Prediction of Mechanical Properties of Al Alloy 6061-T6 by using GMAW

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Abstract— Aluminum and its alloys are having variety of applications in today's industrial scenario. The use of Al and its alloys are increasing day by day due to its specific properties, like light weight, high strength, and excellent corrosion resistance. Present study is conducted on Aluminum 6061 tempered alloy by using semi-automatic MIG welding model PRO-4200 with current range 10A-420A and voltage range 10V-41V.The studies are carried out by using British Welding specification; nine samples are prepared for toughness studies and tensile strength. The CVN samples are prepared by ASTM-E-23 standard. Also tensile specimens are prepared by using ASTM-E28/E8M-09 for identifying the tensile strength of weld specimen. The testing is carried out by using Universal testing machine with hydraulic grip. However the fracture toughness studies are carried out by using Charpy V-Notch testing machine, Pendulum Impact Tester Model AI - IT 30. The maximum and minimum UTS noted for the welded joint is 196Mpa and 84 MPa for 0.80 KJ/mm and 0.3 KJ/mm heat input respectively. However the Maximum and minimum CVN value noted 26 Jules and 8 Jules for 0.80 KJ/mm and 0.30 KJ/mm respectively. The maximum failures of large structures are observed from the Heat affected zone of welding. The HAZ can be minimizing by selecting the appropriate welding parameters like current, voltage and speed etc. S/N ratio analysis and ANOVA analysis are carried out for finding the optimal level of process parameters and significant effect of process parameters on Quality characteristics respectively. By considering above the study is undertaken by conducting the experimental work for getting defect free, robust and cost saving weld structures.

Key words: MIG welding, Aluminum Alloy 6061, CVN Test, UTS Test, ANOVA

I. Introduction

Aluminum alloys are alloys in which aluminum is the predominant metal. It covers the typical alloying elements like copper, magnesium, manganese, silicon, tin and zinc. An Al and aluminum alloy plays an important role in engineering and metallurgy field because of fabrication characteristics like formability. Higher strength 6061 alloy finds broad use in welded structural members such as Truck and marine frames, front and rear suspension frames, hydraulic valve bodies, Jigs, fixtures, gears, fasteners and pipelines. The most common temper 6061 aluminium alloy is T6-solution heat treated and artificially aged.

MIG welding has been used widely to join pieces of aluminum alloys in construction of automotive frame, marine frame, and pressure vessels. In the MIG welding process, a gas shield is usually used to protect the arc and the weld from atmospheric contamination, an electric potential is established between the electrode and the work piece that needs to be welded, such electric potential will cause the current to flow and consequently a thermal energy will be generated in the partially ionized inert gas. The circuit diagram of GMAW is illustrated in figure 1. It consist of various parts as 1) welding power source and cables 2) Inert Gas cylinder 3)filler wire and wire feed unit 4) welding gun and cooling water supply. Various Inert gases are used in MIG welding, like Argon, carbon dioxide, Argon and CO2 mixtures, argon mixtures with oxygen or helium mixtures. [13]

