Design for DOE: Development of a CNC platform to Evaluate Effect of Operator's Skill in Gas Metal ARC Welding (GMAW)

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Abstract:

Gas Metal Arc Welding (GMAW), commonly known as MIG welding, is the dominant industrial welding method. GMAW is preferred due to its ease of operation, versatility of material types to be joined, relative high speed and low cost. Though GMAW can be adapted for robotic application, semi-automatic version with a human operator is still common. This project aims to determine the effect of human operator's skill on the joint quality. Given that important factors, such as wire feed rate, shielding gas supply rate, voltage etc., are predetermined, it was decided that the operator's speed, zig-zag width of weld and contact tip-to-work (CTWD) distance might impact the weldment quality. A full factorial DOE with center points was designed. However, with a human operator, it is impossible to maintain or verify that the level of the factors was held constant during the experiment. This necessitates the design of a fixture which will mimic the human operator's motion while holding the input level of the factor's constant throughout the weld length. This paper describes the design and development of CNC controlled fixture to perform the welding operation along with the effects of factors on the weldment quality as obtained from the full factorial DOE. Using the fixture experiments were conducted on AISI 1018 cold rolled steel plates. The quality of the weldment was judged by the tensile strength obtained from an Instron universal testing machine. It was found that operator's speed and CTWD had significant impact on the welded joints whereas zigzag motion does not affect the joint strength at a level of significance.

Keywords: DOE, GMAW, Welding Fixture

1. Introduction

Gas metal arc welding (GMAW) is a process of joining metal parts using filler wire, fed through the welding torch and melting the base metal with an electric arc. An inert gas, CO_2 and/or Argon, is supplied to prevent the molten metal from the environment. Though the process can be automated, still a wide range of operations are done by manual operators. Joining with GMAW welding torches is a rather low-cost, highly-productive process which can be used to weld almost all types of commercially available alloys and metals. It can be performed in all positions except for overhead welding [1]. In manual GMAW process, quality of the welded joint depends on operator's skill. This paper investigates the relative importance of different factors that comprises operator's skill.

2. Background

In manual GMAW welding there are multiple parameters that are very difficult to control, some of which are welding speed, zig-zag width of weld, and nozzle height. These parameters can be categorized under operator's skill. In order to determine the effect and interactions of these factors, this research decided to conduct a DOE by varying those factors. However, even for the most skilled operator, it is impossible to maintain the set level of input constants during a manual welding operations. This challenge necessitates design and development of a welding fixture which will allow to weld a joint while holding input values of the factor at a given constant level. The design and building of the fixture is discussed in section 4.

3. Methodology

DOE in this research paper is a full factorial design with three variables with center points and one repetition as shown in Table 1. It is decided that effect of the factors will be determined by measuring the tensile strength of the welded joints.

Table 1. Factors and levels of the experiment

Variable Factors	**Notation**	**Levels**			**Units**
		I	**II**	**III**	
Code		-1	0	1	
Weld Speed	W	100	200	300	(mm/min)
Zig Zag width	Z	3.5	5.5	7.5	(mm)
Nozzle Height	N	5	10	15	(mm)

Appropriate measures have been taken to reduce the effects of other variables such as metal coupon preparation, holding them together etc... Cold rolled AISI 1018 is chosen as sample material as it can be easily welded by all the conventional welding processes, low carbon welding fillers are relatively less expensive, and pre and post heating are not necessary [1-4]. Figure 1 describes the welded samples and mechanical.

AISI 1018 Steel Properties	**Metric Units**
Density	7861 kg/m³
Hardness, Brinell	126
Tensile Strength, Ultimate	440 MPa
Tensile Strength, Yield	370 MPa
Modulus of Elasticity	205 MPa

Figure 1. Welded work-piece sample (GVSU Workshop)

4. Design of the Fixture

The design requirements for a fixture which will imitate a human operator while providing opportunity to hold the input level constants during an experiment are listed below:

1. able to carry the welding gun without significant deflection in the structure
2. provides opportunity to fix (a) linear speed along the x-axis, (b) amplitude of the zigzag motion along the way (c) contact tip-to-work distance
3. maintains the set values at #2 during the welding operation
4. able to withstand the welding temperature.

