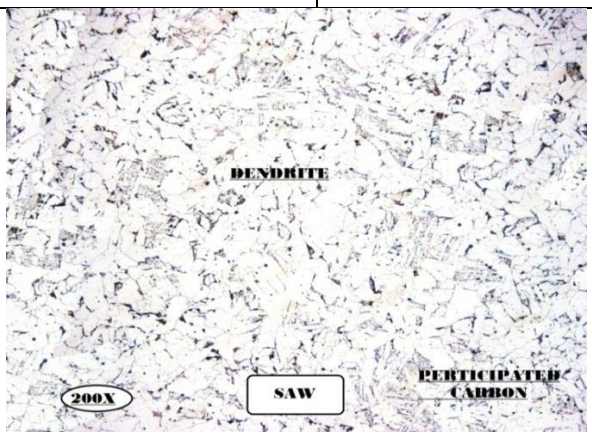
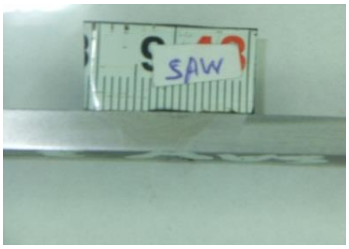


Fig.23. Weld Metal Microstructure In Case Of Submerged Arc Welding

There was a difference between the three microstructures due to the difference in cooling rates which came from contrast in used heat input for each welding process as mentioned previously.

Macrostructure

The macrograph produced indicated good penetration and side wall fusion for all welds.as shown in Figs 24 to 26.

		
Fig. 24. Shielded Metal Arc Welding Joint Macrostructure	**Fig. 25. Gas Metal Arc Welding Joint Macrostructure**	**Fig. 26. Submerged Arc Welding Joint Macrostructure**

Mechanical properties

Ultimate Tensile Strength Results for the ultimate tensile test shown in Fig. 27 & 28.

