Optimization of MIG Welding Productivity with the Aid of Artificial Neural Network.

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ABSTRACT

Automated MIG welding has huge industrial application especially in ship building where long lengths of radiographic quality welding is necessary. This constant demand for high quality welding on varying base metal dimensions without sacrificing productivity is something that have posed a problem for these industries since the advent of automated welding machines. Welding parameter optimization for a given application is mostly done using a series of trial runs using a variety of power settings and the most acceptable setting is taken after adequate metallurgical examination of the welds. However this is a time-consuming and tedious process especially in industrial establishments. Deterministic relations between the several welding parameters are hard to come by and they are not accurate in the wide range of welding demands that the industries call for. Artificial Neural Network can provide a possible solution to this problem by predicting optimized variables.

A large number of trial runs have been made using the MAILAM ® MGA 40 flux cored electrode on a large number of mild steel plates of varying thickness at the Welding Technology Centre, Jadavpur University. Voltage, torch travel speed, wire feed rate and current were some of the variables that were taken into account. The developed network optimized the values of Wire feed rate and current drawn from supplied data which include torch travel speed, voltage and plate thickness. Apart from these welding parameters another aspect of industrial large scale welding that has been taken into account is operator productivity. Most welding productivity optimization studies so far has not taken into account the actual time study of welding. Since operator activities like fettling, interpass cooling etc. has a great bearing on welding productivity, the present study aims at giving a more complete picture of welding productivity optimization.

Key Words: MIG welding, welding productivity, artificial neural network, welding parameter optimization, welding time study

INTRODUCTION

Industries seeking higher production rates and weld quality improvements are increasingly interested in robotic gas metal arc welding (GMAW). In robotic GMAW, it is important to minimize robot cycle time so that the highest volume of products are produced per hour and maximum return on investment can be achieved. A component of minimizing cycle time is maximizing the welding travel speed, to which the weld cycle time is inversely proportional (ref 1). However a high welding travel speed decreases the deposition rate and the weld needs to be completed in a number of passes. However multirun weldings pose a problem of their own in terms of decreasing productivity as time is wasted in fettling the slag layers from the previous runs. A way to increase the deposition rate even at relatively high welding speeds is to increase the electrode feed rate. However an increased feed rate is accompanied by increase in the amperage (ref 2) and hence a higher heat input, which may lead to excessive metallurgical damage. So the key to acceptable large scale welding in terms of both metallurgical properties as well as productivity is to calculate the particular set of optimized welding parameters for a given welding application.

Perhaps the most important variable in case of arc welding is the heat input required for the joint. (ref 3) The heat input in joules of energy given per unit length of the welding is given by (ref 4)

$$H = \frac{V*I}{(s/60000)}*\eta \qquad \text{Equation 1}$$

Where
V = Potential difference applied in Volts
I = Current through the arc in Amperes
S = welding speed in mm/min
η = arc efficiency factor

MIG welding are almost exclusively carried out using a constant voltage power supplies (ref 5) and the operator is at liberty to set any desired voltage that is suitable. However the current developed across the arc cannot be maintained directly and there exists no front panel control which lets one select the current and hence the heat input. Current must be indirectly set by varying the wire feed rate. However this exact relation between the voltage and wire-feed rate and current is non-deterministic and statistical modeling has been done to establish a function which calculates current and hence the heat input developed in a weld. This heat input calculation is the basis by which we have considered metallurgical soundness of the welding. If we use a very low heat input we may have incomplete fusion or penetration while too high a heat input may result in a burn through or very high metallurgical damage. The number of runs required for the welding was calculated by the volume of the "V" Groove per unit weld length divided by the amount of metal deposited per unit length for each run

A detailed study of the productivity of the welding operation was also undertaken to take into account the human element into the operation in the form of operator efficiency (ref 6). A time study was done as a qualified welder completed a multirun test weld using a Ferro-Curves Universal welder. The data obtained both from the neural network as well as the time study was incorporated into the final optimized variables.

METHODOLOGY

MIG welding being a versatile welding method, it can involve a large variety of base metal as well as electrodes. For the present study a single metal to electrode combination commonly used was chosen to display the efficacy of the approach. All weldings were done on Hot rolled 0.15% C steel using MAILAM ® MGA 40 flux cored electrode. Table 1 (ref 7) shows the data sheet for the said electrode. CO2 gas at 12 LPM was used as shielding gas and all welding currents and voltages were kept close to the prescribed limits given in the electrode manual. All weldings were done following ISO 15792-1standard (ref 8) groove design (Figure 1) and weld runs were staggered one top of another to slowly and uniformly build up the joint (Figure 2).