These requirements led to an electro-mechanical design endeavor. Figure 2 shows the completed fixture which fulfills above requirements.

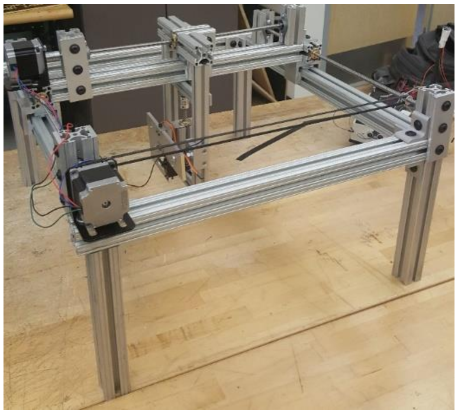

Figure 2. The Welding Fixture

The frame for the fixture is going to be made of 80/20 Aluminum extrusion 1515 series. The nozzle will be able to move across the frame sliding with a 6825 triple slot double flange linear bearing, which will be driven by lead screws. The lead screw will be rotated by stepper motors, a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor step is commanded using an Arduino based driver shield, G-Shield V5. The shield is compatible with a GUI CNC software, Universal G Code Sender on the Arduino IDE. The power supplied to the system is from an AC to DC conversion unit that can with stand 15 A current and able to generate 24 V. The nozzle is driven along the frame of the fixture similarly to the working principles of a simple CNC machine where multiple lines of codes describes every instantaneous positions of the nozzle. The command lines is fed to an open source computer platform called Universal G-Code sender. The software will send these commands to the Syntethos GShield using an Arduino port and the nozzle will be driven through the described path. This CNC welding machine is designed and built to meet very close accuracies. And once the welding is completed any kind of post treatment will have to be done manually [2-3]. The complete bill of material is presented in Appendix A.

5. The Experiment

3 factors, 3 levels, 2 repetition required 54 total experiments. A total of 108 pieces of AISI 1018 steel coupons were prepared as shown is Figure 1 for this experiment. The welding voltage is set to 20 V, CO_2 is used as shielding gas at a pressure of 100 KPa, wire feed rate is chosen to be 5500 mm/min. The welding type for this experiment is a single V groove weld, where two pieces are milled at a constant edge angle of 30^O with an allowable maximum face distance between the materials being 0 to 3mm [3, 8]. Once welding is done, tensile testing samples, shown in Figure 3, is prepared.

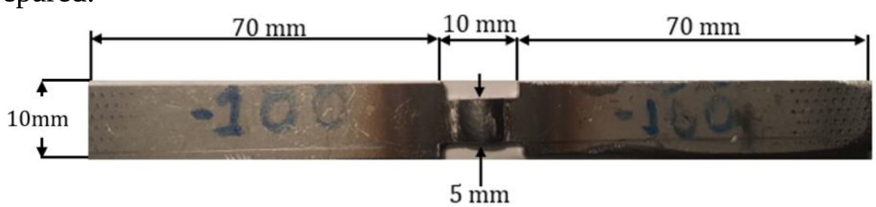

Figure 3. Tensile testing sample

The final step is conducting the tensile strength test. Under the tensile load, all the samples failed at the welded joints as the joints are made to have much smaller cross-sectional area compared to the rest of the sample [6-9].

6. Result and Discussion

The recorded measurements of the joints for each combination is quantified in the following table for each variable level combination of welding speed, zig zag width and nozzle height. Note that the response measured is the tensile force at the point of fracture. Complete results for all 108 experiments are reported in Appendix B.

