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Effect of GTAW on the Mechanical Properties of Mild Steel

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Abstract: Tungsten metal arc welding (GTAW) is a highly popular welding technique in manufacturing. The welding factors such as welding current, voltage, speed, and gas flow rate play a significant role in determining the welding quality. This study discusses the effect of GTAW factors on the mechanical properties of commercial steel welding. Base metal thickness, welding speed, and current are the factors to be optimised for maximum tensile strength and hardness by Taguchi design (TD). The analysis showed that higher tensile strength welding has higher hardness. The increased tensile strength is obtained at increased base metal thickness, higher welding speed and lower welding current. In addition, higher tensile strength has been shown to obtain higher hardness—the higher hardness demonstrated at welding exposed to increased heat input that caused higher internal stresses. The higher base metal thickness obtained higher tensile strength due to the increased welding sample cross-section area and due to the phenomenon of the heat sink that minimised the effect of heat input and, thus, internal stresses. The welding made at 10 mm base metal thickness affected the results the most and obtained higher means, followed by samples fabricated at 150 A, while welding speed variation did not have much difference on the results. To obtain higher tensile strength, it is recommended to go for more increased base metal thickness, lower welding current, and faster welding speed when welding mild steel by GTAW.

Keywords: GTAW, mild steel, Taguchi design, tensile strength, hardness

1. Introduction

GTAW is a welding technology that is considered an important process, as it has multiple goals and factors in the industrial sector [1]. Quality GTAW depends on finding out the optimum practical welding condition. Such optimisation should satisfy the desired welding objectives [2]. The welding quality depends on the welding process factors, leading to a specific chemical, mineral, and mechanical properties [3,4].

GTAW has the advantage of welding dissimilar welding because it produces a minimum heat-affected zone (HAZ) without slag and bead geometry that is narrower than other known fusion welding technologies [5]. GTAW, similar to gas metal arc welding (GTAM), uses shield gas to protect the weld pool from air contamination, and it's distinct in using non-consumable tungsten as an electrode [6,7].

GTAW quality depends on the welding parameters, which later affect the welding microstructure and its mechanical properties [1,8]. The process factors interact complexly, leading to direct or indirect effects on the mechanical properties of the welding [1]. TD is a technique that uses an orthogonal array as a design method. This design proposed studying more parameters with fewer experiments than the Design of Experiments [9]. TD is simple, and it is getting popular in manufacturing industries [10]. Ramadan and Boghdadi [2] studied the effect of welding gas

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flow rate and welding current on the tensile strength of low-carbon steel dissimilar joints using TD. Another study by Anand, Mittal and Scholar [6] showed the effect of welding gas flow rate, welding voltage and welding current on the tensile strength and hardness of mild steel dissimilar joints using TD and found that welding current had a higher effect on the tensile strength and hardness of the welding. This study will investigate and optimise the effect of GTAW welding current, base metal thickness, and welding speed to find the factors leading to the optimum tensile strength and hardness using the TD for mild steel. Other parameters, such as environmental pressure, temperature, and welding voltage, could be included. However, only three factors were in hand to study because other studies have clearly defined the relationship between tensile strength and hardness. TD is a tool to optimise the welding parameters to find stronger and more effective welding.

2. Methodology

2.1 Materials and Experimentation

Mild steel was purchased from the local market and was prepared in the Tasamim workshop at Benghazi using a CNC laser cutter. The samples were prepared according to the American society of testing materials (ASTM) E8 / E8M for the tensile test [11]. fig. 1 shows an illustration of the sample with dimensions for the tensile test with a V groove of 60°. Also, other samples were prepared for hardness testing in the same workshop. The samples have been welded in Altaibat Food Inc in Benghazi. Welding was achieved by Daewoo Inverter Welder TIG/MMA, as shown in fig. 2 (a), with the aid of the welding speed machine YSG-12 Beetle Portable Gas Cutter (Fig. 2 (b)). The tungsten electrode tip was kept 3 mm from the base metal (Fig. 3 (a)). The welding process is shown in fig. 3 (b). The shielding gas comprises 90% argon and 10% carbon dioxide with a flow of 10 millilitres per minute. table 1 lists the composition of the base metal and filler wire. The base metal is non-alloyed structural steel under the European standard of EN 10025-2, grade S235JR (1.0038) and the welding filler used is E6013 (2.5 mm in diameter) mild steel. table 2 shows the properties of tensile strength and hardness of the material and filler wire. The base metal thickness, welding current and welding speed are the factors used for the welding process. Each has two levels, as listed in table 3. The voltage is estimated to be between 20 V and 30 V.