K. P. Kolhe and C. K. Datta [1] were studied microstructure, phase analysis; mechanical properties and HAZ width of submerge arc welded specimens for different passes with different heat inputs. They investigated the microstructure of 16mm thick mild steel plate was carried out using metallurgical microscopy with image analysis software. The hardness, impact energy and micro hardness of multipass welded joint were tested by using Rockwell hardness testing machine and charpy V- notch testing machine. The proportionate value of micro hardness was observed for low heat input whereas for increased heat input variations in hardness value was observed. They concluded welding parameters of SAW used to control the microstructure, phases and mechanical properties of welded joint and help to get the robust welded structure of mild steel. P.A.Stathers, et al. [2] were found relationship between hardness and tensile properties for HAZ in Al alloy 6061-T651. They used Vickers micro hardness testing machine for measuring hardness and tensile testing by using IN-STRON 8501 Servo-hydraulic testing machine for MIG welded specimens. They were found that hardness is a sole variable for estimating the yield and tensile strength of the heat affected zone (HAZ) in welding. The relations have been expressed mathematically as follows 0.2% Yield stress = 2.9263 HV – 44.289… (1) Tensile strength = 2.4079 HV + 46.39 … (2) X.Yue, et al. [3] were investigated the effect of heat input and preheats on the HAZ and hydrogen induced cracking tendency of BA-160 (Blast resistance steel). Welding of specimens were carried by using GMAW with (Ar+15% H2) gas shield. Lower critical stress was checked by implant test and hardness test carried using Vickers hardness testing machine. Microstructures of welded specimens were studied using optical microscopy and transmission electron microscopy (TEM). Fracture behavior after implant test observed by Scanning electron microscopy (SEM). They observed lowest hardness in the course grained HAZ of weld specimen. However the hardness of the fusion zone is lower compared to HAZ and Base metal for low heat input. Whereas fusion zone hardness decreases as compared to using low heat input without preheating. When welded with high heat input with preheating, are beneficial to reduce the cracking tendency for BA-160. Because the lower critical stress (LCS) with preheat is higher than that without preheat. K.S.Bang, et al. [4] were studied HAZ hardness and tensile strength in welds made with different heat inputs in fine-grained ferritic-pearlitic TMCP steel. First they estimated softening zone by micro hardness distribution using Vickers hardness Test, after that the degree of softening was also predicted using an established microstructural evolutional model and al rule of mixtures. Microsturural study along softening zone was carried out with optical microscope, tensile strength of MIG Welded specimens tested with universal testing machine. They observed that softening zone width increased continuously to 10 KJ/mm, the minimum hardness in the softened zone decreased slightly after a rapid decrease up to 6KJ/mm due to the softening effect, welded join tensile specimens were broken at the HAZ instead of Base metal. The reduction of tensile strength was similar to that of hardness and showed a maximum of 20% at 6 KJ/mm. M.Miyazaki, et al.[5] were investigated the influence of the grain size on the weld heat affected zone cracking of Gas metal arc(GMA) welds on A 6061 was studied using a varestraint test. The maximum crack length increased when the grain size was increased from 0.005 to 2mm. the crack lengths were measured using a magnifying glass eyepiece, crack photographs taken by Scanning electron microscopy (SEM). They observed the solidus temperature was increased by Si and decreased by Mg, the maximum crack length was longer in the case of 4043(silicon based filler metal) than 5356(Magnesium based filler metal). Filler metals may affect the weld chemistry and respective mechanical and thermodynamic properties. S.Y.Marchant [6] was investigated the effect of welding current on welding speed and hardness of heat affected zone and weld metal of mild steel material, mild steel weldment was welded under varying welding current by using MMAW process in 1G position. The test specimen was then grinded and hardness of each specimen was measured at three points i.e. Parent metal, HAZ and weld metal by using Brinell hardness tester. It was observed that with increase in welding current melting rate of electrode was increased hence welding time was reduced. So welding speed was increased. With increase in welding current hardness of HAZ and weld metal was also decreased due to increase in heat input. A.N.Boob and G.K.Gattani [7] were studied effect of manual arc welding process parameters like heat input and welding speed on width of Heat affected zone for Ms 1005 Steel. All the samples were dipped in 2% nital agent and finally dried by using air blower. The microstructure of base metal, weld zone as well as heat affected zone of all the samples have been carried out by optical microscope having 400X zoom. It was observed that welding speed increase the width of HAZ decreases and by increasing heat input decreases the toughness. C.Rodriguez, et al. [8] Were used the small punch test (SPT) for the mechanical characterization of small areas such as the different zones of HAZ in any material, as it uses very small test specimens (10x10x0.5mm3). SPT can be used to obtain mechanical properties like yield strength, ultimate strength and elongation of small regions. This test was used to evaluate how these properties change inside the HAZ of a welded joint made on quenched and tempered steel. During test the applied load and deflection of the specimen central point (DCP) measured with the help of a crack opening displacement (COD) type extensometer. . Micro hardness of specimen was measured by using Vickers micro hardness testing machine. Load deflection curve is the only information collected in the small punch test. Mechanical properties were found by using some mathematical relations. R.R.Ambriz, et al. [9] were investigated Local mechanical properties of a weld zone, in a 6061-T6 aluminum alloy subjected to modified indirect electric arc technique. The mechanical properties of the base metal, the weld metal and the heat affected zone (HAZ) were determined by means of usual and instrumented indentation testing, as well as micro-traction testing. It showed the intress of the hardness mapping for identifying the different zones resulting from the welding process J.A.Vargas, et al.[10] were studied yield strength and microstructure during welding (GMAW) for different heat inputs. A transient thermal analysis was developed to model the problem in a numerical form using finite element method (FEM) and these results were compared with experimental data showing good agreement. All the mechanical tests carried out by using universal testing machine, Hardness testing on Vickers microdurometer and temperature measurements by Thermocouples. The methodology and results of this work could be used as a tool to optimized welding processes based on the prediction of mechanical properties such as yield strength and micro hardness. S.D.Ambekar and S.R.Wadhokar [12] were studied Parametric Optimization of Metal inert gas welding process by using Taguchi method on stainless steel AISI 410.Sixteen experimental runs (L16) based on an orthogonal array Taguchi method were performed. The ANOVA and signal to noise ratio is applied to identify the most significant factor and predicted optimal parameter setting. This paper presents the effect of welding parameters like welding speed, welding current and wire diameter on penetration.

