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Quality Improvement in the Fabrication of Nuclear Vessel of 20MnMoNi55 Low Alloy Steel

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Abstract
20MnMoNi55 is very critical material to weld, as the material is grouped into the P3 category according to the ASME Standard, which has lower weldability than other steel. The various parameters affecting the welding of 20MnMoNi55 like welding current, welding speed, voltage, wire feed rate, stick out etc. should be in optimizing range. In this research paper, the attempt has been made to optimize the welding process parameters using Design of Experiments with help of Taguchi method. A number of experiments were performed for finalizing the optimum range of welding current, welding speed and voltage using Submerge Arc Welding (SAW).

Keywords: *20MnMoNi55, Taguchi method, SAW*

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INTRODUCTION

Welding is the process of joining different materials. It is more economical and much faster process compared to both casting and riveting. SAW is one of the oldest automatic welding processes introduced in the 1930s to provide high-quality weld. The quality in SAW is mainly influenced by the independent variables such as welding current, arc voltage, welding speed and electrode stick out [1]. The prediction of process parameters involved in SAW is a very complex process [2]. Researchers have made many attempts to predict the process parameters of SAW to get a smooth quality weld. Taguchi method was used to formulate the experimental layout, to analyze the effect of each welding on welding performance, and to predict the optimal setting for each welding parameter [3].

The schematic diagram of the SAW process is shown in the Fig. 1. Submerge arc welding involves the formation of an arc between a continuous fed bare wire electrode and the work piece. The process uses the flux to generate protective gas and slag, and also helps to control the composition to deposited metal by providing the alloying elements to the weld pool [4]. Prior to welding, a thin layer of flux powder is placed on the work piece surface. The arc moves along the joint line with arc fully submerged into the flux. As the arc is completely covered by the flux, the heat loss is minimum. It provides no visible arc light and spatter-free welding. The flux, apart from the shielding the arc and the molten pool from atmospheric contamination, plays the following roles [5]:

1. The stability of the arc is dependent on the flux.
2. Chemical and thus the mechanical properties of the weld metal can be controlled by flux [6].
3. The quality of the weld may be affected by the quality and the quantity of the flux used over the arc [7].

Fig. 1: *Submerge Arc Welding at the Industry.*

EXPERIMENTAL DESIGN AND SET-UP

The experiment was conducted with the following set up:
Calibrated Lincoln semiautomatic SAW machine with constant voltage and rectifier type power source with 1000 A capacity was used to join the 20MnMoNi55 low alloy steel plate of 250 mm (L)×250 mm (W)×28 mm (T). Copper coated wire spool EF 1 of having 4.0 mm diameter was used to weld the material and UV 420 TTR, an agglomerated flux of fluoride basic type was used. Single V-groove of 6 mm root face and no root gap was created using plasma machine for welding as shown in Fig. 2. As the material is low alloy steel, the preheat, inter-pass and post heat temperature must be maintained before, during and after the welding respectively.

Groove Design

Table 1 shows the chemical composition of 20MnMoNi55 material with its alloying elements.

The mechanical properties of 20MnMoNi55 material like tensile strength, yield strength, % elongation and minimum impact strength are given in Table 2.

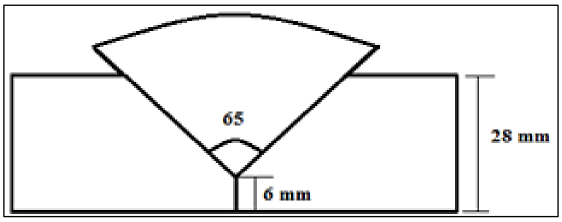

Fig. 2: *Groove Design.*

Table 1: *Chemical Composition of 20MnMoNi55 [8].*

Base Metal	% C	% Mn	% Mo	% Ni	% Si	% P	% S
20MnNoNi55	0.17–0.23	1.2–1.5	0.4–0.55	0.5–0.8	0.15–0.3	0.012 max	0.01 max

Table 2: *Mechanical Properties of 20MnMoNi55 [8].*

Mechanical Properties	Value (Single Digit are Minimum)
Tensile strength (MPa)	550–690
Yield strength (MPa)	345
% Elongation	18
Min. Impact strength (–10°C) (J)	150 J