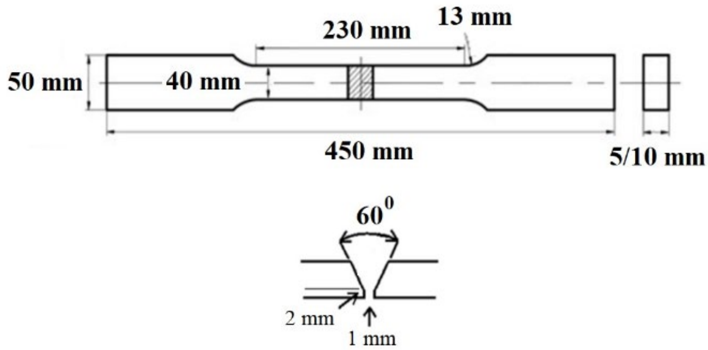

Fig. 1 - Samples dimensions for the tensile test made according to ASTM E8/E8M [11]

Fig. 2 - (a) Welding machine Daewoo Inverter Welder TIG/MMA; (b) Welding speed machine YSG-12

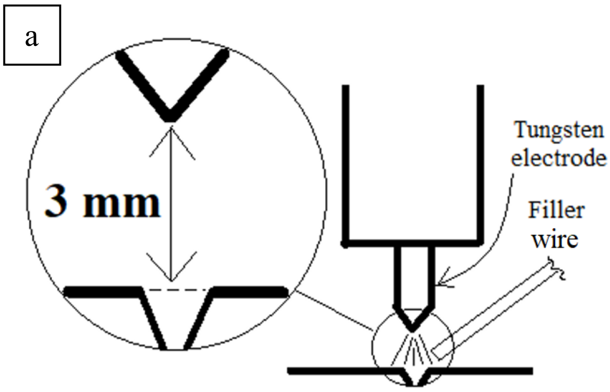

Fig. 3 - (a) Tungsten tip position with respect to the base metal; (b) welding process

Table 1 - The gradients of the material and welding wire used in the experiment [12]

Component	Composition									
	C	Mn	S	Ni	Cr	P	Si	Cu	Mo	V
Base metal (EN 10025-2)	0.17%	1.4%	0.025%	0.012%	-	0.025%	-	0.55%	-	-
Welding filler (E6013)	0.10%	0.6%	0.03%	0.3%	0.2%	0.035%	0.5%	0.35%	0.2%	0.05%

Table 2 - The tensile strength and hardness of base metal and filler wire [12], [13]

Component	Tensile properties			Hardness properties
	Yield strength	Tensile strength	Elongation	Rockwell hardness B
Base metal (EN 10025-2)	235	360-510	26%	66.7 HRB
Filler wire (E6013)	482 MPa (70 ksi)	558 MPa (81 ksi)	27%	83 HRB

Table 3 - Factors used for the welding process

Code	Factors	Unit	Level 1	Level 2
A	Base metal thickness	cm	5	10
B	Welding current	A	150	200
C	Welding speed	mm/min	100	150

2.2 Taguchi Design

The experiment layout follows the 2-level's four factors resulting in 8 runs. This method is known as Taguchi's L8 array. table 4 below contains the experimental orthogonal design layout. table 5 shows the welding factors combination according to Taguchi's and their mechanical properties of the welding. The analysis target was to maximise the results because the goal of this experiment was to obtain which parameters obtain higher mechanical properties. Therefore, 'Larger is better' were chosen for design analysis. The analysis was made with the help of Minitab 18®. The base metal thickness factor is included to see hardness at each thickness with respect to the resulted tensile. Each thickness has a different solidification rate after welding, and it is crucial to analyse its mechanical properties concerning the welding current and welding speed.

