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Effect of GMAW on the Tensile Strength and Hardness of Commercial Steel

Saleh Suliman Elfallah

College of Mechanical Engineering Technology, Benghazi, Libya

Author's Mail Id: sselfallah87@gmail.com, Tel.: +00-218917251288

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***Abstract*—** Gas metal arc welding (GMAW) is very popular welding processes in the industry. The welding parameters that has significance in demonstrating the welding quality such as welding current, welding voltage, Gas flow rate, wire feed speed, welding speed and wire size. Taguchi's design is considered an efficient and a powerful optimizing tool for better quality and higher output performance of manufacturing processes. In this study, GMAW has welded commercial steel under controlled parameters of base metal thickness, welding current and wire feed speed. The analysis using Taguchi's design made on the influence of welding parameters on the strength of the welding, the tensile strength and hardness. Higher tensile strength and hardness were obtained at higher base metal thickness, lower voltage and wire feed speed (WFS). The hardness increased with the increased internal stresses. Higher base metal thickness obtained higher effect on the higher tensile strength and hardness according to the noise conditions analysis and also higher tensile strength and hardness results followed by lower wire feed speed. The optimal process parameters favorable for strong and effective welding are base metal groove shape V, 20 V and 5.9 m/min WFS. These settings are recommended when welding commercial steel (EN 10025-2) using mild steel filler in GMAW.

***Keywords*—**GMAW, Commercial steel, Taguchi method, Tensile strength, Vickers microhardness

I. Introduction

Welding is a manufacturing process to join metals that is well known in industry. GMAW is a widely used welding technique for joining ferrous and non-ferrous metals. It uses shielding gas such as argon or helium, and active gas such as carbon dioxide and oxygen. GMAW is used on steels such as carbon steel, stainless steel and alloy steel, and on aluminum and its alloys. GMAW has four types of metal transfer across arc, they are short circuit, globular, spray and pulsed transfer. The final welding characteristics depend on the arc voltage, welding current, size and gradient of electrode, electrode travel speed, and composition and flow rate of shielding gas. GMAW can apply different type of joints including, T-joint, edge joint, corner joint, butt joint, lap joint and [1,2,3].

Traditionally, it has been necessary to study the weld input parameters for welded products to obtain a welded joint with the required quality [4]. Commercial steel or Mild steel has very good weldability and considered very suitable steel for carburized parts. It offers a good balance of toughness, strength and ductility. Provided with higher mechanical properties. The commercial steel that is used widely in Libyan market is mild steel grade S235jr. A European standard of alloy structural steel and is equivalent with the American standard of ASTM A283C. Its carbon composition below 2%. The S235JR mild steel have very good welding performance. For S235JR it is supplied in steel plate besides steel round bar, steel hexagonal bar, flat bar, square bar and pipe [5].

Taguchi's design is a method proposed by Dr Genichi that suggests "orthogonal array" a powerful and efficient method and optimization technique for the quality and performance output of manufacturing processes and one of the most convenient tools to optimize various parameters with fewer experimental runs in the Parameterial Design of Experiments with more design parameters [6]. Taguchi suggested value of loss function to measure the characteristic's performance. It has further transformed into signal-to-noise (S/N) ratio. The S/N ratio is a logarithmic function and its also defined as an inverse of variance. The optimization of the process or the design lies in minimization of the variability used. Because in maximizing the S/N ratio, the variability of the process is reduced against the undesirable changes in noise parameters. Therefore, the chosen parameters should demonstrate maximum S/N ratios in order to get minimum variability. Its determination falls under one of three categories. Nominal the best, larger the best and smaller the best as listed in Table 1 [7,8]. Ross [9] proposed the following step to implement Taguchi's design. First selection of the targeted parameters. Second identify the input parameters and their levels. Third determine the orthogonal array. Fourth assign the parameters and the interactions to their respective columns. Fifth run the experiment and last obtain the statistical analysis, S/N ration and the optimum settings. The orthogonal array section according to the number of parameters and levels chosen based on Table 2. The orthogonal array for the parameters assignment for the experiment is shown in Table 3 [7,8].