MGA - 40 Low Alloy Steel Gas Shielded Flux Cored Wire

Mailam MGA -40 is a basic alloyed flux cored wire conforming to AWS A 5.29 E110 T5-K4

Applications	Specially designed for welding of high tensile fine grained quenched and tempered steels like USS T1 and other similar grade steels used in earth moving equipment etc.
Weld Metal Chemistry (With CO2 shield)	C=0.10% Max Cr=0.25 - 0.60% Mn=1.30 - 2.0% Mo=0.30 -0.60 % Si=0.60% Max Ni=1.75 - 2.50 % Max S=0.03% max P=0.03% max
Typical all weld mechanical properties (With CO2 Shield)	U.T.S =770N/mm 2 Min Y.S=680N/mm 2 Min Elongation(%)=15% Min Typical charpy V-notch Impact value at -51°C=27 Joules Min.
Shielding Gas	CO_2 or Argon+20% CO_2 gas with flow rate of 10-15 liters/minute
Characteristics	Flux cored wire with highly basic slag having stable and smooth arc. good slag detachability and uniform weld bead. It produces radiographic quality welds with very low level of hydrogen and excellent low temperature notch toughness.
Polarity	DC wire positive
Size	1.20 mm, 1.60 mm
Welding Position	Down hand and Horizontal

Table 1 Product data supplied by MAILAM ® for their commercially available electrode MGA 40

Packing	12.50 Kgs spool sealed in polythene bag and shrink wrapped in a corrugated box.		
Welding parameter guidelines	Size	Range	Recommended
(With CO_2 shield)	1.20 mm 1.60 mm	90-300A,18-28V 125-400A,18-30V	180-300A,22-26V 220-350A,25-30V
Wire Extension(Sickout)	15-20 mm		
Mixed gases like Argon +20% CO_2 should be used with 1-2 Volts less than for CO_2.			