WELDING PARAMETERS AND ITS EFFECTS

Welding Current

The welding current or amperage controls the deposition rate, the depth of penetration, and the amount of base metal melted. If the current is too high at a given travel speed, the depth of fusion or penetration may be excessive. The resulting weld may melt through the metal being joined. Excessively high current also leads to the waste of electrodes in the form of excessive reinforcement or over welding. Over welding increases weld shrinkage and causes greater distortion. Conversely, if the welding current is too low, inadequate penetration or incomplete fusion may result. Adjusting the welding current produces two effects. Increasing the current increases penetration and melting rate and increases the consumption of flux. Decreasing to a welding current that is too low produces an unstable arc.

Welding Voltage

Welding voltage adjustments vary the length of the arc between the electrode and the weld pool. If the overall voltage is increased, the arc length increases; if the voltage is decreased, the arc length decreases. Voltage has little effect on the electrode deposition rate, which is determined by welding current. The voltage mainly determines the shape of the weld bead cross section and its external appearance. Increasing the constant-current welding voltage and the travel speed may have the effect of producing a wider concave bead, increasing flux consumption, increasing porosity caused by rust or scale on steel, and increasing pickup of alloying elements from an alloy flux. Lowering the voltage produces a forceful, stiff arc that improves penetration in a deep weld groove and also resists arc blow. An excessively low voltage produces a high, narrow bead and causes difficult slag removal along the bead edges. Excessively high arc voltage may produce the following:

1. A wide bead shape that is subject to cracking.
2. Difficult slag removal in groove welds.
3. A concave-shaped weld that may be subject to increased undercut along the edges of fillet welds.

Welding Travel Speed
With any combination of welding current and voltage, effects of changing the travel speed conform to a general pattern. If the travel speed is increased, power or heat input per unit length of weld is decreased, and less filler metal is applied per unit length of weld, resulting in less weld reinforcement. Thus, the weld bead becomes smaller. Weld penetration is affected more by travel speed than by any variable other than current. This is true except for excessively slow speeds when the weld pool is beneath the welding electrode. Then the penetrating force of the arc is cushioned by the molten metal. Excessive speed may cause undercutting. Within limits, travel speed can be adjusted to control weld size and penetration. In these respects, it is related to current and the type of flux. Excessively high travel speeds promote undercut, arc blow, porosity, and an uneven bead shape. Relatively slow travel speeds provide time for gases to escape from the weld pool, thus reducing porosity. Excessively slow speeds may produce the following:

1. A bead shape that is subject to uneven wetting.
2. Excessive arc exposure, which is uncomfortable for the welding operator.
3. A large weld pool that flows around the arc, resulting in a rough bead and slag inclusions.

EXPERIMENTAL WORK

Experimental work has been carried out using the submerged arc welding for the optimizing of a process parameter of 20MnMoNi55 material using the EF 1 wire having 4.0 mm diameter. 20MnMoNi55 steel is a type of ferritic steel which is used as reactor pressure vessel (RPV) in the nuclear power plants. It is important to characterise critical mechanical properties like strength and fracture toughness to ensure safety of the reactor during operation as well as during unexpected accidental conditions. The ductile to brittle transition temperature (DBTT) increases due to the neutron irradiation of the RPV. In order to ensure safety of the reactor, the fracture toughness of the steel used as RPV should be sufficiently high in the DBTT regime. The Lincoln electric arc generator machine was used for the power source. For the welding of 28 mm thickness test piece, different processes of welding like GTAW, GMAW, SMAW and SAW are available. But SAW has the higher deposition rate and the bead width and the bead height of the passes in this is much higher than any other process.

Table 3 indicates the data and value which was used during the welding of the test coupons like welding process, material, plate dimensions, flux, preheating and inter-pass and preheating temperature.

In DOE welding current, welding speed and voltage are expressed in terms of impact strength and hardness as shown in the Fig. 3.