Table 1. Types of problems and respective signal-to-ratio function

Choose…	S/N ratio formulas	Use when the goal is to…
Smaller the better	$\frac{S}{N} = -10\log[\frac{1}{n}\sum_{i=1}^{n} y_i^2]$	Minimize the response
Nominal the better	$\frac{S}{N} = 10\log\frac{\mu^2}{\sigma^2}$	Target the response
Larger the better	$\frac{S}{N} = -10\log[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}]$	Maximize the response

Table 2. Orthogonal array selection

Number of parameters	Number of levels			
	2	3	4	5
2	L4	L9	L16	L25
3	L4	L9	L16	L25
4	L8	L9	L16	L25
5	L8	L18	L16	L25
6	L8	L18	L32	L25

Table 3. Orthogonal array parameters assignments to experimental array columns

A	B	C	D	E	F	G
1	1	1	1	1	1	1
2	1	1	2	1	2	2
1	2	1	2	2	1	2
2	2	1	1	2	2	1
1	1	2	1	2	2	2
2	1	2	2	2	1	1
1	2	2	2	1	2	1
2	2	2	1	1	1	2

Taguchi ‘s design is considered simple with increasingly used in manufacturing industries [10,11]. Several researchers used the Taguchi method to determine the optimal GMAW process parameters for higher tensile strength. For instance, Raghu et al. [12] have optimized welding parameters using the Taguchi method to obtain higher tensile strength for mild steel. By using variable wire feed speed and welding current it was found that welding current had the higher effect on the tensile strength. Patil et al. [13] have similar study on a AISI 1030 mild steel using parameters of welding speed, current and voltage and concluded that welding current and speed had major influence over the tensile strength. Mahesh et al. [4] had also used different combination of welding speed, current and voltage and resulted in similar influence of welding current and speed over the tensile strength of AISI 1050 mild steel. A study by Elfallah [14] found that base metal thickness had superior influence over the WFS and welding voltage on the mild steel’s tensile strength and hardness.

The hardness of the welding area has been investigated for fusion zone (FZ) [15,16,17,18,19,20], and base metal [17,19,21]. Researchers reported that the tensile strength and hardness decreased with the increased welding current, voltage or filler material, because they raise the heat input into the welding that causes more internal stresses in the FZ. Which results in deterioration of the mechanical properties in these areas [16,17,22,23]. The increased base metal thickness was also reported to increase the hardness of welding [3,15]. In general, the welding that have higher tensile strength, have higher hardness [12,22,24]. However, Talabi et al. [25] stated that welding that has higher tensile strength and toughness has lower hardness. In general, it is reported that hardness in the FZ is higher than in the base metal area [6]. Also, the base metal without welding obtain lower tensile strength than welded ones [18,19], but shows higher toughness [19]. In this study an investigation on the effect of welding parameters, that is, base metal thickness, welding voltage and WFS on the tensile strength and hardness of commercial steel or mild steel and the relationship between the tensile strength and hardness with respect to the welding parameters. Also the welding parameters will be optimized to obtain best practical conditions for stronger, more effective welding and consistent welding.

II. METHODOLOGY

Materials and Experimentation. The material used for GMAW is non-alloy structural steel (commercial steel or also called mild steel) European standard EN 10025-2, grade S235JR (1.0038) brought from the local market and prepared using a CNC laser cutter in Tasamim workshop at Benghazi. The preparation of the samples was according to the ASTM E8 / E8M for the tensile test which is a standard designed by the American society of testing materials. Figure 1 shows a tensile test illustration for the sample with dimensions for both base metal thicknesses of 5 and 10 mm. The groove of samples was prepared at the College of mechanical Engineering Technology using a grinder with water for cooling. Each angle has 30 degrees and with both base metal joints, the angle becomes 60 as seen in Figure 1. Also, other samples were prepared for hardness testing using a similar technique. The welding was conducted at the welding lab at ambient temperature in Saad Elkarimi Institute of Technology in Benghazi. The GMAW machine used is CEA MAXI 321 as shown in Figure 2 and the welding process is shown in Figure 3. The welding filler NEXUS copper-coated mild steel welding wire (AWS ER70 S-6). The shielding gas used is a combined of 82% argon and 18% carbon dioxide with a gas flow rate of 18 ml/min. The wire thickness is fixed for the experiment at 0.045 in (1.143 mm) thick. The current is estimated to be 106 A at 20 V and 287 A at 27.5 V. The welding was done manually with both hands with an approximate welding speed of 150 mm/min. The base metal is fixed on a welding table with clamps. The gradient of base metal and filler materials is listed in Table 4, while Table 5 shows their mechanical properties. Table 6 shows the experiment setup including three parameters, and each has two levels according to Taguchi’s design. While Table 7 shows the orthogonal array for welding parameters and their corresponding tensile strength and Vickers microhardness.