Table 2. Sample of Recorded Measurements (Newtons)

Speed (mm/min)	**Zig Zag Width (mm)**	**Nozzle Height (mm)**	**Tensile Strength of Weld (N)**		**Mean**	**Standard Deviation**
			Response 1	Response 2		
-1	-1	-1	15190.91	15245.46	15218.2	27.275
-1	-1	0	15208.12	15108.28	15158.2	49.92
-1	-1	1	11251.19	10902.02	11076.6	174.585

Guidelines for test of significance are specified and pooling are randomized. The plot of average response at each level of a parameter indicates the trend for an expected confidence level of 95%. Table 3 presents summary of the effect of factors on the responses [5].

Table 3. Summary of Analysis of Variance

Parameter Interactions	**Log Worth**	**P-value**	**t-Ratio**	**ADJ SS**
Nozzle Height (mm)	15.272	0.00000	-11.88	132025385
Speed (mm/min)	14.888	0.00000	2.04	3907093
Speed (mm/min) * ZIG ZAG width (mm)	2.5130	0.00307	-12.18	138845609

Speed(mm/min) * Nozzle Height (mm)	1.9310	0.01172	-3.13	914163
Zig Zag width (mm)	1.3300	0.04676	2.63	6447300
Speed * Zig Zag * Nozzle Height	0.7230	0.18936	-0.56	292498
ZIG ZAG width (mm) * Nozzle Height (mm)	0.2370	0.57879	1.33	1660542

ANOVA table shows the Nozzle height seems to have the highest effect on the strength of the weld. Most likely causes at higher distance the shielding gas fails to protect the weld from contamination and the electric arc spreads too much reducing heat concentration thereby affecting the joint strength. Also, speed seems to have a large effect. As the speed increases the time available to melt the base material becomes shorter, thereby the weld beads will be very thin resulting in weaker joints [5, 7].