Table 3: *Welding Condition.*

Welding process	Submerge Arc Welding (SAW)
Material	20MnMoNi55
Plate dimensions	250 mm×250 mm×25 mm
Filler wire	EF 1, 4.0 Diameter
Flux	UV420TTR
Preheating temperature	150°C
Inter pass temperature	200°C

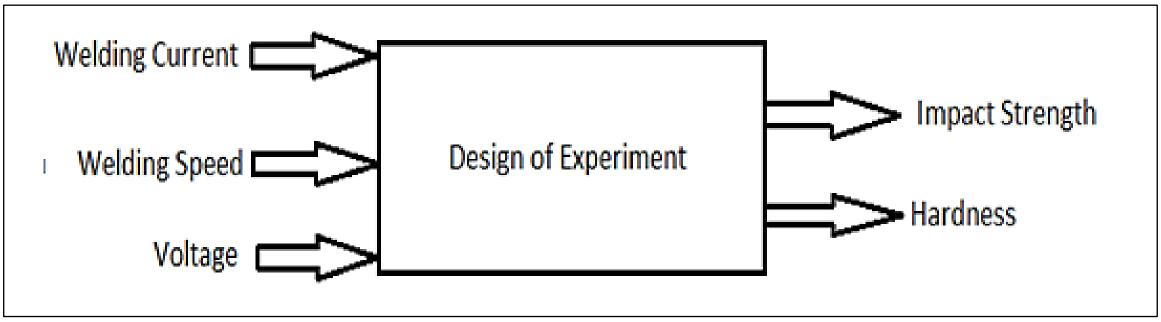

Fig. 3: *Schematic of DOE Model.*

Table 4: *Design of Experiments: Parameters and Range.*

Factor	Level 1	Level 2	Level 3	Level 4	Output
Current	350	450	550	650	Notch toughness hardness
Travel speed	300	400	500	600	
Voltage	28	30	32	34	

Table 4 shown below shows the factors and the level of the design of experiments which has three factors and four levels with two output variables.

Welding parameter for trials of SAW welding process was designed using Design of Experiments, Taguchi Method. Three factors and four levels were identified and are as shown in the Table below. Based on these factors and levels, 16 trials with different combinations were developed which is known as L16 modified orthogonal array.

Figure 4 shows the sample weld with optimized parameter marked with bold in Table 5.

RESULT AND DISCUSSION

Table 5 shows the results of all 16 trials with the impact strength and hardness and signal to noise ratio.

Fig. 4: *Test Samples as per Design of Experiments for Trial 11.*

Table 5 shows that the trial number 11 is giving the highest value of S/N ratio for impact, so, for the better result in the mechanical properties like toughness, the welding essential parameter like welding current, traveling speed and the voltage should be according to the trial number 11.

Fig. 5 shows the value of the impact strength; it shows that the best value of impact comes at 550 A welding current, 500 mm/min traveling speed and 28 V voltage. Table 6 shows the main effect plot with different levels.

Table 5: *Parameters with Output Result.*

Trial No.	Welding Current	Travelling Speed	Voltage	Impact	Hardness	S/N Ratio
1	350	300	28	123	303	41.798
2	350	400	30	136.5	252.5	42.702
3	350	500	32	144.5	228	43.197
4	350	600	34	156.5	243.5	43.890
5	450	300	30	128.5	346.5	42.178
6	450	400	28	134.5	335	42.574
7	450	500	34	166.5	235.5	44.428
8	450	600	32	129	225	42.211
9	550	300	32	122.5	317.5	41.762
10	550	400	34	136.5	324.5	42.702
11	**550**	**500**	**28**	**173**	**272**	**44.760**
12	550	600	30	151.5	306	43.608
13	650	300	34	108	354.5	40.668
14	650	400	32	117.5	347	41.400
15	650	500	30	131	324	42.345
16	650	600	28	141.5	305.5	43.015