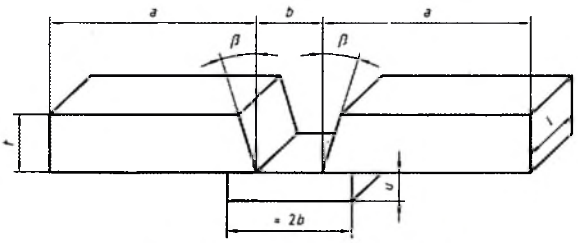


Fig. 1 : Design of welding groove according to ISO 15792-1 specifications

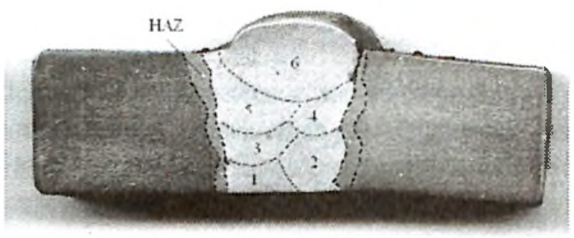


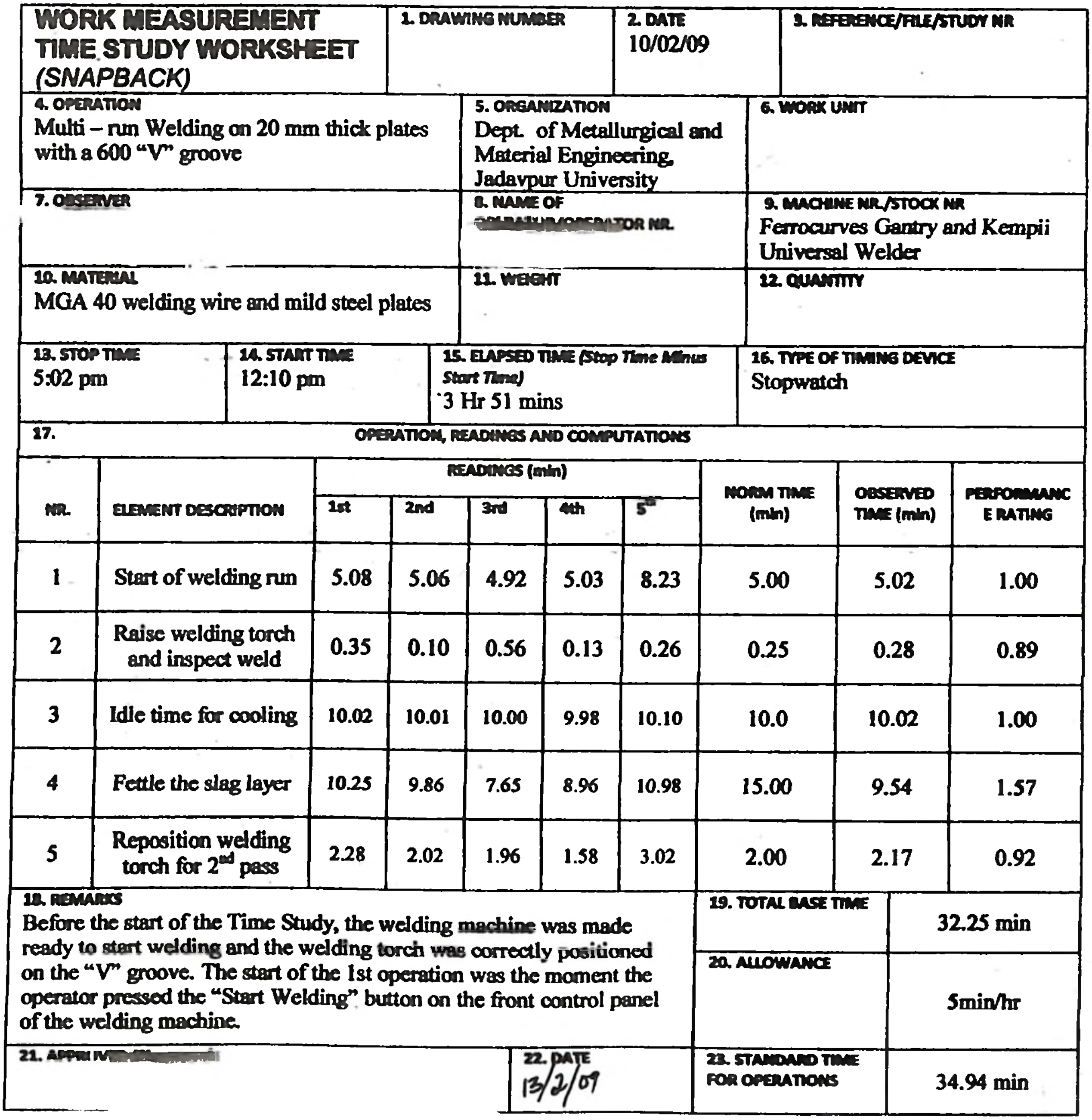
Fig. 2 : Macroetched seld section on a 16 mm thick plate

Table 2 : Dimensions of ISO standard groove design

Type	t	a	b	u	β	l
1.0	12	>= 80	10	>=6	10	>=150
1.1	12	>=90	12			
1.2	16	>=100	14			
1.3	20	>=150	16			
1.4	25	>=150	20			
1.5	30	>=200	25			
1.6	20	>=150	20			
1.7	25	>=150	24			

RELATION BETWEEN HAT INPUT AND PLATE THICKNESS:

The detailed flowchart of the method has been described in figure 3.The first and most important step was to form a relation between Heat input and the thickness of the plate. A large number of welds were done on varying plate thicknesses. In all cases a cross section of the weld was taken and first subjected to visual examination and macroetching. Samples which showed incomplete fusion, porosity, large HAZ or complete melt through pointed to incorrect heat inputs. Maximum metallurgical damage to the base metal was fixed at a HAZ region thickness of 3mm, any thicker and the welding heat input was decreased. The final heat input variables which gave relatively small HAZ and good penetration and no porosity was double checked by making all weld tensile specimens. Welded joins were considered satisfactory if the UST and YS values of the all weld tensile specimens were within 10% to that reported by the manufacturer. A



WORK MEASUREMENT TIME STUDY WORKSHEET (SNAPBACK)