II. DESIGN OF EXPERIMENT

Pre-selected weld parameters are selected before to the start of the welding process and they cannot be changed during the welding process. These parameters, variables, include the electrode type, size, the torch nozzle size, and the shielding gas type. The indirect weld parameters of the welding process include the arc voltage, arc current, travel speed, shielding gas, and wire feed rate. Indirect weld parameters are parameters that can be modified in process. Once the pre-selected variables are properly chosen, the quality of the weld can be controlled through proper selection and modification of the indirect weld parameters. In any welding process, the input parameters have an influence on the weld joint mechanical properties. By varying the input process parameters combination the output would be different welded joints with significant variation in their mechanical properties. The input parameters play a very significant role in determining the quality of a welded joint. Generally most of the researcher uses Taguchi approach for Design of experiment (DOE) because it can significantly reduce time required for experimental investigations but in present investigation the DOE carried out nine experiments as per welding current range from 75A to 275A having nine levels, welding voltage range from 20V to 26V having three levels and welding speed constant. Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, used as objective functions for optimization, help in data analysis and prediction of optimum results.

A. Signal to Noise Ratio (S/N)

The following three types of S/N ratio are employed in practice:

- Smaller-The-Better: S/N = -10 Log_{10} [mean of sum of squares of measured data]
- Larger-The-Better: S/N = -10 Log_{10} [mean of sum squares of reciprocal of measured data]
- Nominal-The-Best: S/N = 10 Log_{10} [square of mean / variance]

III. EXPERIMENTAL PROCEDURE

The experiments are carried out on Semi-automatic Metal Inert Gas arc welding machine model PRO-4200 in a single Run which is shown in figure 2. Argon gas with gas flow rate 25 L/min used as a shielding gas to protect the arc and weld bed from atmospheric contamination. 1.2mm diameter ER 4043 Filler wire used to weld the test specimens. The material chosen for the present study was aluminium alloy 6061-T6. Sample of 150mmx100mmx10mm size has been used as a work piece material. The chemical Composition results are shown in Tabe-1. The aluminium alloy 6061-T6 Sheet is converted in to nine samples as per desired work piece size by using cutting operation. 60o V edge preparation was made on these specimens as shown in figure 3. Set up was made by tack welding. Root gap and root face kept 2mm each. Welding process parameters taken as per Table-2. Welding current, Welding Voltage varied and Welding speed, Gun Nozzle tip to plate distance, and gas flow rate remained constant. A specific code were made for each welded specimen in which “M” assigned for MIG welded specimen, “A61” assigned for aluminium alloy 6061-T6 and The number followed by this code indicates Experiment number. Total nine experiments were carried out within the welding current range from 75A to 275 A. After welding CVN Sample prepared as per ASTM-E-23 Standard from the MIG welded specimens shown in figure 4(a) & (b). Toughness test were made using the Charpy impact test machine, Pendulum impact model- AI-13.Tensile samples were prepared as per ASTM-E8/E8M-09 Standard from the MIG welded specimens which is shown in figure 5(a) & (b). Tensile test were made using Universal Testing Machine (UTM) with hydraulic grip.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Min	0.40	0.0	0.15	0.0	0.8	0.04	0.0	0.0	98.61
Max	0.8	0.7	0.40	0.15	1.2	0.35	0.25	0.15	95.8