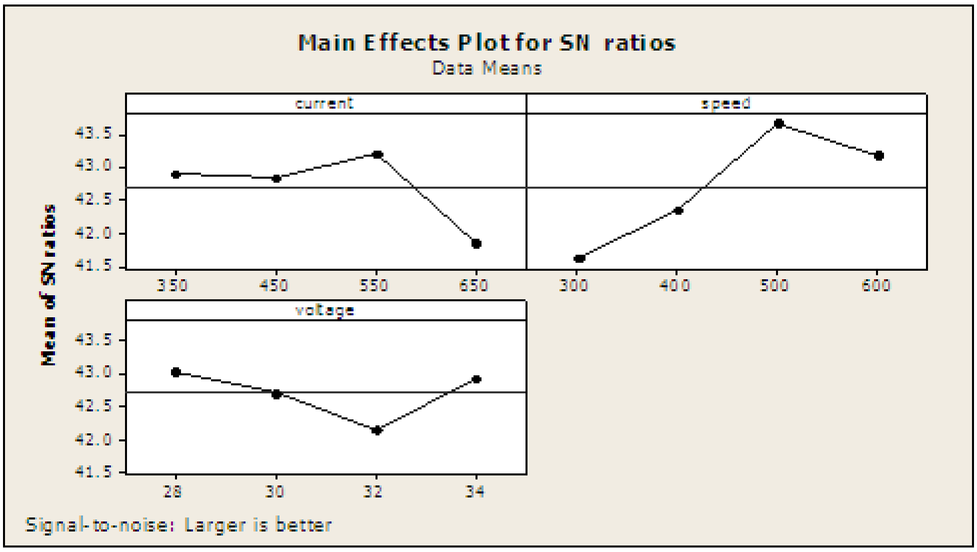

Fig. 5: *Main Plot of S/N Ration for Impact.*

Table 6: *Main Effect Plot.*

Main Effect Plot			
Taguchi analysis: Impact vs. Current, Speed, Voltage			
Level	**Current**	**Speed**	**Voltage**
1	42.9	41.6	43.04
2	42.85	42.35	42.71
3	43.21	43.68	42.14
4	41.86	43.18	42.92
Delta	1.35	2.08	0.89
Rank	2	1	3

Here we can see from the above that the significance of the welding speed is higher among all three, followed by welding current and voltage.

The effect of the parameter on the impact comes in the way like:
1) Weld travelling speed,
2) Welding current, and
3) Voltage.

VALIDATION OF THE SOFTWARE RESULT

After the performance of 16 experiments, it can be said that the the optimum parameters values are as under based on experimental and software results.
Welding Current: 550 A,
Welding speed: 500 mm/min
Voltage: 28 V

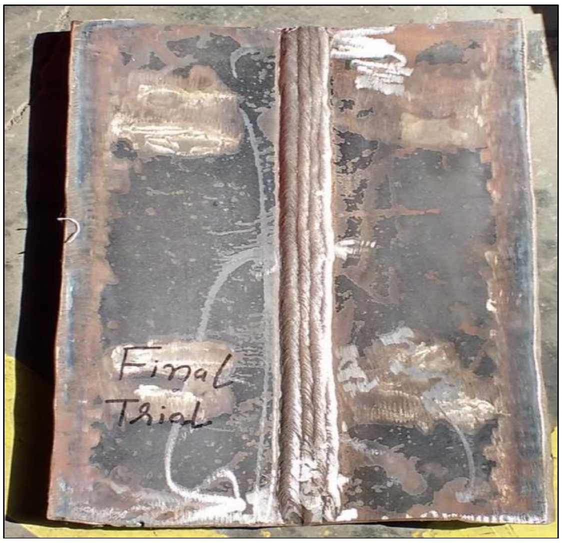

Fig. 6: *Final Trial as per Optimized Parameters.*

After the 16 experiments performed according to the Taguchi method, the conclusion has arrived that the major parameters, (1) welding current 550 amps, (2) welding speed 500 mm/min and the voltage 28 V, is the optimized range according the experimental results and the software results. To prove the software result, another experiment has been performed with the same parameters which had the final optimized range as shown in Figure 6.

So, from the above, we can conclude that the effect of voltage on the toughness property is lower and the effect of traveling speed on the toughness is maximum.

The results obtained from the previous optimized range and the final trial which was welded using the optimized range, both are best values; so, here it proves that the optimized range is true with the help of software as well as the actual experimental value.

Here, there are six impact specimens, which were tested to prove the software result with help of experimental results and at different six points, the hardness was measured, the results of impact and hardness are given in Table 7.