1. DRAWING NUMBER

2. DATE 10/02/09

3. REFERENCE/FILE/STUDY NR

4. OPERATION Multi – run Welding on 20 mm thick plates with a 600 "V" groove

5. ORGANIZATION Dept. of Metallurgical and Material Engineering, Jadavpur University

6. WORK UNIT

7. O[redacted]ER

8. NAME OF [redacted]OR NR.

9. MACHINE NR./STOCK NR Ferrocurves Gantry and Kempii Universal Welder

10. MATERIAL MGA 40 welding wire and mild steel plates

11. WEIGHT

12. QUANTITY

13. STOP TIME 5:02 pm

14. START TIME 12:10 pm

15. ELAPSED TIME *(Stop Time Minus Start Time)* 3 Hr 51 mins

16. TYPE OF TIMING DEVICE Stopwatch

17. OPERATION, READINGS AND COMPUTATIONS

NR.	ELEMENT DESCRIPTION	READINGS (min) 1st	2nd	3rd	4th	5th	NORM TIME (min)	OBSERVED TIME (min)	PERFORMANCE RATING
1	Start of welding run	5.08	5.06	4.92	5.03	8.23	5.00	5.02	1.00
2	Raise welding torch and inspect weld	0.35	0.10	0.56	0.13	0.26	0.25	0.28	0.89
3	Idle time for cooling	10.02	10.01	10.00	9.98	10.10	10.0	10.02	1.00
4	Fettle the slag layer	10.25	9.86	7.65	8.96	10.98	15.00	9.54	1.57
5	Reposition welding torch for 2nd pass	2.28	2.02	1.96	1.58	3.02	2.00	2.17	0.92

18. REMARKS Before the start of the Time Study, the welding machine was made ready to start welding and the welding torch was correctly positioned on the "V" groove. The start of the 1st operation was the moment the operator pressed the "Start Welding" button on the front control panel of the welding machine.

19. TOTAL BASE TIME 32.25 min

20. ALLOWANCE 5min/hr

21. APPR[redacted]

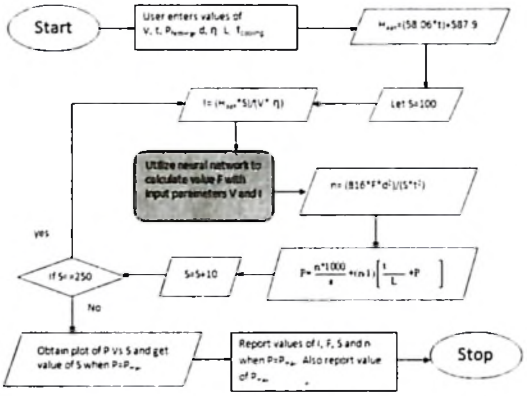
22. DATE 13/2/09

23. STANDARD TIME FOR OPERATIONS 34.94 min

Fig. 5 : Time study chart for multipass welding

been made on the exact interpass temperature. The actual study was made kept in mind the high volume industrial welding practices which in most cases are restricted to hot rolled mild steel plates. Since they are seldom subjected to any heat treatment either pre or post to welding, the exact interpass temperature is of lass importance. The temperature should be low enough to be safely handled by the worker.

In the present time study shown in figure 5, the worker was provided with a automated welding machine all setup to start welding, i.e. the compressor is up to rated pressure, the CO_2 system is properly purged and ready, etc. Here we also assume that the piece to be welded is properly set up on the machine with the welding torch correctly positioned



Variable	Description
V	Voltage used during welding
t	Thickness of plate in mm
$P_{fettling}$	Fettling speed of worker in min/mt
d	Diameter of electrode in mm
η	Arc efficiency factor
L	Length of weld in mt
$t_{cooling}$	Interpass cooling time in mins
H_{opt}	Optimum heat input
S	Torch travel speed in mm/min
I	Current flowing through the arc in Amps
F	Electrode feed rate in mt/min
n	Number of passes
P	Welding productivity in min/mt

Fig. 3 : Flowchart followed in obtaining the optimized welding parameters

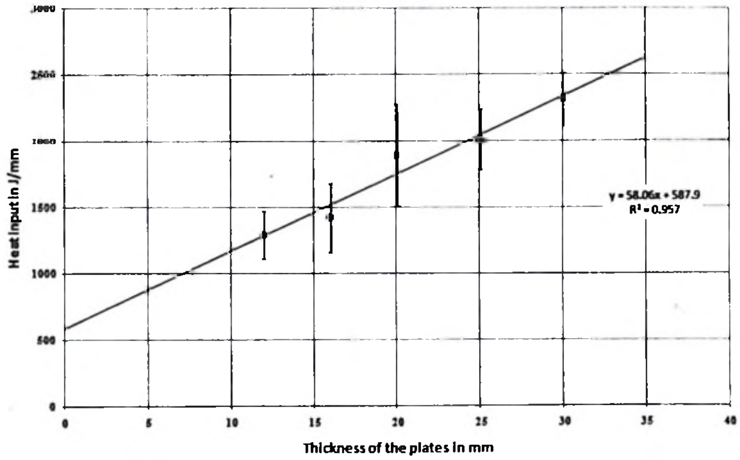


Fig. 4 : Plot of optimum heat input Vs plate thickness

constant potential difference of 25 volts and a horizontal travel speed of 200 mm/min. Heat inputs were varied by changing the current drawn, that is, by changing the wire feed rate. The results are plotted in figure 4. Linear curve fitting provided an empirical relation between the optimum heat input and thickness of the plate