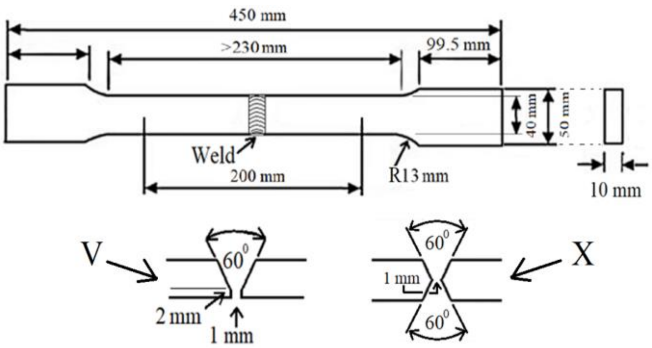


Figure 1. Tensile strength test dimensions according to ASTM E8/E8M

Figure 2. Welding machine CEA MAXI 321

Figure 3. Welding process

Figure 4. Tensile strength samples

Taguchi's Design. The experiment setup follows the orthogonal array of three parameters (2^3) with 2-level at each resulting in a total of 4 runs (L4). However, Minitab 18® couldn't estimate the experiment's coefficient with such a design. Therefore, Taguchi's design allows for the runs to be extended to 8 runs (L8). This method is known as Taguchi's L8 array. Table 4 shows Taguchi's design layout concerning welding parameters with the corresponding tensile strength and Vickers microhardness of the welding samples. The analysis was made with help of Minitab 18®.

Tensile Strength and Vickers microhardness Testing. Tensile test carried out on Shimadzu (UEH-20) universal testing machine at Libyan Iron and Steel Company at Misrata. The tested sample is shown in Figure 4. The hardness test was conducted in the High Vocational Center of Casting at Tripoli using a BMS Bulut Makina Sanayi microhardness tester. The indenter used is a diamond cone with a load of 1 kg as pressure force as seen in Figure 5. The indenter used is a diamond cone with 120 degrees. The hardness of the welding area or the fusion zone was measured to demonstrate the change in the welding parameters on them. The vickers microhardness value in Table 7 is an average of three runs taken for each sample.

Table 4. The chemical compositions of the metal joint and welding wire used in the experiment

Component	Composition								
	C	*Mn*	*S*	*Ni*	*Cr*	*P*	*Ni*	*Cu*	*Fe*
Base metal	0.17%	1.4%	0.025%	0.012%	-	0.025%	0.012 %	0.55%	Balanced
Welding filler	0.12%	1.8%	0.035%	0.15%	0.15%	0.035%	-	0.35%	Balanced

Table 5. The tensile strength and hardness of base metal and welding filler [26]

Component	Tensile properties			Hardness properties	
	Yield strength	*Tensile strength*	*Elongation*	*Brinell hardness*	*Vickers microhardness*
Base metal	235	360-510	26%	≤120 HBW	≈2025 HV
Welding filler	483 MPa (70 ksi)	583 MPa (81 ksi)	26%	-	-

Table 6. Experiment setup for the welding process

Code	Parameters	Unit	Level 1	Level 2
A	Base metal thickness	mm	5	10
B	Voltage	V	20	30
C	Wire feed speed (WFS)	m/min	5.9	10.6

Table 7. Welding parameters and their corresponding tensile strength and Vickers microhardness