Contour Plot

Fig. 7 shows the contour plot of current vs. Speed, and dark region shows the better result of impact strength.

Fig. 8 shows the macro-structure after the submerged arc welding of test plates.

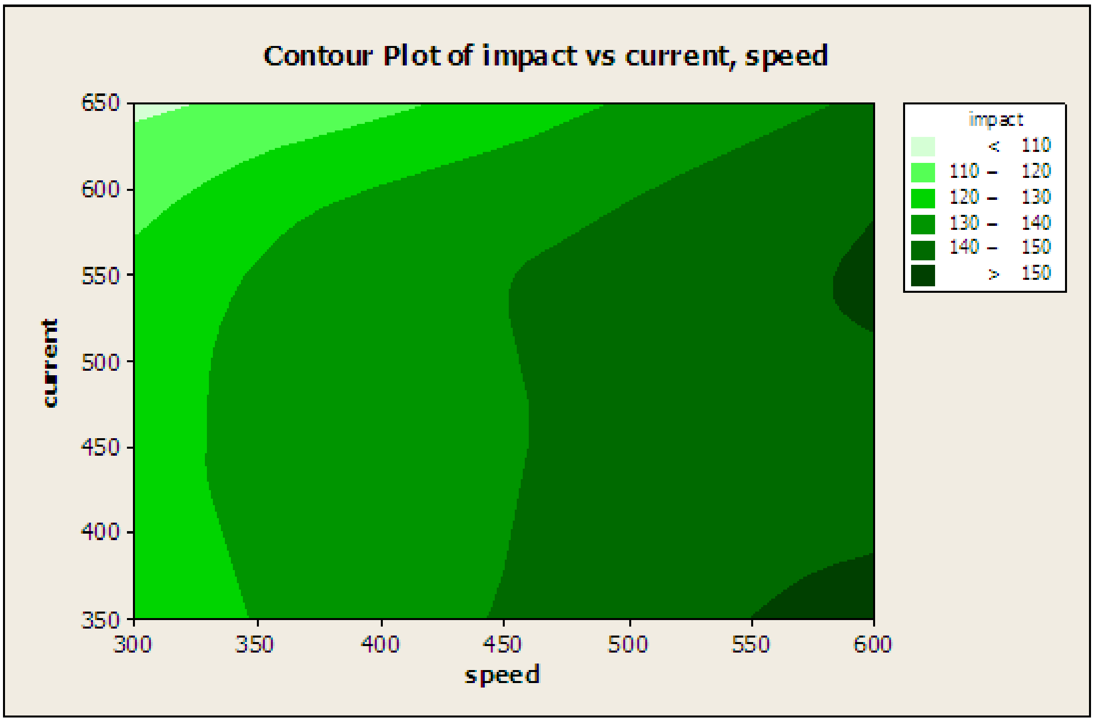

Fig. 7: *Contour Plot.*

Fig. 8: *Macro-Structure of Trials 11.*

Table 1: *Final Result of Impact and Hardness.*

Impact (J)	Hardness (HV)
170	271
176	278
158	269
180	279
178	277
176	280

CONCLUSION

After performing 16 experiments with changing the variables we conclude that there are following effects of the welding parameters i.e. welding current, welding voltage and welding speed on the mechanical properties:

As the heat input increases it will make the material more hard and inturn brittle. The material which has higher hardness will not sustain the impact load and it will fail in the impact test, in trial number 13 to 16, heat input is higher leading to brittle structure with less impact values.

Welding speed and welding current are the two main important factors for SAW welding to achieve required impact strength. Heat input is the significant factor which directly affects the impact value, higher the heat input lower the impact strength.

On increasing the welding current and decreasing the welding speed we get the higher input, at that kind of condition the value of impact strength is much lower. Hardness is also the affected by the heat input; higher the heat input higher the hardness.

Voltage has no significant effect on impact value as compared to the welding speed and welding current but it affects to penetrate the metal properly. For the welding of 20MnMoNi55 material, pre-heating, post heating and inter-pass temperature must be maintained according to the requirement.

From the above discussion, it can be said that welding speed and the welding current are two parameters which have higher significant impact on the hardness and strength.

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