

Optimization of Fluence Energy in Relation to Weld Properties Based on Vogel Approximation Method

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Abstract - This paper explores the use of the Vogel Approximation Method to determine the best suitable Fluence energy that can produce a mild steel weld of acceptable Ultimate Tensile Strength (UTS). Although this model is most often utilised for optimizing facility location problems, in this study it is uniquely adapted to accurately determine and predict acceptable mild steel fluence energy weld parameters. The UTS was the mechanical property chosen in this study because it defines the ductility and malleability of the weldment, making it suitable for a wide range of engineering applications. In this study, a fluence energy of 3.79kW achieving a UTS of 506 MPa of weldment. W_2 was obtained and found to be suitable. This value falls within an average range of 50 MPa/kW and 150 MPa/kW obtained by other investigators. Other properties were investigated such as the Micro-structural analysis, Brinell Hardness Number (BHN), Charpy V-Notch (CVN) Impact energy, and weld factor. The values obtained show that weldment W_2 has the best weld quality. This study elucidates a step by step approach in the application of the Vogel Approximation Model in determining the optimized Fluence energy.

Index terms: BHN, CVN, fluence energy, microstructure, vogel approximation method, weld factor

1. INTRODUCTION

Different welding machines produce varying amounts of energy input during the welding process for melting the welding electrodes, which in turn, form droplets. Some of this energy input is used to transfer these droplets to the weld pool. This weld pool transition action therefore reduces the amount of the calculated initial input energy. Once this expected loss is taken into account, the input energy will eventually always be in equilibrium with the output energy.

Yang and Debroy [1] wrote that the total energy absorbed by the workpiece in the Gas Metal Arc Welding (GMAW) process consists of two parts: Energy transfer from the arc, and transport of heat along with the metal droplets. The authors emphasized that in the GMAW process, hot metal drops carry a significant amount of thermal and kinetic energy into the weldpool. Khan [2] wrote that energy supplied in welding is usually in the form of heat generated by a flame, an arc, the resistance to an electric current, radiant energy, or by mechanical means (friction, ultrasonic vibrations, or by explosion).

Some of this energy is absorbed by the work pieces being welded, and some energy is also lost as a result of the convective process that occurs between the welding environment and the arc heat. The determined input – output energy has a significant effect, contributing to the achievement of good weld penetration, as well as the formation of desirable, and uniform bead geometry. The ascertained mechanical properties of the eventual weldment, serve as a reliable criteria for determining the success and desirability of the weld itself.

Thus, understanding, influencing, and optimizing the fluence energy inherent in the weld process could lead to significantly improved weld bead geometry, with the desired mechanical properties especially the Ultimate Tensile Strength (UTS).

Studies have shown that applying too much heat input energy would increase the kinetic energy of the metal droplets which could lead to the formation of spatter. Spatter tends to encourage the formation of weld micro-craters, and since blazing hot metallic materials quickly absorb atmospheric moisture, these undesirable micro-craters are likely to absorb and retain moisture. If left uncontrolled, this moisture content initiates an unwelcome domino effect. The presence of water leads to oxidization of the adjacent weldment molecules surrounding the micro-craters. What invariably follows is that the weldment, upon solidification, becomes brittle, which would eventually exert a negative effect on the quality of the weld bead geometry in general.

On the converse, a less than optimal energy input could lead to undercuts, inadequate weld penetration, and inadequate molten weld metal mixing; conditions which similarly lead to unsatisfactory weldments.

In this study, the equilibrium conditions, which balance the input energy and output energy is considered for the optimization process. The output energy includes the energy losses to the environment during welding, as well as the energy absorbed by the workpiece during welding. The precise balancing act between input-output energy is used for selecting the proper fluence energy required to produce a bead geometry expected to have the desired mechanical properties. The model used for this delicate optimization process is the Vogel Approximation Method. Hence, although the Vogel Approximation Method is originally an optimization tool used for determining the most appropriate location of production facilities, in such a way that cost and distance are optimally controlled, this method has here been adapted in a novel approach, modifying and elevating it to make significant improvements in the selection of a suitable welding fluence energy required to produce welds of satisfactory quality.