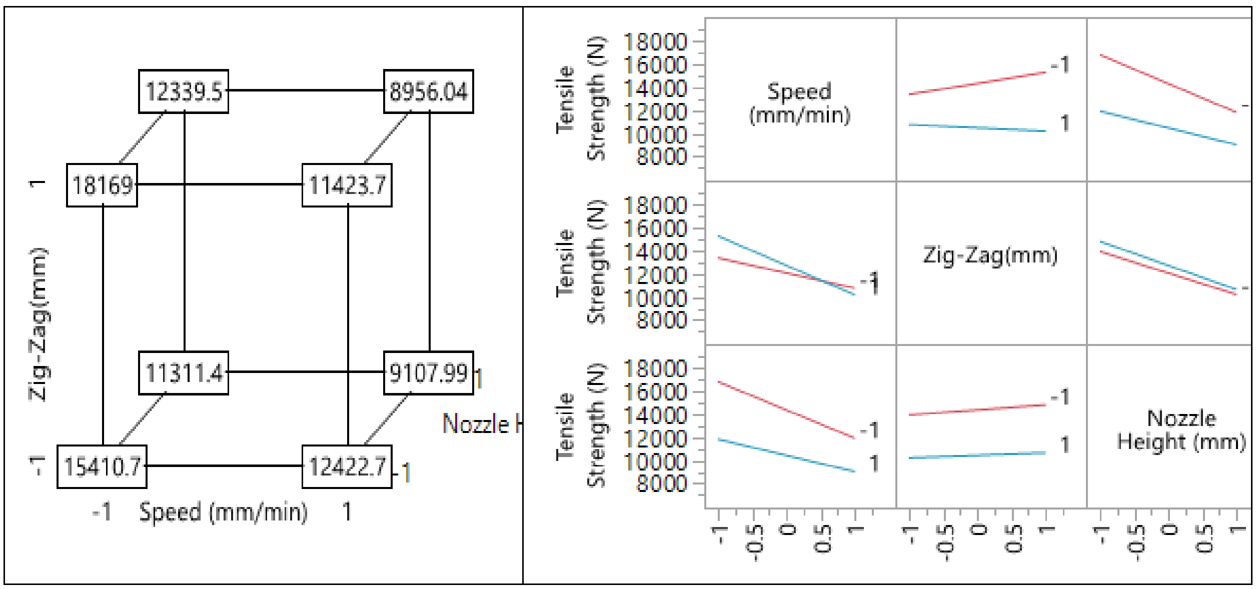

Figure 4. (a) Cubic interaction plot (b) 2-level interactions

The cubic interaction plot reveals the highest tensile strength is at combination of (-1, 1, -1) corresponding lowest speed, 100 mm/min, highest zig zag width 7.5 mm, and lowest nozzle height, 5 mm. This is due to the complete shielding, high concentration of heat flux and sufficient time to melt the material. On the other hand, the combination (1, 1, -1) has the lowest strength. This can be explained by lack of complete shielding and inadequate melting of the material. The CO_2 gas is not reaching the weld in time to prevent oxidation and bubbling. This will cause weak and unattractive weld beads [5].

The interaction between the factors reveals that the zig-zag width has the highest interaction with the speed. Combination of these two factor will influence the heat input at any point of welded joint. Hence this high interaction effect is reasonable. The main effect of zigzag width is minimum among the three factors. Since the maximum welding gap in this experiment was 3 mm zigzag motion might not influence melting of the surrounding material. According to the interaction plot the relationship between the nozzle height and zig zag width seems to be very low. This shows that if the nozzle height is higher than the optimum value, it is very unlikely for the strength of the weld to be compensated by varying the zig zag width of the welding process [5].

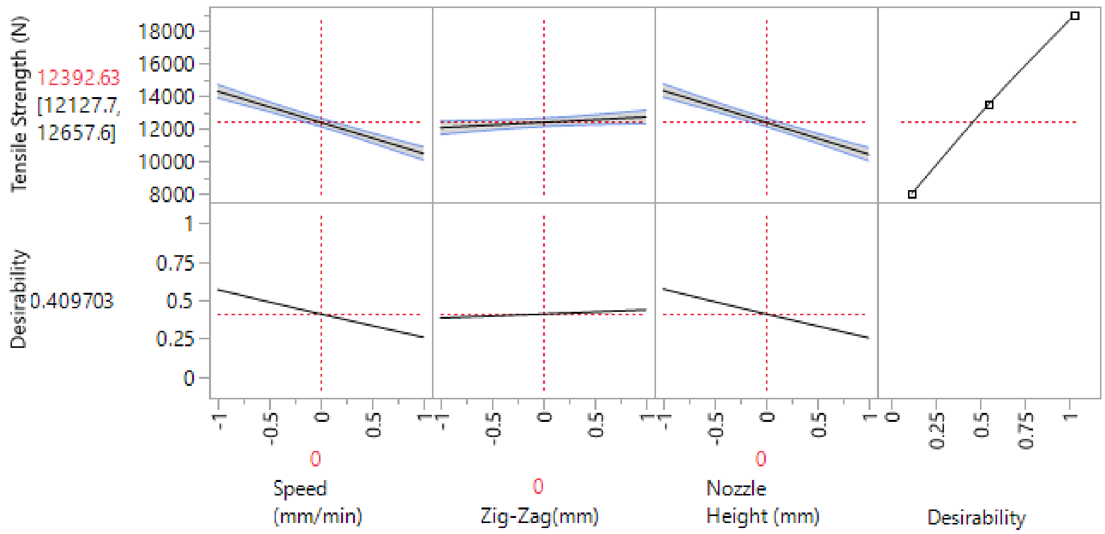

Figure 5. Prediction Plot

According to the prediction plot the lower the speed the higher the strength of the workpiece. As for the width of the zig-zag formation it has little to no impact on its own. Finally, the higher nozzle is from the work piece the weaker the joint will be. The resulting prediction curve is given by:

➢ Strength = 12392.63 – 1915.04(S) +329.44(Z) – 1963.88(N) – 617.17(SZ) +518.3(S*N);
Where, S is speed of weld, Z is Zigzag Width, and N is Nozzle height

7. Conclusion

In this work, an attempt was made to determine the effect important skill factors in a manual GMAW process. Three most skill factors were welding speed, zig-zag width and nozzle height from work piece. Other influential factors such as type and geometry of material, voltage, gas pressure, gas type, weld position and weld type etc. were kept constant. A three-level full factorial design was carried out and tensile strength of the welded joint was chosen as the response variable. In order to set and maintain the input level, an elaborate electro-mechanical design work was done and a fixture was developed to mimic the human operator.