Tensile test carried out on Shimadzu (UEH-20) hydraulic Universal Testing Machine at Libyan Iron and Steel Company at Misrata that has maximum force capacity of 2000 kN. The tested samples are shown in fig. 4 (a) following ASTM E8 / E8M [11] tensile test standard, as mentioned earlier. Samples 5 and 8, as shown in fig. 4 (a) are not tested yet at the time the picture was taken. Some of these samples were repeated due to the failure of the first ones. The hardness test was conducted in the College of Mechanical and Engineering Technology at Benghazi using the Ernst Rockwell hardness tester (Fig. 4 (b)). The indenter is a diamond cone (120^0 in angle) with a load of 100 kg as pressure force. The hardness of the fusion zone area was measured to demonstrate the change with respect to welding factors. fig. 5 (a) show the elongation calculation after the tensile test. The elongation for each sample is shown in table 5. fig. 5

(b) show the hardness testing positions, which demonstrate that hardness values in table 5 were an average of three readings for each sample.

Table 4 - Orthogonal array L8 layout

Standard order	A	B	C
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

Table 5 - TD layout with responses

Std order	Base metal thickness (mm)	Welding current (A)	Welding speed (mm/min)	Tensile strength (TS) (N/mm^2)	Heat input (J/mm)	Hardness (HRB)	EL%	TS/HRB
1	5	150	100	183	2700.0	23.5	4	7.79
2	5	150	150	190	1800.0	23.2	3	8.19
3	5	200	100	159	3600.0	22.1	2	7.19
4	5	200	150	171	2400.0	22.8	2	7.50
5	10	150	100	304	2700.0	26.3	6	11.56
6	10	150	150	270	1800.0	24.9	5	10.84
7	10	200	100	237	3600.0	24	4	9.88
8	10	200	150	251	2400.0	25	5	10.04

Fig 4 - (a) Samples used for tensile strength; (b) Ernst Rockwell hardness tester

3. Results and Discussion

The results showed that hardness increased whenever the tensile decreased and vice versa. An exception was made for sample number 2, which has oddly decreased hardness compared to other samples. In addition, the increased tensile strength and hardness showed with the increased thickness of base metal and welding speed (except for samples 5 and 6), while the welding current decreased. It is reasonable for higher base metal thickness to obtain higher tensile strength due to the increased cross-section of tensile samples, which provides more resistance to fracture. However, the tensile strength to hardness ratio (TS/HRB) in table 5 showed lower ratios at higher heat input. It indicates that hardness is proportionally higher concerning the resulted tensile strength, which is noticeable to be lower at welding with

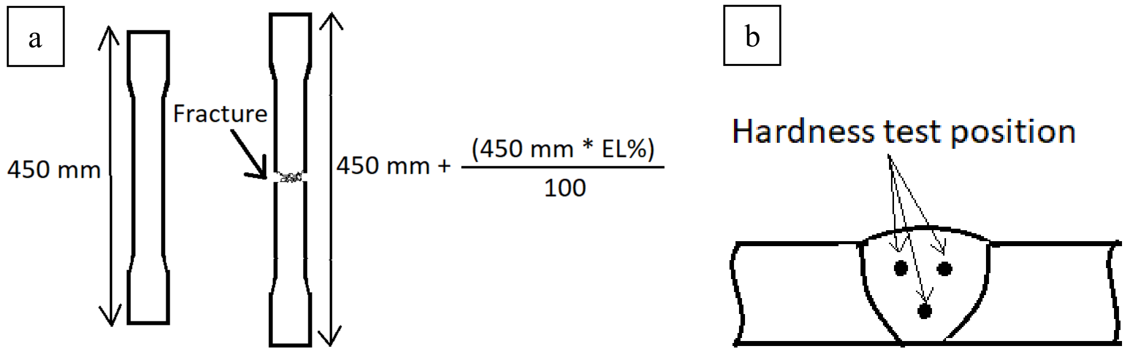

Fig 5 - (a) Elongation formula for tensile strength samples; (b) hardness-tested positions in welding

increased heat input. Such an increase in heat input is due to increased welding current and slower welding. The denser electron flow and prolonged local heat in the welding lead to higher dilution of the fusion zone, which means a wider weld bead [14]. Higher heat input caused higher internal stresses [14,15]. Higher internal stresses can cause lower mechanical properties [16-19]. The increased heat input caused higher internal stresses in the welding, which results in increased hardness and deterioration in the mechanical properties, for example, the tensile strength [20]. Higher base metal thickness is advantageous because of the heat sink phenomenon, which provides a faster cooling rate. The heat disperses to the adjacent metal due to the higher amount of surrounding metal compared to lower base metal thickness [10]. A faster cooling rate means minimising the effect of the heat input and, consequently, internal stresses, which provides higher tensile strength. Yadav et al. [17] showed that the base metal thickness increase has contributed to increased mechanical properties such as tensile and hardness properties of the welding.