$$H_{opt}(J/mm)=58.06t(mm)+587.9$$

CALCULATION OF WELDING PRODUCTIVITY

Automated welding adopted industrially are complicated processes consisting of many interdependent steps which all have a profound effect on time taken to complete the weld. These intermediate steps are both operator as well as machine dependant. Steps constrained by the operating and characteristic capabilities, are easier to take into account as compared to calculations based on worker or operator efficiency. Basically any and every activity that an operator performs when the actual welder is idle increases the effective time taken to complete the weld and hence decreases the productivity. These activities may span just a few seconds, for example putting on the welders` glasses or positioning oneself to start the run or possibly in tens of minutes like changing an electrode, or fettling the previous weld deposit.

These intermediate steps bear an even higher importance in multi run welding where time consuming fettling and grinding operations need to be done in-between passes. In an order to estimate the time taken for an average welder to accomplish these tasks, a detailed time study of welding was undertaken. Observations were made while a qualified welder from Garden Ship Builders and Engineers carried out a multi-run test weld on a 1mt long mild steel plate. Figure 5 shows the results of the time study. However time study using a single worker employed in one establishment may not be indicative of the average operator efficiency and hence the time study was undertaken just to ascertain the most time consuming steps that needs to be performed to complete a welding. To ensure no loss of generality during the development of the software, we have thus included worker efficiency for activities like fettling and grinding for the worker as user inputs.

During the course of the study, the following activities were observed to be essential.

- Weld run #1: After the required arrangements have been made, the operator selects the required welding parameters from the front panel controls of the welding machine and the weld run is initiated.
- Interpass cooling: Ideally for multi-pass welding, fettling and grinding operations follow a weld run. However just after a run the weld piece is mostly too hot to be safely handled by the operator and sufficient time must be given so that the test piece may reach lower temperatures. Here no reference has

above it. However such is almost never the case in actual industries and adequate setup time is required to start welding. The following is a brief discussion on these other time consuming activities of automated welding.

- Fettling and grinding: After a weld run the weld bead is covered in a layer of slag and if care is not taken to remove the last traces of it, the resulting welding may be filled with slag inclusions and other defects. First a chipping hammer is used to chip away as much of the slag as possible and then a medium grit grinder is used to remove as much of the surface oxidation as practicable.
- Electrode setup: Most specialized MIG welding are electrode specific and before any welding may be started the appropriate electrode spool must be installed in the welding machine, and sufficient length of the wire pinched till we have the required length of stick-out at the torch head.
- Gas system setup: All MIG welding requires either CO_2 Ar and other or their mixtures as shielding gasses. In the workshop all the required gas lines were connected. Time was taken by the operator to open the CO_2 regulator to desired pressure for the required gas flow rate and to purge the gas lines free of any residual gasses by CO_2
- Setup of weld-piece: The worker was provided with two 16 mm thick mild steel plates with required 600 "V" grooves already machined on to the edges to be joined. Setup time was taken as the time taken to position the pieces on the pneumatic vice and align it just along the direction of travel of the welding torch.

Apart from the activities mentioned above, there were several other identified operator activities, which were neglected. Some of these activities were of very small duration and negligible in reference to the other more time demanding steps. Furthermore these steps like putting on the welding glasses, positioning oneself to start the welding etc, take such small time that they are well within the relatively large errors associated with this type of time study and such accuracy are not essential. However there are some activities that are more time consuming but still we have neglected them for the high level of deviation from one operator to another, these activities including breaks from work due to fatigue and other mechanical glitches etc.

With a fairly accurate picture of the time study, an attempt was made to derive an equation that relatively accurately calculates the time required to complete a welding.

Let T = time required to complete the multipass welding

T = (Electrode setup time)+(Gas Setup time)+(Time to setup weld piece)+ n*(Time of welding run)+(n-1)* (interpass cooling time)+(n-1)*(Fettling and Grinding Time) Equation 2

Where n= number of passes required to complete the welding.