Table 1. Chemical Composition of 6061 AA

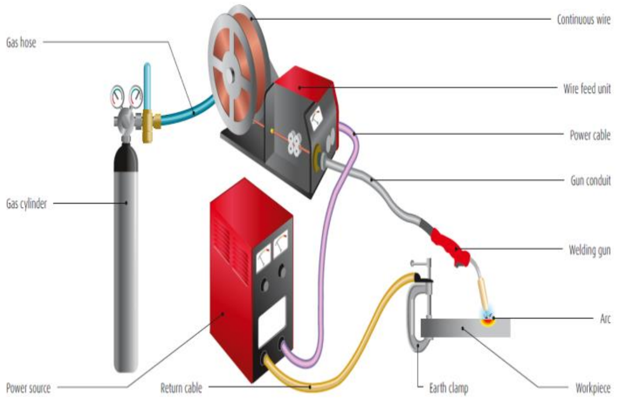

Fig. 1: GMAW Machine Setup [13]

Fig. 2: Gas Metal Arc Welding machine

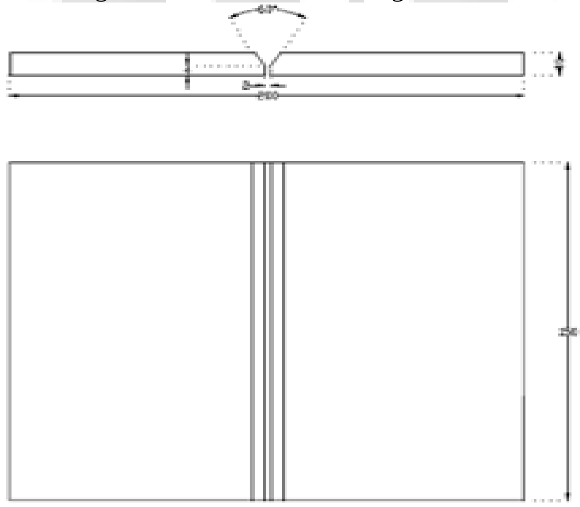

Fig. 3: MIG Welding Sample

Exp No.	Welding current (I) in Ampere	Welding Voltage (V) in Volt	Welding Speed (S) in mm/min	Heat Input in KJ/mm
1	75	20	300	0.300
2	100	20	300	0.400
3	125	20	300	0.500
4	150	23	300	0.690
5	175	23	300	0.805
6	200	23	300	0.920
7	225	26	300	1.170
8	250	26	300	1.300
9	275	26	300	1.430

Table 2. Welding parameters and their levels

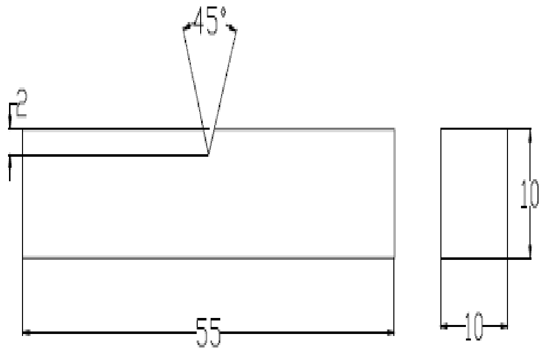

Fig. 4: (a)

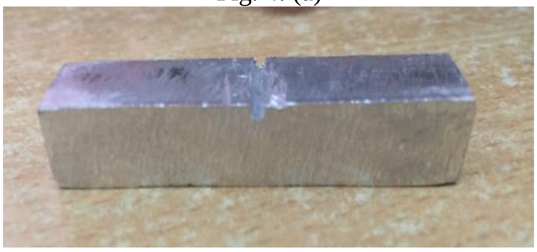

Fig. 4: (b)

Fig. 4: (a) & (b) Charpy Impact Test Specimen as per ASTM-E-23

Fig. 5: (a)

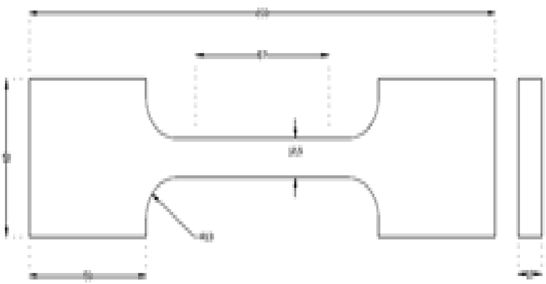

Fig. 6: (b)