The following plots (fig. 6) and (fig. 7) are the main effects plots for signal-to-noise (S/N) ratios and means of the welding factors, respectively. The two plots show an almost similar orientation of results. The S/N ratios in fig. 6 illustrate the effect of the welding factors by showing their S/N ratios in relation to the S/N mean. The S/N ratio measures how the response (tensile strength and hardness values) varies relative to higher values under different noise conditions. The higher S/N ratio is labelled in fig. 6 and table 6 as "Larger is Better", which corresponds to the experiment goal chosen, that is, to maximise the response. The means plot in fig. 7 shows response means in relation to the average of means. table 6 and table 7 show the mean of each response for each level of each welding factor. The Delta statistic is the highest minus the lowest average for each factor. The assigning ranking is based on the values of delta, which indicate the effectiveness of welding factors. Ranking indicates the strength of each factor, as also indicated by the absolute values of the coefficient for S/N ratios in table 8. However, the coefficient values in table 8 are only for Level 1 factors, as listed in table 2.

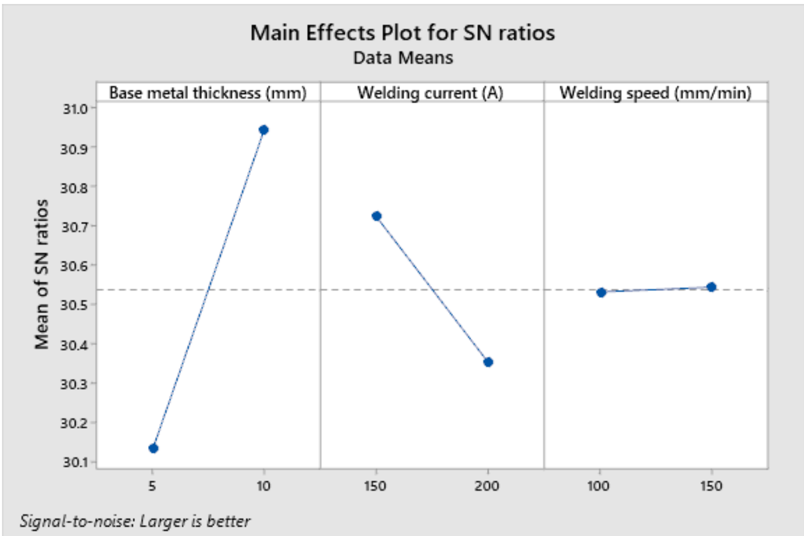

Fig 6 - S/N ratio plot for the welding factors

Fig 7 - Means plot for the welding factors

Table 6 - Response ranking for S/N ratios

Level	Base metal thickness (mm)	Welding current (A)	Welding speed (mm/min)
1	30.13	30.72	30.53
2	30.94	30.35	30.54
Delta	0.81	0.37	0.01
Rank	1	2	3

*Larger is better

Table 7 - Ranking of response for means

Level	Base metal thickness (mm)	Welding current (A)	Welding speed (mm/min)
1	99.32	130.61	122.36
2	145.28	113.99	122.24
Delta	45.95	16.63	0.13
Rank	1	2	3

Fig. 6 shows that welding with a 10 mm base metal thickness has a higher noise ratio than at 5 mm. Therefore, it has a higher effect on the higher response. table 6 also illustrates where the values at Level 1 (30.13) corresponding to welding with 5 mm base metal thickness is lower than Level 2 value (30.94) at 10 mm. The noise ratio values are also illustrated in table 6 for the welding current and speed. It showed that welding samples experimented at a welding current of 150 A have more influence over 200 A. In contrast, the welding run at a welding speed of 150 mm/min (30.53) has a slightly higher influence than 100 mm/min (30.54) on the higher response. The results also showed from fig. 5, and table 6 show that a base metal thickness of 10 mm has the highest noise ratio (30.94) than the other factors levels. It means it has the most influence on the response, followed by the welding current at 150 A, while the welding speed shows a lower influence at 150 mm/min.