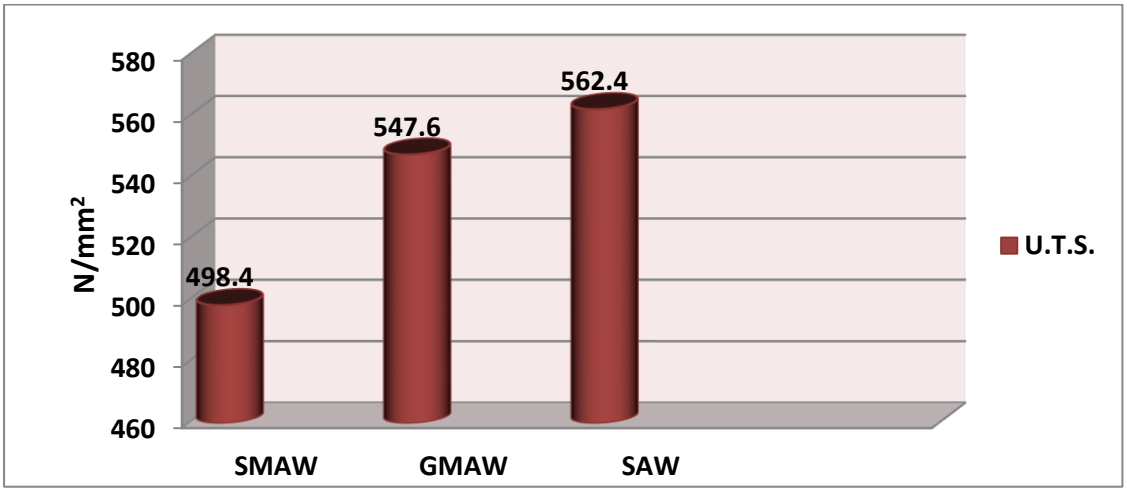


Fig .27. Ultimate Tensile Strength of the Joints in MPa

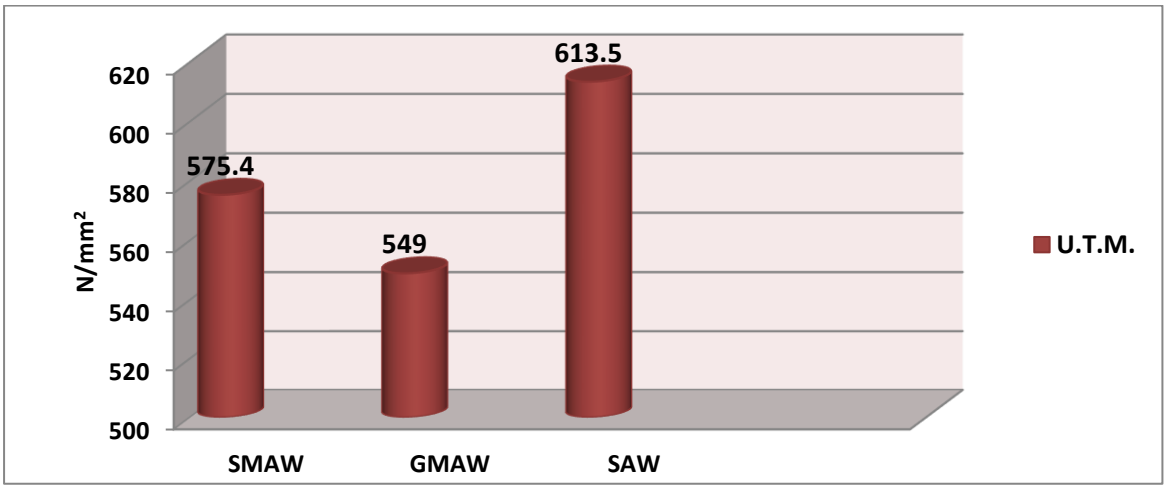


Fig .28. Ultimate tensile strength of the weld metal in MPa

It is appeared that the ultimate tensile strength of welded joints of all welds using all the various welding parameter exceeded the corresponding specified minimum value for St.52-N3 base metal [490 MPa], as mentioned in Iron & Steel Handbook [13].

Elongation Percentage

Table 8 Elongation Percentage after Tension Test

Specimen type	Elongation
SMAW	34%
GMAW	23%
SAW	28%

Because of microstructure and same causes of ultimate strength. Table 8 shows that SMAW has the highest elongation, then SAW & finally GMAW showed the lowest elongation.

Hardness Results

Table 9 Hardness of Joints in Vickers Hardness

Hardness (HV10)			
ITEM	SMAW	GMAW	SAW
Base metal	186	180.5	182.5
HAZ	190	189	193.5
Weld metal	211	223	217

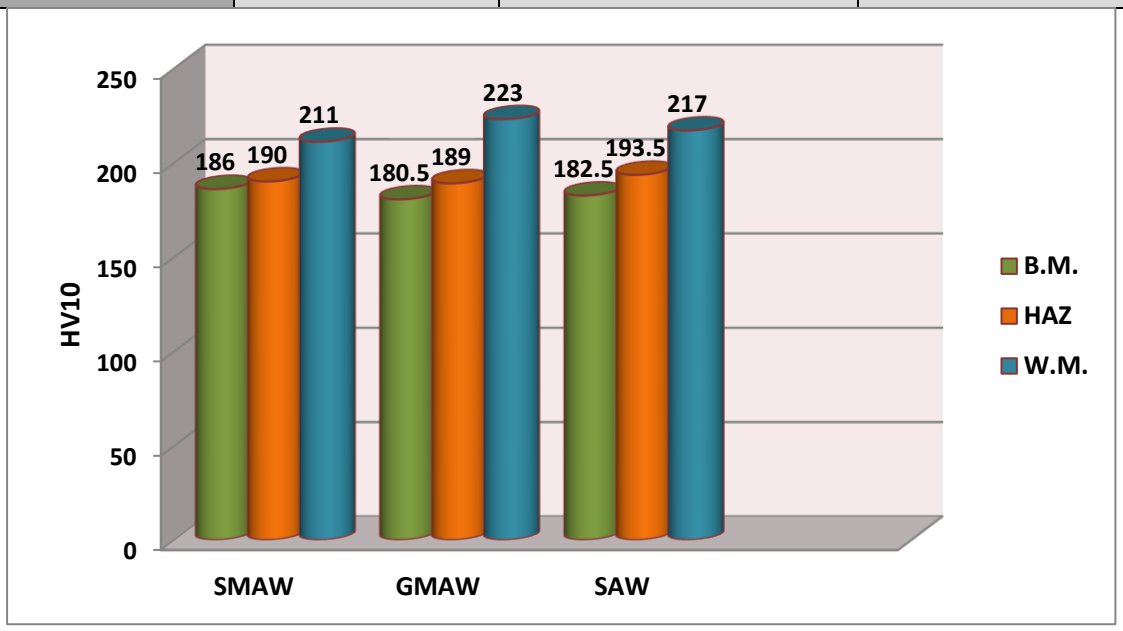


Fig .29. Hardness of joints in Vickers hardness

As shown in table 9 and Fig. 29, generally, the hardness of deposited weld metal in case of GMAW showed the highest values, while the hardness in case of SMAW showed the lowest values. This might be due to the reheating of the lower pass from the upper heated pass.