Here we have assumed that the final surface finish after the last weld run in not the responsibility of the welder and the operator does not spend time fettling and grinding the last run. Now in Equation 1, Electrode setup time and Gas setup time are largely constants, independent of the welding parameters and the number of passes, to maximize the productivity we must minimize the following term, assuming our time starts from the moment the arc is struck for the first weld run. It is also assumed that the welder has no responsibility of either cooling or fettling after the weld is over that is after the last run has been completed.

T_1 = n*(Time of welding run)+(n-1)* (interpass cooling time)+(n-1)*(Fettling and Grinding Time) Equation 3

So let L be the length of weld in meters
T1=time taken in minutes to complete the welding
n=number of passes
s=speed of the welding in mm/minute

$$\text{Time of welding run}=\frac{(L*1000)}{s}\ \text{minutes}$$

Equation 4

Let $P_{fettling}$ be the time taken by the operator to fettle unit length of a weld in minute/meter.

Therefore

Fettling and Grinding time = $L*P_{fettling}$ minutes Equation 5

Combining equations 2,3 and 4

$$T_1=\frac{(n*L*1000)}{s}+(n-1)*t_{cooling}+(n-1)*P_{fettling}*L$$

Equation 6

Where $t_{cooling}$ is the actual time taken for the work piece to sufficiently cool down, in minutes.

Productivity P, of the welding is defined as the time in minutes taken to complete one meter of the welding

$$\therefore P=T_1/L=\frac{n*1000}{s}+(n-1)*\frac{t_{cooling}}{L}+(n-1)*P_{fettling}$$

$$\Rightarrow P=\frac{n*1000}{s}+(n-1)\left[\frac{t_{cooling}}{L}+P_{fettling}\right]$$

The above equation has been used in our productivity optimization. The exact values of n and s have been calculated from other input values entered by the operator like voltage and plate thickness and length of plate. $t_{cooling}$ is to be entered be obtained by timing how long it took a similar test weld to sufficiently cool down, while $P_{fettling}$ for a particular operator may be obtained by noting the time he takes to clean 1 meter of a test weld. For example in the time study shown in figure 5, the operator has a fettling productivity of 9.54 min/mt of weld.

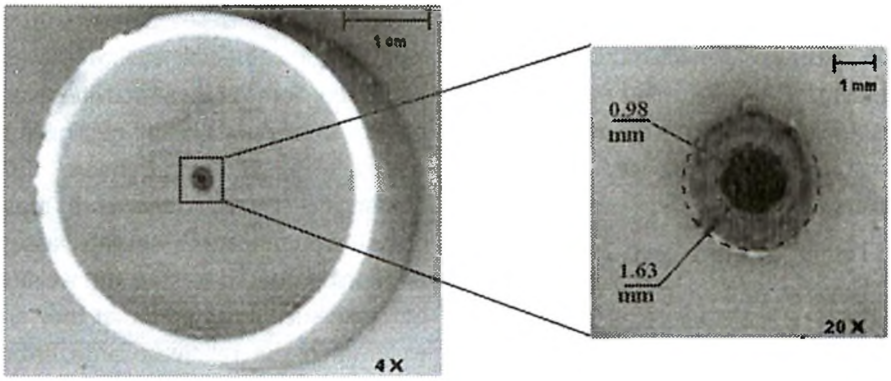


Fig.6 : Photo-micrographs of MGA 40 MIG welding electrode (cross section)

CALCULATION OF NUMBER OF PASSES

The number of passes required to fill up the weld groove was done by dividing the total volume of the weld groove by the volume of metal deposited in a single pass. We have assumed a 60^0 "V" groove on a metal of thickness t mm, and of length L mt.

So volume of the groove = $(t^2*1000L)/\sqrt{3}$ cubic mm.

From Equation 4,

$$\text{Time of welding run} = \frac{(L*1000)}{s} \text{ minutes}$$

Volume of metal deposited per welding run = $X(25*10^4 \ *F\pi d^2L)/S$

Where X= the volume fraction of metal in the flux cored welding electrode.

$$n = \frac{X(25*10^4 \ *F\pi d^2)/S}{(t^2*1000)/\sqrt{3}}$$

The value of X was calculated by mounting a piece of the welding wire perpendicularly in epoxy resin and examining it under low magnification. Figure 6 shows the micrographs. The radius of the core is observed and the volume fraction of the metal is calculated.