Fig. 5(a) & (b): Tensile Testing Sample as Per ASTM-E8/E8M-09

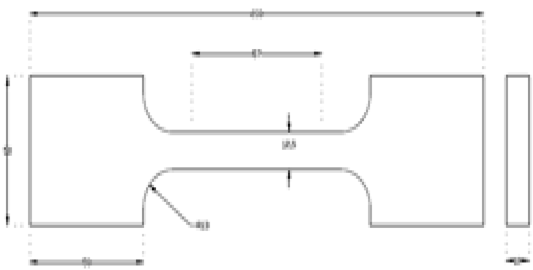

Fig. 5: (b)

Fig. 5(a) & (b): Tensile Testing Sample as Per ASTM-E8/E8M-09

IV. ANALYSIS OF S/N RATIO

In S/N Ratio analysis the term 'Signal' represents the desirable value (mean) for the output quality characteristics like Penetration, Toughness and Tensile strength. The term 'Noise' represents the undesirable value (standard deviation) for the output quality characteristics. Therefore S/N Ratio is the ratio of Mean to Standard Deviation and used to measure the quality characteristic deviating from the desired value. Mathematically it is represented as

$$S/N = -10 \log (M.S.D.) \qquad (1)$$

Where, M.S.D. is the mean square deviation for the output quality characteristic. For obtaining optimal welding performance, Larger-The-Better quality characteristic for penetration, Toughness and Tensile strength must be taken. The M.S.D. for Larger-The-Better quality characteristic can be expressed as.

$$M.S.D = 1/n \left(\sum 1/y^2\right) \qquad (2)$$

Where 'n' is the number of measurements in a trial / row, in this case, n=1 and y is the measured value in a run / row. S/N ratio values are calculated by using equation 1 and 2. Experimental results (the output characteristics values) and their corresponding S/N ratio values are listed in table 3. Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the welding parameters is the level with the greatest S/N value. The S/N Response table Performance characteristics are shown in Table No.4 to 6.

	Penetration in (mm)	S/N ratio	Toughness in (Joule)	S/N ratio	Tensile Strength in (MPa)	S/N ratio
MA61-1	5.0	13.98	08	18.06	84	38.48
MA61-2	4.0	12.04	09	19.08	124	41.87
MA61-3	4.5	13.06	14	22.92	127	42.07
MA61-4	6.0	15.56	12	21.58	152	43.63
MA61-5	7.0	16.90	26	28.30	196	45.84
MA61-6	6.0	15.56	14	22.92	161.6	44.17
MA61-7	6.5	16.26	04	12.04	176	44.91
MA61-8	4.8	13.62	10	20	118.4	41.46
MA61-9	3.0	9.54	10	20	122.4	41.75

Table 3. Experimental Results for Performance characteristics and S/N ratio

Welding Parameters	Mean S/N Ratio of Welding parameter levels								
	1	**2**	3	4	**5**	6	7	8	9
Current	13.98	12.04	13.06	15.56	**16.90**	15.56	16.26	13.62	9.54

Voltage	13.02	**16**	13.14	-	-	-	-	-	-
Speed	**14.06**	-	-	-	-	-	-	-	-

Table 4. S/N response table for Penetration

Welding Parameters	Mean S/N Ratio of Welding parameter levels								
	1	**2**	3	4	**5**	6	7	8	9
Current	18.06	19.08	22.92	21.58	**28.30**	22.92	12.04	20	20
Voltage	20.02	**24.26**	17.34	-	-	-	-	-	-
Speed	**20.55**	-	-	-	-	-	-	-	-

Table 5. S/N response table for Toughness

Welding Parameters	Mean S/N Ratio of Welding parameter levels								
	1	**2**	3	4	**5**	6	7	8	9
Current	38.48	41.87	42.07	43.63	**45.84**	44.17	44.91	41.46	41.75
Voltage	40.80	**44.54**	42.70	-	-	-	-	-	-
Speed	**42.68**	-	-	-	-	-	-	-	-

Table 6. S/N response table for Tensile strength

V. AVOVA (ANALYSIS OF VARIANCE)

The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the quality characteristic. ANOVA help in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. The sum of square (SS), the degrees of freedom (D), the variance (V) and the percentage of contribution to the total variation (P) are used in ANOVA; Results are illustrated in Table No.7 to 9.