No	Base metal thickness (mm)	Voltage (V)	WFS (m/min)	Tensile strength (N/mm^2)	Heat input (J/mm)	Vickers microhardness (HV)	(N/mm^2) / HV
1	5	20	5.9	176	363.43	2154	0.08
2	5	20	10.6	145	363.43	2146	0.07
3	5	27.5	5.9	173	1353.00	2155	0.08
4	5	27.5	10.6	120	1353.00	2108	0.06
5	10	20	5.9	305	363.43	2170	0.14
6	10	20	10.6	238	363.43	2162	0.11
7	10	27.5	5.9	233	1353.00	2152	0.11
8	10	27.5	10.6	192	1353.00	2157	0.09

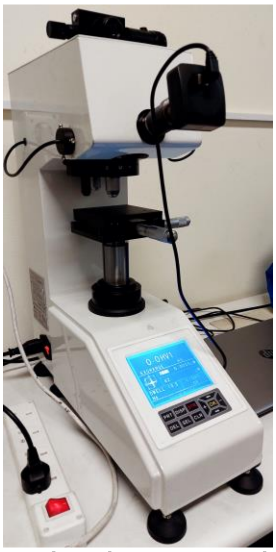


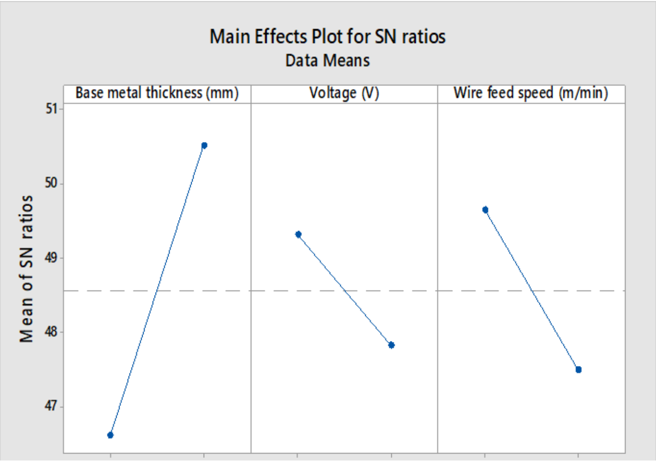
Figure 5. BMS Bulut Makina Sanayi microhardness terster

III. RESULTS AND DISCUSSION

As shown in Table 7 the tensile strength increased whenever the hardness decreased and the opposite. The tensile strength and the hardness of welding increased with the increased base metal thickness, decreased welding voltage and WFS. It is also noticed that the increased welding heat input is caused by increased voltage and WFS resulted in lower tensile strength. However, at higher heat input the hardness shows a propositional increment to the decreased tensile strength. This is shown in the ratio of tensile strength over hardness. For example, sample no. 2 has a higher ratio compared to sample no. 4, while sampling no. 3 has shown higher hardness than sample no. 1. 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 [25]. Jeet et al. [15] stated that increased base metal thickness means an increased surrounding area around the welding area, which acts as a heat sink that absorbs heat from the welding area and distributes it along with the base metal. A study by Yadav et al. [17] showed that 5 to 10 mm base metal thickness has contributed to the increase in tensile strength and hardness of the welding.

The plots in Figure 6 and Figure 7 are the plots for signal-to-noise (S/N) ratios and Means of the welding parameters respectively. The S/N ratios in Figure 6 are the values that demonstrate welding parameters' effect or influence by measuring their noise conditions on the values of higher tensile strength and hardness as stated in "Larger is better" under Figure 6 and Table 8. The effect or influence on the larger or higher tensile strength and hardness results was chosen because the higher the strength the sounder and the quality of welding which is the objective of this study. The purpose is to identify which level at each parameter has a strong effect on the higher results. The S/N corresponding to each level for each parameter is also shown in the response table (Table 8). Figure 6 shows the S/N ratio for each level at each parameter. The base metal thickness for instance shows the highest S/N ratio at 10 mm thickness, while at 5 mm obtained the lower noise ratio. The gap between the two levels is higher than the other parameters. The S/N ratio at wire feed speed or WFS showed a closer gap between the two levels with 5.9 m/min and showed a higher noise ratio than WFS at 10.6 m/min. While the welding voltage showed a shorter gap with 20 V has higher noise on the higher results than at 27.5 V. The Delta in Table 8 is a result of the highest S/N ratio minus the lowest for each parameter. The ranking is assigned based on Delta, which indicates the effectiveness and strength of welding parameters. It's also indicated in Table 10 by the absolute values of the coefficient. The Delta value in Table 8 shows a higher value and therefore ranked first at base metal thickness. Which is a result of the highest S/N (50.51) which corresponds to a thickness of 10 mm minus the lowest (46.61) at 5 mm. The rank at WFS showed second while the welding voltage showed third or last. The order of the ranks in Table 8 confirms with slopes in Figure 6. It indicates that base metal thickness has the highest effect on higher values of tensile strength and hardness. Also, the thickness at 10 mm has should higher effect than at 5 mm by showing a higher S/N ratio. The WFS at 5.9 m/min came second in their influence on the higher results, while the voltage at 20 V came third.