$X=(R_{core})^2/(1.6^2-R_{core}^2) = 0.98^2/(1.6^2-0.98^2)=0.60$

Therefore $n=(816*F*d^2)/(S*t^2)$

CALCULATION OF THE RELATIONSHIP BETWEEN FEED RATE AND VOLTAGE & CURRENT

ANNs are collections of very simple "computational units" which can take a numerical input and transform it, usually via summation, into an output. They have learning ability as human brain. Since ANNs can evaluate the nonlinear behaviors between the data, they can solve real world problems. In a ANN analyze first the architecture must be determined then learning process begins after learning the analysis finishes with testing the network with the data that has not presented to network ever before. For any given ANN, set of connection weight values, and training set there exists an overall root mean squared (RMS) error of prediction. [Ref 9]

Artificial neural network analysis was useful for deriving a relationship between the parameters as no particular theoretical relationship existed. Therefore data from the Robotic MIG Welder was used to train, test and validate the network.

A network was developed with the help of tool called MATLAB. A network was built with the help of the Neural Network Toolbox of MATLAB Version 7.3.0.267 (R2006b). The back propagation algorithm was utilized which gave the best representation of the data. The network consisted of two input nodes and one output nodes. The input nodes consisted of the Voltage & Current and the output was the feed rate. Then the optimum number of hidden nodes was found by error and regression analysis. The Levenberg-Marquardt theorem was utilized as it had the fastest of all the learning techniques, Since it gives extremely fast convergence with lower RMSE (Root Mean Square Error).

RESULTS FROM THE NEURAL NETWORK ANALYSIS

The results obtained from the analysis were extremely satisfying and a very high value of regression was obtained. Table 3 shows a few sample tada points that were used to train the neural network.

A graph was plotted for regression values obtained for various hidden nodes. The trend showed that regression increases as lesser nodes are insufficient to model the data set and higher nodes also seem to over fit the training data. Therefore an optimum number of nodes are selected which comes out to be the one giving highest regression value, that is 12.

The following performance curve was obtained on training, testing and validation of the data using MATLAB. The performance of the network was satisfying with the MSE of 0.016. (Figure 8)

Table 3
Some sample data points used for the ANN

Voltage (V)	Current (A)	Feed rate (m/min)
19.9	117.2	4.51
20.2	117.2	4.50
20.1	115.0	4.52
19.9	162.8	5.09
19.9	165.2	5.02
20.0	160.5	4.99
20.1	160.1	5.03
20.3	165.5	5.06
25.1	105.0	4.01
25.0	110.0	4.03
24.8	108.0	4.00
25.0	108.0	3.99

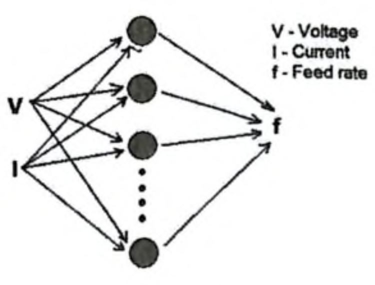


Fig. 7
Genetic diagramof the ANN used

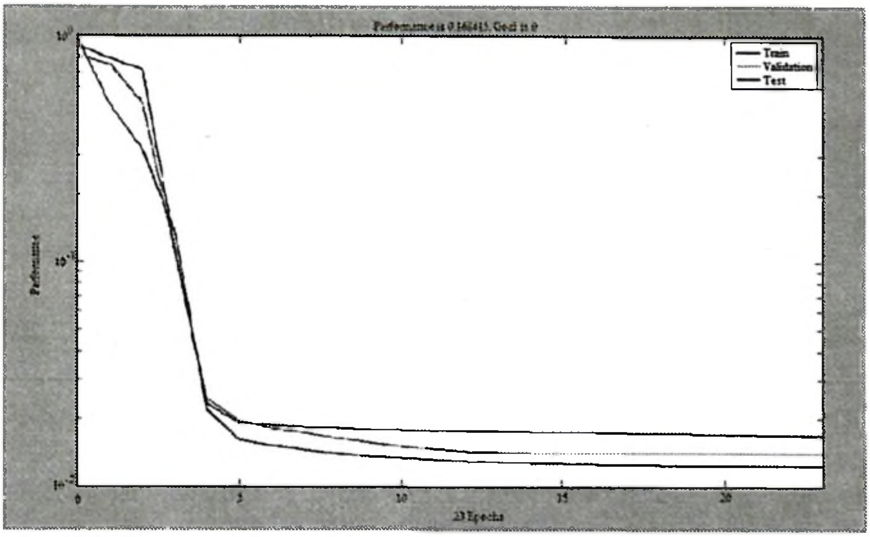


Fig. 8 : Performance curve obtained for the artificial neural network

The regression plot of output vs target was obtained with 10 hidden nodes, and regression value of 0.97077 was reached. This was quite an acceptable model for the above problem.