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II. MATERIALS AND METHODS

A GMAW machine is used to melt 3.2 mm mild steel electrodes, utilizing a combination of 90%Ar + 10% CO₂ shielding gas with a flow rate of 18 l/min. Measurements of process parameters were taken as indicated in the equations specified here under:

Paleocrassas and Tu [3] proposed an equation for determining the amount of energy deposited per area for a unit length of weld also known as Fluence, *F* as:

$$F = \frac{P}{\pi r^2 v} \quad (1)$$

Where *P* is the total power, defined as *P* = *IE*, where *I* is the welding current in Amperes, and *E* is the arc voltage in volts, *v* is the welding speed, m/s, whereas, *r* represents the wire radius, mm.

In this study the Fluence was regarded as the input energy, *E_{in}*. Different energy levels were achieved by varying the welding speed.

The output energy was obtained from the equation:

$$E_{out} = \frac{C_p(T-T_0)q_v\rho}{v} - E_{in} \quad (2)$$

Balkan et al [4] determined the total amount of energy transferred onto the weld surface as:

$$E_w = \frac{C_p(T-T_0)q_v\rho}{v} \quad (KJm^{-1}) \quad (3)$$

where *T₀* is the preheat temperature, *C_p* is the specific heat capacity, *q_v* is the volume flow rate of liquid metal, obtained from:

$$q_v = \frac{v_{weld}}{welding\ time,t} = \frac{w_f \pi r^2}{t} \quad (m^3/s) \quad (4)$$

w_f is the wire feed rate obtained from *w_f* = 0.0258*I_m*

Where *I_m* is the mean current and *r* is the radius of the welding wire.

C_p is the specific heat capacity, *ρ* is the density of the molten metal, *v* is the welding speed and *T* is the melting temperature.

In this case, the welding speed and melting temperature were varied in order to achieve the output energy. Balkan et al [4] proposed an equation for evaluating weld strength, weld factor (*f_w*), which is also known as comparative weld strength, it is expressed as:

$$f_{weld} = \frac{\sigma_{weld}}{\sigma_{base}} \quad (5)$$

Where *σ_{weld}* and *σ_{base}* are strengths of a weld and its base material.

The Ultimate Tensile Strength, UTS of the material was obtained from a stress-strain curve developed by an Avery Extensometer used to conduct the weld tensile test. A Charpy V-Notch (CVN) Impact tester was used to determine the toughness of the weld material. The hardness tester was used to determine the Brinell Hardness Number (BHN) of the weld.

III. VOGEL APPROXIMATION METHOD

Banjoko [5] described this model as an improvement over North West Corner Rule. He explained the steps to be followed in using this model as follows:

1. Calculate the difference between the two smallest unit cost cells for each row and column;
2. Then select the row or column with the largest difference and make the largest feasible allocation into the cell having the smallest unit cost;
3. Once a row or column requirement has been satisfied, remove it from further consideration;
4. Repeat steps 1, 2, and 3 until *m* + *n* - 1 (i.e, number of rows plus number of columns minus one) cells have been occupied.

IV. PRESENTATION AND DISCUSSION OF RESULTS

The Vogel Approximation Method is utilized considering the equilibrium input-output energy equations in this study as expressed in Tables 1 – 6.

Table 1: Input-Output Energy with their corresponding UTS

		Welding Electrode, UTS (MPa)			Input Energy, KJ/m
		C ₁	C ₂	C ₃	
Basemetal	X ₁	595	468	506	4.05
	X ₂	709	405	610	5.95
	X ₃	350	586	427	8.54
	Output Energy KJ/m	5.19	6.21	7.14	18.54

In applying the Vogel Approximation Method, we allocate energy to the least UTS value and also from the two least UTS values in each row and column, subtract the smallest value from the other one. This leads to the creation of Table 2.

Table 2: Step 1 of the Fluence Energy Optimization Process

		Welding Electrode, UTS (MPa)			Input Energy KJ/m	Row Difference
		C ₁	C ₂	C ₃		
Basemetal	X ₁	595	468	506	4.05	38
	X ₂	709	405	610	5.95	205
	X ₃	350	586	427	8.54	77
	Output Energy KJ/m	5.19	6.21	7.14	18.54	
	Column Difference	245	63	79		

From Table 2, column C₁ has the highest value difference. Therefore, it is eliminated from the table. This elimination leads to the formation of Table 3.