Figure 7 shows the means of tensile strength and hardness for each parameter at each level. The objective of obtaining Means is to obtain which level on which parameter has obtained a higher strength value. It is important to obtain which level at each parameter has obtained higher tensile strength and hardness value for more desirable welding. Table 9 shows the average Means at Level 1 and Level 2 for each welding parameter. From Figure 7 and Table 9 it is shown that base metal thickness at 10 mm has a larger range of means (1201) than the other welding parameters as indicated in Rank 1 based on higher Delta in Table 9. It indicates that the average of higher tensile strength and hardness values are obtained at 10 mm, while the values dropped drastically at the thickness of 5 mm with a mean value of 1147. The WFS at 5.9 m/min followed by welding voltage both have shown close response means at 5.9 m/min (1190) and 20 V (1187). Both of them showed lower means of tensile strength and hardness. In another word, higher tensile and hardness values are obtained at 10 mm thick base metal followed by WFS at 5.9 m/min and welding voltage at 20 V.



*Larger is better

Figure 6. Plot for S/N ratio for the welding parameters

Table 8. S/N Ratios response (Larger is better)

Level	Base metal thickness (mm)	Welding voltage (V)	WFS (m/min)
1	46.61	49.30	49.64
2	50.51	47.82	47.48
Delta	3.90	1.48	2.16
Rank	1	3	2

The coefficients model for the S/N ratio for the welding parameters and Means are shown in Table 10 and Table 11 respectively. Table 10 obtain the coefficient constant value which corresponds to the value of the mean of the S/N ratio as shown in Figure 6. Each parameter has a coefficient value that by which when added to the constant value results in the S/N ratio. The population value (P-value) for the base metal thickness of 5 mm is 0.001, which is considered statistically significant because it is less than the significance level of 0.05. The P-value for 20 V and WFS at 5.9 m/min also showed significance with the value of 0.007 and 0.025 respectively. The S/N ratio was the lowest at base metal thickness at 5 mm. However, its P value state that their effect on the tensile strength and hardness has a 99.9% rate of occurrence which rejects the null hypothesis. While the effect of WFS at 5.9 m/min has 99.3% and voltage at 20 has 97.5% they still have a strong probability of repeating a similar effect on higher results values. Table 11 also shows base meta thickness at 5 mm has a higher probability of occurrence with 99.7% on obtaining similar means followed by WFS at 5.9 m/min has 98.1% and voltage at 20 has 99.6%. Unfortunately, Minitab 18® didn't show the p-values for Level 2 parameters.

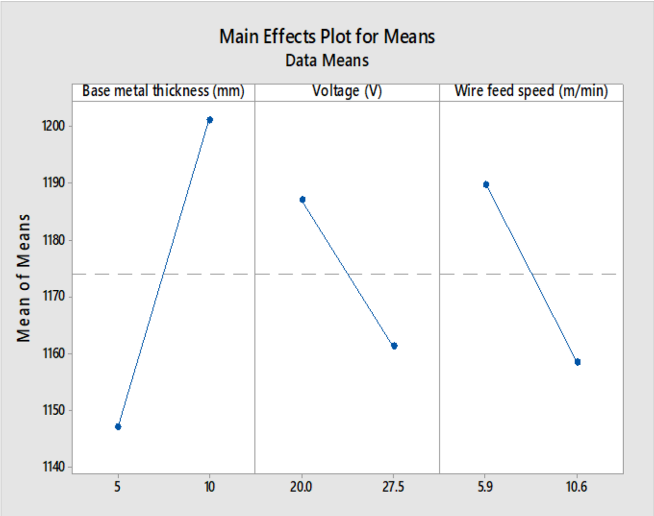


Figure 7. Plot for means for the welding parameters

Table 9. The Means response

Level	Base metal thickness (mm)	Welding voltage (V)	WFS (m/min)
1	1147	1187	1190
2	1201	1161	1159
Delta	54	26	31
Rank	1	3	2