Impact Results

Toughness Values in Joules Due To Impact Test

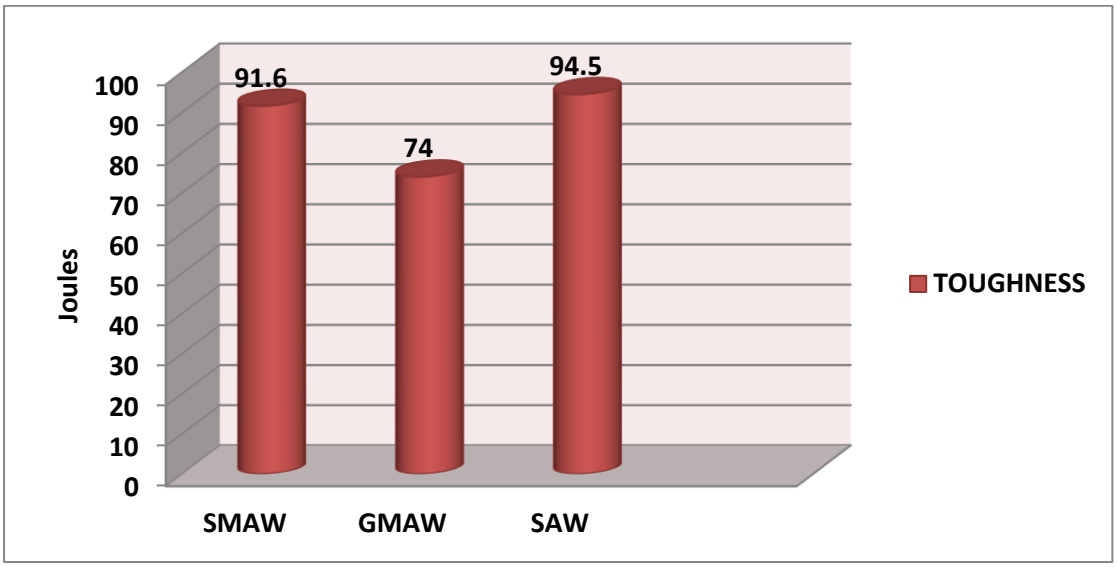


Figure .30. Toughness values in joules due to impact test

The charpy impact toughness test results (absorbed energy values) are being listed in table 4.18 and shown in Fig. 30. There is a strong relationship between the microstructure & absorbed energy. The value of toughness in case of GMAW is the lowest one may be due to the percent of CO_2 in the shielding gas. Whereas the CO_2 % increases, the impact toughness of weld metal decreases.

Direct welding Time

Total welding direct time is the summation of preparation time and welding time (welding time is the summation of arc time and time between passes). All these times depend up on welder skill, welding position and joint length so; these values are for the comparison and can't be taken as absolute values.

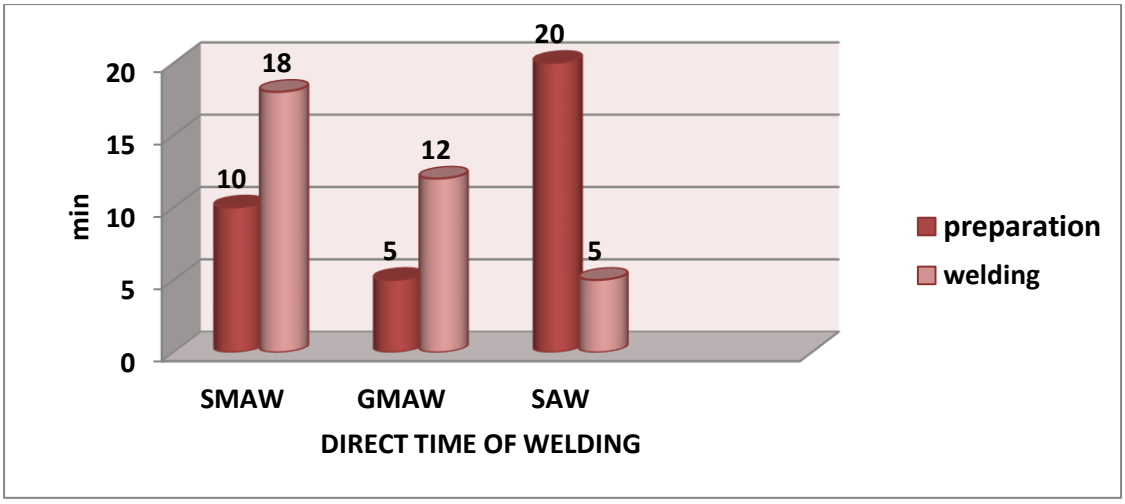


Fig .31. Total direct welding time of a 25 cm joint

Preparation time in GMAW is the least as it doesn't need long time as in case of SAW machine set up due to automation and filler metal feed rate limits the preparation of electrode in SMAW. Welding time is the least one in case of SAW because of fast regular welding arm then GMAW because of continuous filler metal feeder which prevents wasting time of replace electrode in SMAW.

CONCLUSIONS

In the present work, it is concluded that the travel speed is main effective parameter on heat input. Heat input is the keyword of microstructure and then mechanical properties. Impact energy is more affected obviously by elongation of joint than strength. For quality-based scope of work GMAW is preferred. For high productivity projects or thick joint SAW method is preferred. For impact-based joints SMAW is preferred.

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