ANOVA was performed and the results were generated using JMP Pro statistics tool. Nozzle height and welding speeds have most significant main effects. Speed and zigzag width have the most significant 2-level effect.

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Appendix A

Table A: Bill of Materials

No.	Part Name	Quantities	Vendor
1	1515 Series 80/20 Aluminum Extrusion	2.5m	Bond Fluidaire Inc
2	1010 Series 80/20 Aluminum Extrusion	0.5m	Bond Fluidaire Inc
3	6825 Triple Flange Linear Bearing	3	Lake Michigan Asset Solution
4	Nema 23 Stepper Motor	2	www.amazon.com
5	T8 Stainless Steel Lead Screws	2	www.amazon.com
6	T8 Bronze Lead Nuts	6	www.amazon.com
7	GT2 6mm close loop Timing Belt, 1 m	1	www.amazon.com
8	GT2 Driver Pulleys	2	www.amazon.com
9	Aluminum Shaft Coupling 5.0 to 6.25mm	2	www.amazon.com
9	Syntethos V5 GShield	1	Adafruit Industries
10	Arduino UNO Board	1	Adafruit Industries
11	15A 24V AC to DC Power Supply	1	www.amazon.com
12	Generic Jumper Cables	-	www.amazon.com
13	L-Angle Aluminum Connector	12	Bond Fluidaire Inc
14	Flat Aluminum Connector Plate	4	Bond Fluidaire Inc
13	5/16 Screws	36	Bond Fluidaire Inc
14	5/16 Slider Nuts	36	Bond Fluidaire Inc

Appendix B

Table B: Recorded Responses from the Instron tensile Strength Test

Speed (mm/min)	**Zig Zag Width (mm)**	**Nozzle Height (mm)**	**Tensile Strength of Weld (N)**		**Mean**	**Standard Deviation**
			Response 1	Response 2		
-1	-1	-1	15190.91	15245.46	15218.2	27.275
-1	-1	0	15208.12	15108.28	15158.2	49.92
-1	-1	1	11251.19	10902.02	11076.6	174.585
-1	0	-1	16227.66	16227.34	16227.5	0.16
-1	0	0	14861.17	15419.02	15140.1	278.925
-1	0	1	11152.18	11152.18	11152.2	0
-1	1	-1	18198.71	18419.55	18309.1	110.42
-1	1	0	16522.99	16518.52	16520.8	2.235
-1	1	1	12509.41	12595.03	12552.2	42.81
0	-1	-1	13188.27	13125.02	13156.6	31.625
0	-1	0	10365.71	10365.92	10365.8	0.105
0	-1	1	10117.09	9921.85	10019.5	97.62
0	0	-1	14699.92	14595.32	14647.6	52.3
0	0	0	13111.33	13251.2	13181.3	69.935
0	0	1	9813.62	10129.32	9971.47	157.85
0	1	-1	13026.61	12944.78	12985.7	40.915
0	1	0	13054.1	12659.5	12856.8	197.3
0	1	1	9119.11	9235.25	9177.18	58.07
1	-1	-1	12841.84	12564.81	12703.3	138.515
1	-1	0	11897.14	12027.9	11962.5	65.38
1	-1	1	9053.79	8953.22	9003.51	50.285
1	0	-1	10951.09	10841.99	10896.5	54.55
1	0	0	11500.05	11591.55	11545.8	45.75
1	0	1	8618.44	8541.74	8580.09	38.35
1	1	-1	11892.17	12041.47	11966.8	74.65
1	1	0	11046.63	10946.71	10996.7	49.96
1	1	1	9201.49	9256.33	9228.91	27.42