Table 10. The model coefficients and p-values for S/N ratios

Term	Coefficient	P-value
Constant	48.5603	0.000
Base metal thickness (5 mm)	-1.9521	0.001
Welding voltage (20 V)	0.7423	0.025
WFS (5.9 m/min)	1.0780	0.007

Table 11. The model coefficients and p-values for Means

Term	Coefficient	P-value
Constant	1174.13	0.000
Base metal thickness (5 mm)	-27.00	0.003
Welding voltage (20 V)	12.87	0.034
WFS (5.9 m/min)	15.63	0.019

According the these results it is clear that the tensile strength and hardness higher values are affected the most by the base metal thickness at 10 mm followed by WFS at 5.9 m/min and welding voltage at 20 V. The WFS at 5.9 m/min and welding voltage at 20 has shown significant results with high probability of occurrence, while the Minitab 18 has not shown the probability of base metal thickness at 10 mm. However, the base metal thickness at 10 mm has higher tensile strength and hardness means values followed by WFS at 5.9 m/min, while the welding voltage at 20 has shown lower mean values. The optimum welding parameters according to Taguchi's design which obtained higher effect on higher tensile strength and hardness and higher means values are base metal thickness

10 mm, welding voltage at 20 and 5.9 m/min WFS. It is recommended to take these measurements when welding commercial steel (EN 10025-2) with mild steel welding filler using GMAW for strong and sound, and effective welding.

IV. Conclusion and Future Scope

The commercial steel was welded by GMAW manually using mild steel electrode wire. The welding parameters used for the welding process to be studied are base metal thickness, welding voltage and WFS. The objective is to find the effect of these parameters on the strength of the welding, the tensile strength and hardness properties. The analysis was made using Taguchi's design to the effect of each welding parameter with each of its two levels on the results. Higher tensile strength and hardness were shown at higher base metal thickness, lower voltage and WFS. The hardness increased with the increased heat input which led to increased internal stresses. Higher heat input is obtained by higher welding voltage and WFS, which results in lower tensile strength and higher tensile strength to hardness ratio of the welding. In other words, they showed proportionally higher hardness compared to the welded samples with lower welding voltage and WFS. The welding voltage at 20 and WFS at 5.9 m/min have shown significance which means the obtained results at these levels have shown consistency. Unfortunately, the analysis didn't show information regarding the significance of base metal thickness at 10 mm. The results also showed that higher base metal thickness obtained a higher effect on the higher tensile strength and hardness according to the noise conditions analysis and also higher means of values. Following by lower wire feed speed and lower welding voltage. The welding optimum combination according to Taguchi's design and statistical analysis is base metal groove shape V, 20 V and 5.9 m/min WFS. This setting has obtained a strong effect or influence on the higher tensile strength and hardness of the welding and it's confirmed by showing higher results. It is recommended to use such settings when welding commercial steel (EN 10025-2) using mild steel filler in GMAW for favourable for strong and effective welding.

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AUTHORS PROFILE

Saleh Suliman Elfallah pursed Bachelor of Industrial Engineering from University of Benghazi, Benghazi in 2010 and Master of Science from Universiti Tun Hussein Onn Malaysia in year 2012 and PhD in 2018 from the same university. He is currently working as Lecturer in Department of Mechanical Engineering, College of Mechanical Engineering Technology in Benghazi, Libya since 2018. His duties are teaching mechanical engineering subjects, supervising final year projects. He has published more than 7 research papers in reputed international journals including Thomson Reuters (SCI & Web of Science), Scopus and conferences. His main research work focuses on Material Science and manufacturing technology. He has 5 years of teaching experience and 4 years of Research Experience.