SIMULATION

The next step was to build an interface so that the operator would not have to go for the mathematical hassles. The same was also done with the help of MATLAB. In the designed simulation the following parameters as input which can help the optimization of the feed rate(f), travel speed(S) and number of passes(n) Voltage(V), thickness of plate(t), arc efficiency factor(e), fettling time(Ft), and Wire diameter(d). The screenshot of the Input dialog is shown in Figure 10. This enabled the simulation to be user friendly so that a welder could check his current requirements quickly before going for the actual run. This can increase the productivity in manifolds as the tiresome repeated experimentation will not be required.

CONCLUSION

The algorithm thus developed is both robust as well as user friendly, as it allows a certified welder with limited knowledge about the metallurgical aspects of the welding to effectively use the software. Its simplicity lies in the fact that it uses inputs that are easily understood and measured by the operator instead of relying on complex physical quantities, and it also provides its output as front panel settings that may be easily entered into the welding machine by a welder. Though further developmental work needs to be done before it can be put to general use in the welding shop, the basic idea can effectively provide adequate optimization between both metallurgical as well as the economic aspect of the welding process, especially where large scale weldings of superior quality needs to be obtained.

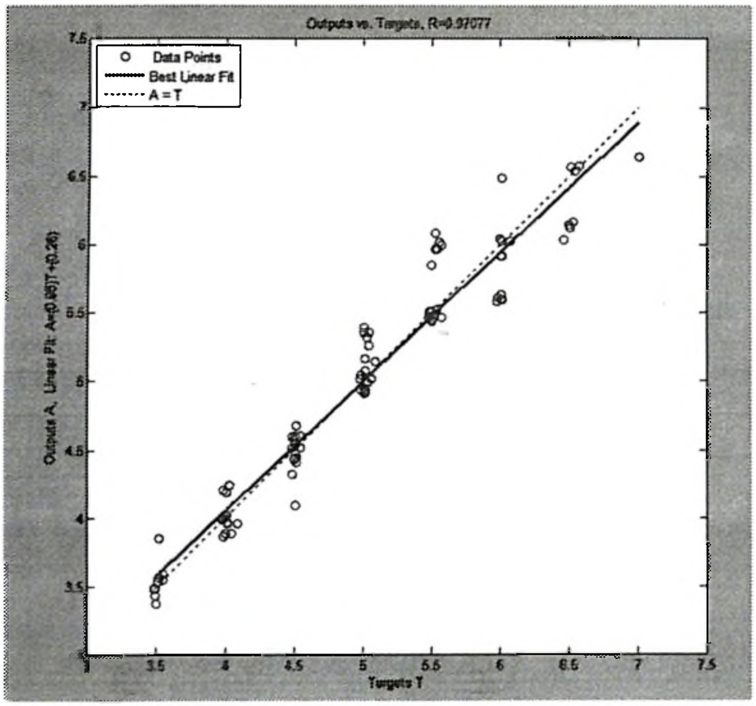
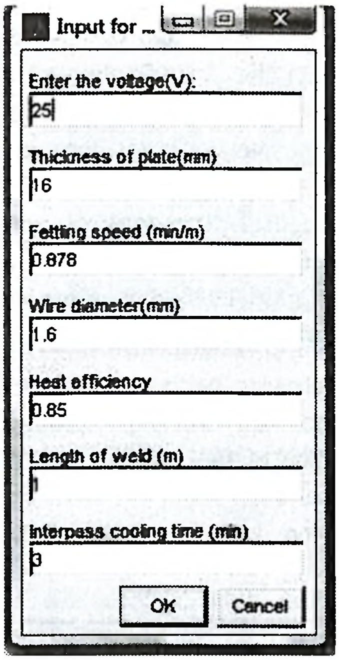


Fig. 9 : Linear fit results for resultant network



Enter the voltage(V):
25

Thickness of plate(mm)
16

Fetting speed (min/m)
0.878

Wire diameter(mm)
1.6

Heat efficiency
0.85

Length of weld (m)
1

Interpass cooling time (min)
3

Fig. 10 : Input window for MATLAB Code

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