Welding Parameters	DOF	SS	MS	P %	Rank
Current	8	26.60	3.32	61.70	1
Voltage	2	15.95	7.97	36.99	2
Speed	0	0.56	0.56	1.30	3
Total	10	43.11		100	

Table 7. Results of ANOVA for Penetration

Welding Parameters	DOF	SS	MS	P %	Rank
Current	8	80.28	10.03	52.22	1
Voltage	2	71.40	35.7	46.44	2
Speed	0	2.06	2.06	1.34	3
Total	10	153.7		100	

Table 8. Results of ANOVA for Toughness

Welding Parameters	DOF	SS	MS	P %	Rank
Current	8	28.36	3.54	72.53	1
Voltage	2	15.86	7.93	40.56	2
Speed	0	-5.12	-5.12	-13.09	3
Total	10	39.10		100	

Table 9. Results of ANOVA for Tensile Strength

VI. CONFIRMATION TEST

In order to validate the methodology, a confirmation test was performed by setting the optimum conditions for three welding parameters are illustrated in Table No.10.The predicted S/N ratio can be calculated using this combination of parameters with the following equation.

$$[S/N]_{Predicted} = [S/N]_{Mean} + \sum_{i=1}^{y} ([S/N]_i - [S/N]_m) \quad (3)$$

Where [S/N] m is the total S/N ratio, [S/N] i is the mean S/N ratio at the optimal level, and y is the number of main design parameters that affect the quality characteristic.[14] Table 11, 12 and 13 shows good agreement between the predicted and the experimental depth of penetration, Toughness and Tensile strength respectively. The optimum combination of process parameters is almost matching with the parameters used for producing track 5 in the present study.

Serial No.	Welding parameters	Penetration		Toughness		Tensile strength	
		Level	Value	Level	Value	Level	Value
1	Current (A)	5	175	5	175	5	175
2	Voltage(V)	2	23	2	23	2	23
3	Speed(mm/min)	1	300	1	300	1	300

Table 10. Optimum process parameters for quality characteristics

	Parameters			S/N ratio		Performance values for penetration(mm)	
	Current (A)	Voltage (V)	Speed (mm/min)	Prediction	Experiment	Prediction	Experiment
Optimum level	5	2	1	18.84	16.90	7.9	7.0
Optimum Value	175	26	300				

Table 11. Confirmation Testing for Penetration to validate the approach.

	Parameters			S/N ratio		Performance values for Toughness (joule)	
	Current (A)	Voltage (V)	Speed (mm/min)	Prediction	Experiment	Prediction	Experiment
Optimum level	5	2	1	32.01	28.30	39.8	26

Optimum Value	175	23	300				

Table 12. Confirmation Testing for Toughness to validate the approach

	Parameters			S/N ratio		Performance values for Tensile strength (MPa)	
	Current (A)	Voltage (V)	Speed (mm/min)	Prediction	Experiment	Prediction	Experiment
Optimum level	5	2	1	47.7	45.84	223.8	196
Optimum Value	175	23	300				

Table 13. Confirmation Testing for Tensile strength to validate the approach

VII. Result and Discussion

From the available results of Quality characteristics the direct effect of Heat Input on the Depth of Penetration, Toughness of weld joint and ultimate tensile strength of the weld joint was studied and plotted as shown in Figure 6, 7 and 8.

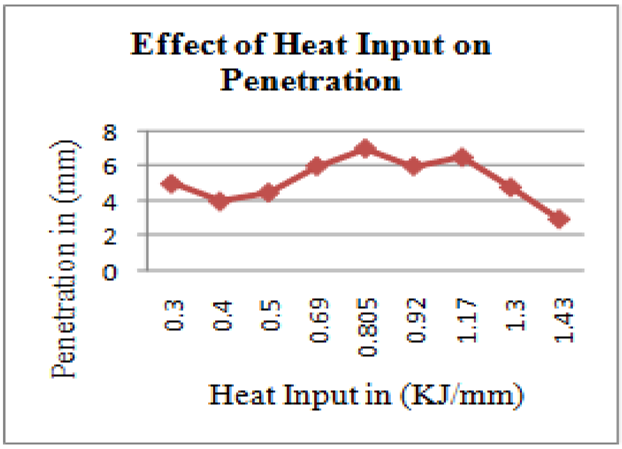

Fig. 6: Relation between Heat Input and Depth of Penetration

Figure 6 depicts the direct effect of Heat Input on Depth of Penetration. From the figure it is observed that the value of Penetration increases as Heat Input increases till 0.805KJ/mm. after that value of penetration decreases against the increment in Heat input. The maximum penetration 7 mm observed at 0.805KJ/mm of heat input and minimum penetration 3 mm observed at the peak value of Heat input 1.43KJ/mm.