Table 3: Step 2 of the Fluence Energy Optimization Process

	Welding Electrode, UTS (MPa)		Input Energy KJ/m	Row Difference
	C ₂	C ₃		
X ₁	468	506	4.05	38
X ₂	405 5.95	610	5.95	205
X ₃	586	427	3.35	159
Output Energy KJ/m	6.21	7.1 4	13.35	
Column Difference	63	79		

In Table 3, row X₂ has the largest difference between the two least UTS values. Therefore, it is eliminated and the energy value is allocated to the least UTS value in the matrix. This eventually leads to the formation of Table 4.

Table 4: Step 3 of the Fluence Energy Optimization Process

	Welding Electrode, UTS (MPa)		Input Energy KJ/m	Row Difference
	C ₂	C ₃		
X ₁	468	506	4.05	36
X ₂	586	427 3.35	3.35	159
Output Energy KJ/m	- 0.26	7.14	7.40	
Column Difference	16	79		

In Table 4, energy value is allocated to the least UTS value and the larger row difference is eliminated. This exercise leads to the formation of Table 5.

Table 5: Step 4 of the Fluence Energy Optimization Process

	Welding Electrode, UTS (MPa)		Input Energy KJ/m
	C ₂	C ₃	
X ₁	468 0.26	506 3.79	4.05
Output Energy KJ/m	0.26	3.79	4.05

Table 6 shows the final optimization process, where all the selected parameters are presented including the computed weld factor.

Table 6: Step 5 of the Fluence Energy Optimization Process

	Welding Electrode, UTS (MPa)			Input Energy KJ/m	Base metal, UTS σ _b	Weld Factor $F_w = \frac{\sigma_w}{\sigma_b}$	
	C ₁	C ₂	C ₃				
Basemetal	X ₁	595	468	506	4.05	417	W ₁ = 1.12 W ₂ = 1.21
	X ₂	709	405	610	05.95	416	W ₃ = 0.97
	X ₃	350	586	427	8.54	410	W ₄ = 0.35 W ₅ = 1.04
	Output Energy KJ/m	5.19	6.2 1	7.14			

From Table 6, the selection process outlays are determined as shown in Table 7:

Table 7: Weldment Selection Outlay

Weldment				
W ₁	W ₂	W ₃	W ₄	W ₅
$\frac{C_2}{x_1}$	$\frac{C_3}{x_1}$	$\frac{C_2}{x_2} = \frac{405}{5.95}$	$\frac{C_1}{x_3}$	$\frac{C_3}{x_3} = \frac{427}{3.35}$
= $\frac{468}{0.26}$	= $\frac{506}{3.79}$	= 68.07	= $\frac{350}{5.19}$	= 127.5
= 1800	= 133.5		= 67.4	

From Table 7, it is seen that 1kW of Fluence Energy was used to achieve a weldment with a UTS of 1800 MPa. This value of UTS has not been reported in the literature for mild steel. This further indicates that a UTS of 1800 MPa/kW of Fluence energy may not be achievable. Mostly an average range of 50 MPa/kW – 150 MPa/kW has been reported for low to high strength steels, but since W₂ (see Table 7) was found to have the highest UTS value, it is therefore, regarded as the most viable requiring a considerable lower energy input. The UTS value of 506 MPa is the most economically desirable weldment strength with a Fluence energy of 3.79kJ/m (see Fig. 1 and 2). Eagar [6] wrote that heat energy power densities of approximately 1000 W/cm² are required to melt most metals. Fluence energy is the energy utilized for welding per spot per area, compared with the initial welding energy of 18.54 KJ/m, only about 20.4% of the entire input energy was used. Eagar [6] cited in his paper that for arc welding, as little as half of the heat generated may enter the plate, and only 40% of this heat is used to fuse the metal. For oxyacetylene welding, Eagar [6] said that the heat entering the metal may be 10% or less of the total heat, and the heat necessary to fuse the metal may be less than 2 % of the total heat. Shih [7] wrote that 35% of the energy of an AC welding machine was used to produce good quality welds. The amount of energy used to weld the base metal can be affected by the type of alloying elements, the atmospheric condition of the arc column, and welding