Fig. 7 and table 7 show that base metal thickness at 10 mm also has the highest means of the response (145.28), which indicates the average of all the tensile strength and hardness values of the welding fabricated at 10 mm base metal thickness. It demonstrates that the highest response values were obtained at the welding with the base metal thickness of 10 mm, followed by welding experimented under a current of 150 A (130.61). In comparison, the welding run under a welding speed of 100 mm/min shows lower response means (122.36). However, both the welding speeds, 100 mm/min and 150 mm/min, show very close response means of 122.36 and 122.24, respectively, as seen in fig. 6 and table 7.

Table 8 shows the S/N ratios coefficients model for the S/N ratio with welding factors, while table 9 shows the coefficients model for means. The coefficient value shows the position for level 1 of each factor according to the constant position. The constant position is the mean of S/N ratios in table 8, illustrated in fig. 6 and the mean of means in table 9, and shown in fig. 7. The coefficient values correspond to table 8, showing the smallest population value (P-value) for the base metal thickness of 5 mm at 0.008. Such value is considered statistically significant because it is lower than 0.05, which corresponds to the significance value. Which therefore rejects the null hypothesis. In other words, the effect of welding fabricated at a base metal thickness of 5 mm has a 99.2% chance of repeating or maintaining a similar effect or influence on the results because it is higher than the significance level of 95%. The welding made using 150 A current and 100 mm/min welding speed showed to be non-significant, with 91% and 5.5%, respectively. It means minimising their influence on tensile strength and hardness, especially for welding speed results. Such a low percentage of occurrence has also been shown for the response means of welding at welding speed, as seen in table 9. The coefficient table for means (table 9) shows that the tensile strength and hardness means at a welding speed of 100 mm/min have a percentage of 1.6%, which is very much lower than the significant level. While the means of welding at 5 mm base metal, thickness has the highest level of occurrence with 99.9%. The means at welding current 150 A has shown a 95.4% level of results repetition, which is the edge of significant value. Unfortunately, Minitab 18® did not show P values for level 2 factors.

Table 8 - Coefficients for S/N ratios

Term	Coefficient	P-value
Constant	30.5369	0.000
Base metal thickness (5 mm)	-0.4059	0.008
Welding current (150 A)	0.1859	0.090
Welding speed (100 mm/min)	-0.0061	0.945

Table 9 - Coefficients for means

Term	Coefficient	P-value
Constant	122.300	0.000
Base metal thickness (5 mm)	-22.975	0.001
Welding current (150 A)	8.312	0.046
Welding speed (100 mm/min)	0.063	0.984

These results concluded that higher tensile strength and hardness of the welding are influenced the most by the base metal thickness of 10 mm followed by welding current factor of 150 A, while the welding speed showed a close effect by two of its levels, 100 and 150 mm/min. In addition, the welding at 10 mm base metal thickness has obtained higher tensile strength and hardness, thus, higher mechanical properties. This is followed by welding made at a welding current of 150 A, while the welding speed has shown almost similar means for both of its levels. Therefore, according to these facts, the optimum welding factors are 10 mm base metal thickness, 150 A and 150 mm/min as welding speed because it obtained a higher effect on the maximum results, although it showed a slightly lower mean. According to this study, it is advised to take these settings when welding commercial steel (EN 10025-2) with mild steel welding filler using GTAW for strong, sound, and effective welding. However, a higher or lower range of settings might result in better and more effective welding.

4. Conclusion

GTAW is made to weld mild steel using variables of the thickness of base metal, welding current and welding speed as welding factors. TD was made to analyse the effect of welding factors on the tensile strength and hardness of the welding. The results showed that higher tensile strength was obtained at increased base metal thickness, lower welding current and higher welding speed. In addition, higher tensile strength has showed to obtain higher hardness. However, the increased internal stresses caused by higher heat input have shown higher proportional hardness in relation to the resulted tensile strength. This ratio was higher with decreased welding current and slower welding speed and resulted in higher tensile strength. Higher base metal thickness obtained higher tensile strength due to the increased welding sample cross section area and due to the phenomenon of the heat sink that minimised the effect of heat input and, thus internal stresses. The welding made at 10 mm base metal thickness affected the tensile strength and hardness the most and also obtained higher means followed by samples fabricated at 150 A while welding speed variation did not have much difference on the results. It is recommended to go for higher base metal thickness, lower welding current and faster welding speed to obtain higher tensile strength of mild steel welding made by GTAW.

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