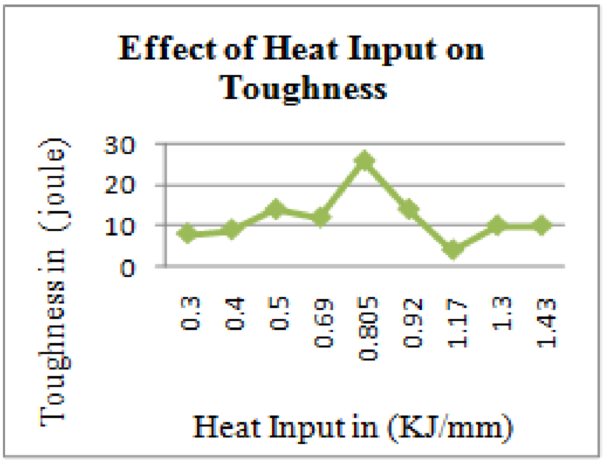

Fig. 7: Relation between Heat Input and Toughness of weld joint

Figure 7 depicts the direct effect of Heat Input on Toughness of weld joint. From the figure it is observed that the value of Toughness increases till 0.805KJ/mm. after that value of Toughness decreases till 1.17KJ/mm and sudden increment in toughness at heat input 1.3KJ/mm after that constant value of toughness observed. The maximum toughness 26 joule observed at 0.805KJ/mm of heat input and minimum toughness observed at 1.17KJ/mm of heat input.

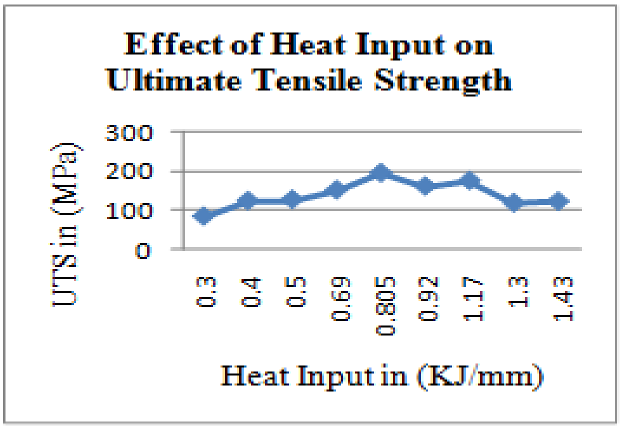

Fig. 8: Relation between Heat Input and Ultimate tensile strength of weld joint

Figure 8 depicts the direct effect of Heat Input on Ultimate tensile strength of weld joint. From figure it is observed that the value of UTS increases as heat input increases till 0.805KJ/mm. after that value of UTS decreases as heat input increases. The maximum value of UTS 196 MPa observed at heat input 0.805KJ/mm and minimum value of UTS 84 MPa observed at heat input 0.3KJ/mm.

VIII. Conclusions

The following conclusions were arrived at based on the present investigations.

1) Taguchi optimization method was applied to find optimal process parameters for penetration, Toughness and Tensile strength of weld joint. Signal to noise ratio(S/N) analysis and analysis of variance (ANOVA) were used for the optimization of welding parameters.
2) The welding current has the most significant influence on the Tensile strength of weld joint, depth of penetration and toughness. Welding Voltage is second

most significant factor. The effect of welding Speed is very small in comparison.

3) 3. The percentage of contribution of the welding current is 72.53% for Tensile strength, 61.70% for depth of penetration and 52.22% for Toughness. The percentage of contribution of the welding voltage is 46.44% for Toughness, 36.99% for tensile strength, 40.56% for penetration.
4) The confirmation test demonstrated good agreement between the predicted and the experimental values of quality characteristics.
5) The optimized welding parameters are obtained at a welding current 175A, welding voltage 23 V, and welding speed 300 mm/min.
6) The common thing is observed during all the tests that maximum values of quality characteristics observed at heat input 0.805 KJ/mm.

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