Table 8: Chemical Compositions of Weldments

Weldment	Alloying Elements												
	Al	C	Mn	Cr	Mo	Si	Cu	N	P	S	Ti	Nb	O
W ₁	0.002	0.16	1.36	0.065	0.04	0.08	0.04	0.005	0.016	0.028	0.002	0.04	0.003
W ₂	0.004	0.23	1.28	0.042	0.06	0.16	0.02	0.002	0.010	0.035	0.004	0.08	0.008
W ₃	0.008	0.12	1.42	0.028	0.12	0.10	0.06	0.008	0.015	0.052	0.010	0.12	0.004
W ₄	0.007	0.19	1.14	0.082	0.09	0.12	0.10	0.008	0.05	0.043	0.012	0.18	0.006
W ₅	0.010	0.18	1.41	0.038	0.07	0.09	0.12	0.006	0.04	0.064	0.021	0.06	0.008

conditions. For instance, carbon is a hardening element, a high amount of carbon would require a great amount of energy to disintegrate. Alloying elements, therefore, have a great influence on the UTS of a weldment, as they can either increase or reduce the UTS.

The weld metals, W₁ – W₅ produced by the selected Fluence energies were subjected to chemical composition test as shown in Table 8.

From Table 8, weldment, w₂, appears to have better strength with a higher value of carbon and silicon, and proportionate values of chromium and sulphur. These alloying elements contribute immensely to improved weld metal strength. This claim is supported by weld factor of 1.21 (see Table 6). This indicates that weldment W₂ has the highest strength value.

Since weldment W₂ is chosen as the weld with the best qualities, some mechanical tests were carried out to validate this claim. From the tests elucidated in Fig.3, it is apparent that W₂ has a better weld quality; with a Brinell Hardness Number (BHN) of 460, and a Charpy V-Notch (CVN) Impact value of 120 J. However, weldment, W₅ has a higher BHN but much lower CVN value. This indicates that W₅ has a lower strength and a lower ability to absorb impact loads, therefore its higher BHN value indicates that the weldment material has traces of brittleness in it.

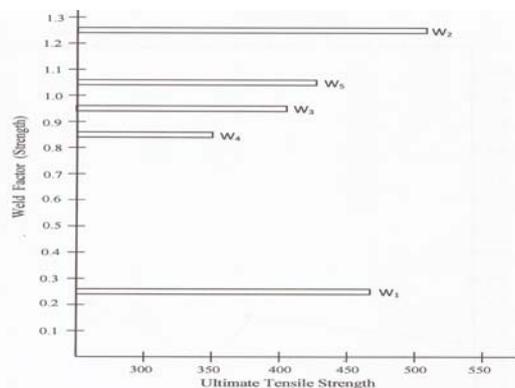


Fig 1: Weld Factor Vs Ultimate Tensile Strength

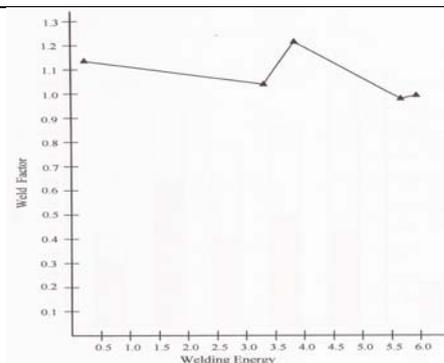


Fig. 2: Weld Factor Vs Welding Energy

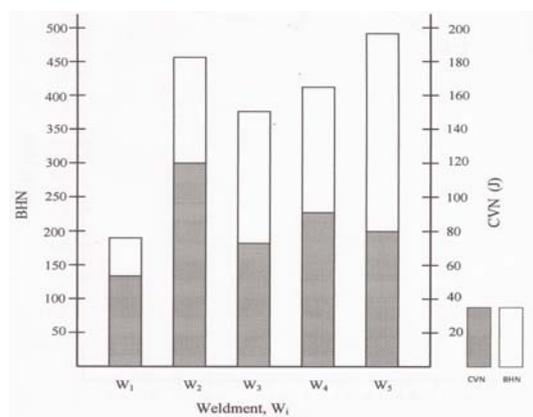


Fig. 3: BHN, CVN Vs Weldment

V. CONCLUSION

The Vogel Approximation method was used to select five weldments with denotations spanning from W₁ to W₅, along with their fluence energies and corresponding UTS. The five weldments' chemical composition analysis, microstructural analysis, BHN, CVN, and weld factor, were carried out. Weldment W₂ was found to have the best mechanical properties, chemical composition, as well as microstructure.

The Vogel Approximation method has been successfully applied to optimally determine the fluence energy that could be used to make weldments with the desired satisfactory bead quality.

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